Air Change Rate and Airtightness in Buildings

M. H. Sherman
editor

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Foreword

This publication, *Air Change Rate and Airtightness in Buildings*, contains papers presented at the symposium of the same name held in Atlanta, Georgia on 16–17 April 1989. The symposium was sponsored by ASTM Committee E-6 on Performance of Building Constructions and its Subcommittee E06.41 on Infiltration Performances. M. H. Sherman, Lawrence Berkeley Laboratory, presided as symposium chairman and was editor of this publication.

Contents

Overview

Air infiltration has been a subject of active research in many countries since the energy crisis of the mid-1970s with early work dating back to early in the century. Air infiltration touches on many topics in buildings research, not the least of which include energy, indoor air quality, and human comfort. Most residential buildings are ventilated primarily by air infiltration, and over a third of the space conditioning energy requirements can be typically attributed to it. The desire to provide adequate ventilation at minimum energy cost, combined with the complex nature of the physical processes involved in air infiltration, has effected the continuing interest in the topic.

While the theoretical scientist may be interested in the subject of air infiltration for its intriguing nonlinearities and other subtleties, those of a more practical bent have specific needs. Questions such as "How tight can buildings be and still supply adequate ventilation?" can only be answered if test methods exist that allow the appropriate quantities to be measured. Similarly, to answer other of the big questions such as "What is the distribution of air leakage in North American housing?" or "How much of an impact will weatherization have?" requires that these test methods get used and the necessary data collected for analysis. Finally, questions regarding how well one can know the values measured by the test methods require that the precision and bias of the measurements be determined.

ASTM has responded to these needs by developing consensus test methods that allow one to measure and study the important properties relating to air infiltration. In November 1975 ASTM subcommittee E06.41 on Infiltration Performances decided to develop standard practices relating to air infiltration: one on measurement of infiltration using tracer gasses and one on the measurement of airtightness using fan pressurization. At the time of this writing the current versions of these standards are E 741-83: Test Method for Determining Air Leakage by Tracer Dilution, and E 779-87: Method for Determining Air Leakage Rate by Fan Pressurization, respectively. Since those two fundamental standards were completed, ancillary ones have been written: E 1186-87: Practice for Air Leakage Site Detection in Building Envelopes, and E 1258-88: Test Method for Airflow Calibration of Fan Pressurization Devices. The consensus process in this area is continuing, and a revision of E 741 is currently underway.

ASTM has actively supported technical efforts surrounding its standards by sponsoring symposia (of which this book documents the third) on air infiltration. In March 1978 the first two standards were presented together with papers dealing with related topics in a symposium entitled Air Change Rate and Infiltration Measurements; the proceedings were published as a special technical publication, *Building Air Change Rate and Infiltration Measurements, ASTM STP 719.* This symposium focussed on measurement techniques and included limited data taken by researchers. In April 1984 a symposium entitled Measured Air Leakage of Buildings brought forth a wide variety of data that had been taken with the two standards; the proceedings were published as a special technical publication, *Measured Air Leakage of Buildings, ASTM STP 904.* This symposium focussed on (relatively) large sets of field data, which could then be used to learn something about the buildings—of various types—from which they came.

Like the 1978 symposium, the current symposium contains information on state-of-the-art techniques for measuring air change rates. In the intervening decade novel techniques for measuring more complex phenomena have been developed. The Axley and Persily papers describe some simplified methods for making single-zone air change rate estimates from tracer gas measurements; the Fortmann and Harrje papers deal with the more complex multizone tracer techniques.

Similarly, airtightness measurement techniques have also developed since 1978. Hayakawa and Shaw describe techniques for measuring the airtightness of large single-zone buildings. Brennan and Modera discuss various techniques for making these leakage measurements in a multizone environment. Because of the relative ease and invariability of making airtightness measurements compared to tracer gas testing, far more tightness tests are done. Ek, Love, and Perera use pressurization techniques to make airtightness measurements in buildings from manufactured housing to row housing to offices.

Like the 1984 symposium, many of the papers in this symposium contained measured data on either airtightness or air change rates, some from large datasets. All of the datasets serve to shed light on various aspects of air infiltration, but the Hadley and Parker papers, which refer to the large database of data being accrued in the Pacific Northwest, may be the most notable. The NOrthwest Residential Infiltration Survey (NORIS) may represent the first statistically justifiable dataset on both airtightness and ventilation.

A major thrust of this symposium, which was lacking in the other two, was to consider the error associated with making field measurements using various techniques. Harrje and Shaw use multiple techniques to measure the same quantity and compare the results. In this field, for which primary standards are lacking, such intercomparisons are the best—perhaps the only—way to estimate the absolute accuracy of some techniques. Charlesworth, Nankta, Tanribilir, and Yoshino all discuss the comparison of different, but related, measured quantities.

Many factors can cause error in a measurement of either airtightness or air change rate. These errors can arise because of instrument error, inappropriate choice of analysis technique, or poor measurement technique. Flanders and Kvisgaard found that occupancy can have very significant effects on the results of air change rate measurements—both on the tracer gas measurement itself and on the interpretation of the result. Due to the nonlinear nature of both the physical processes and some of the analysis techniques, there can be a strong coupling between the precision (normally associated with random errors) and accuracy (normally associated with systematic errors). Lagus and Modera use simulation tools to estimate errors in tracer gas and pressurization tests, respectively, due to factors not taken into account in normal analyses.

An ASTM symposium such as this is intended to elicit information relevant to the development and revision of consensus standards. Accordingly, this symposium focussed its attention on those issues and did not attempt to answer the larger questions such as those associated with air quality, stock characterization, etc. Indeed, the answer to many of these big questions are still beyond the reach of current research. This symposium did, however, hone the tools that those wishing to answer these questions must use.

This book would not have been possible without the work of a large number of dedicated individuals who made my job easy. First and foremost, of course, are the authors who wrote (and in large measure reviewed) the papers that make up this volume. My personal thanks must be given to the ASTM editorial staff for accomplishing the arduous tasks associated with the organization of the symposium, the coordination of review, and the general editioral support. Special thanks must also be given to the session chairmen for their efforts.

When exploring any field of research, understanding the potential of the results leads to enlightenment, but understanding the limitations of the results leads to wisdom. In the field of air infiltration the first two volumes have helped to enlighten us. It is my fervent hope that this volume will help to make us wise.

Max H. Sherman

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Tracer Gas Techniques

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David L. Bohac,[3] Ted W. D'Ottavio,[2] and Darryl J. Dickerhoff[3]

Tracer Gas Measurement Systems Compared in a Multifamily Building

REFERENCE: Harrje, D. T., Dietz, R. N., Sherman, M., Bohac, D. L., D'Ottavio, T. W., and Dickerhoff, D. J., **"Tracer Gas Measurement Systems Compared in a Multifamily Building,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 5–20.

ABSTRACT: The more complex building poses additional challenges to air infiltration measurement, especially in the case of multiple zones and rooms. Today's technology has provided us with a number of measurement choices which include the constant concentration single-tracer gas system, multitracer gas systems using the mass spectrometer, and perfluorocarbon multitracer systems both passive and active. This paper compares simultaneous field measurements in a Princeton-area multifamily building using each of these tracer gas–based air infiltration systems. Personnel from Princeton University, Lawrence Berkeley Laboratory, and Brookhaven National Laboratory were involved in the air infiltration measurement studies. Air infiltration rates in the various zones in each building are compared as well as the ease of implementation of the various approaches in these comprehensive measurements. Sources of errors using the various techniques are discussed.

KEY WORDS: airflow, infiltration, tracer gases, multiple zones, measurement systems

During the past decade, there have been major advancements in the measurement of airflows in buildings. Because of energy considerations, efforts often have concentrated on air infiltration documentation for the building as a whole, since these natural airflows typically may represent 20 to 40% of the heating load in residential buildings. Today, concerns extend beyond air infiltration into the building and place new emphasis on multiple zones and airflow between zones, since both contaminant movement and energy use must be evaluated. Such airflow documentation has required the development of new instruments and measurement concepts.

Although airflow measurement systems have probed a variety of ventilation questions and a variety of tracer gases have been compared [*1*], unfortunately there has been limited emphasis on addressing the questions of how the measurement systems and techniques compare with each other (for example, Ref. 2). This study provides such initial comparison testing in a multifamily building, so as to evaluate more fully the capabilities of each measurement approach and determine the relative strengths and weaknesses of the methods.

Site of the Comparison Tests

The building site chosen for the tests was the Hibben Apartments on the Princeton University campus in Princeton, New Jersey. This eight-story building has housed junior

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faculty and staff since 1965. Ninety-six families occupy two-story apartments in the building. An unoccupied apartment in the lower level of Hibben was used as one of the areas for the airflow measurements and also housed the variety of equipment used during the weeks of the study, which took place in February and March of 1988.

Choices for the measurement zones were based on building accessibility and the capabilities of the measurement equipment. Within the test apartment was a kitchen-living zone and a bedroom-bathroom zone. An apartment with ventilation measurement access to the upstairs and downstairs zones was on floors one and two of the building. Next to the basement apartment was a storage room as well as the mechanical services room; the latter had mechanical exhaust 24 h each day. From these spaces one had access to four or more zones for the test comparisons. The zones are outlined in Table 1.

The Measurement Systems

Each of the laboratories involved in these tests has developed distinctly different tracer gas approaches to the measurement of air infiltration/ventilation. These are described in the following paragraphs and are shown in Fig. 1. Table 2 provides some insight into the strengths of these individual approaches. Also described are the analysis methods used. These are not full descriptions, but rather are provided to convey the analysis concepts.

Constant Concentration Tracer Gas (CCTG) Method

The constant concentration tracer gas system (CCTG) employed by Princeton University depends upon careful maintenance of a target tracer gas concentration in each of up to ten zones to be measured [*3,4*]. The present equipment uses a single tracer, sulfur hexafluoride (SF_6), together with ten tracer injection valves and sequenced sampling. Injection takes place at the circulating fan or at that place in the individual room where natural air currents will help distribute the dilute tracer gas mixture. This is a closed-loop control operation since the system uses (or feeds back) information of the measured concentration and estimated infiltration in order to maintain zone concentrations at the target value. The digital optimal adaptive proportional control algorithm used to compute the injection rate is carefully designed to minimize deviation from the target concentration [*3*]. Readings of just how closely the tracer gas target concentration has been achieved is an excellent indication of measurement system performance.

The computer performs these functions and also keeps a running account of each zonal air infiltration rate, which is approximately proportional to the tracer gas requirements for that zone. The actual CCTG measurement system consists of three modules: the gas chromatograph, which employs an electron capture detector; molecular sieve columns; and backflushing of column flows to achieve a 30-s tracer concentration analysis. The tracer injection module uses a controlled upstream pressure to computer-controlled individual solenoid valves and calibrated orifices to provide a variable flow to each zone. The sampling

TABLE 1—*Details of the test zones.*

Zone	Description	Volume, m^3
1	Upstairs apartment	200
2[a]	Bedroom/bath downstairs apartment	59
3[a]	Living room/kitchen downstairs apartment	111
4[a]	Basement storage room	152

[a]Mixing fans used to increase room circulation.

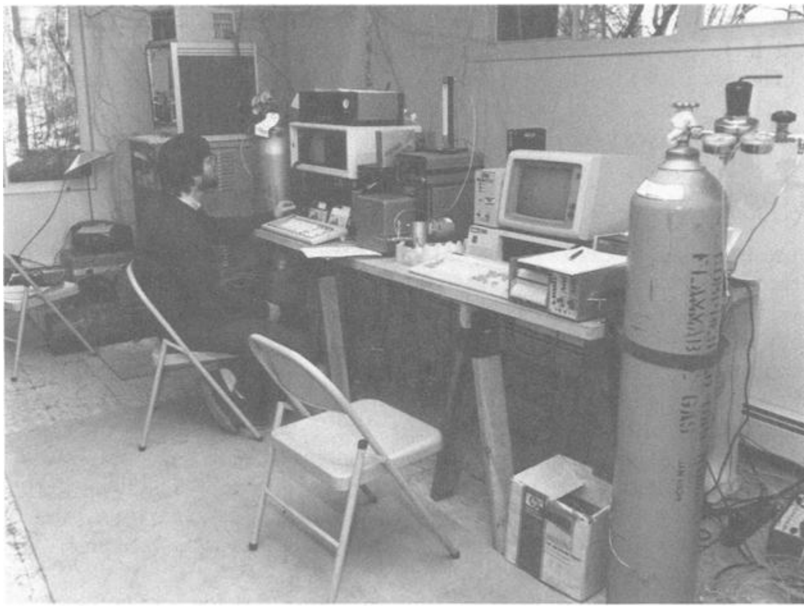

FIG. 1—*The array of airflow measurement systems in the living room of the basement test apartment. From left to right are the multiple tracer measurement system (MTMS), the constant concentration tracer gas (CCTG), and the "real time" version of the perfluorocarbon tracer (PFT). Two other versions of the PFT systems are not shown.*

TABLE 2—*Attributes of the various tracer gas systems.*

CCTG
1. Real-time
2. May be used in many (10 or more) zones to determine infiltration (i.e., airflow from outside)
3. Automated for unattended operation after set up, modem communication
PFT-CATS
1. Quickly installed
2. Determines interzonal flows
3. Low-Cost for long-term application
MTMS
1. Real-time system
2. Determines interzonal flows
3. Insensitive to rapidly changing conditions

module is programmed for the number of zones or repeat measurements that are all controlled by a microcomputer, which also handles the data acquisition requirements and routinely makes use of a modem to transmit data from the building to the lab.

CCTG Analysis—For the analysis of the data, each zone is treated separately. It is assumed that the concentration of the airflows between the zones is at the target level. Thus, the tracer injection rate responds only to changes in zone infiltration rate and not interzone rates. Since the concentration in the zone does not stay exactly at the target, the computation method considers both the concentration and injection rate data. This is accomplished by performing a least-squares regression analysis of the data over the specified time period, normally 1 h. Instrument error has proven generally to be of the order of 2.5% for the detector. The uncertainty of the gas concentration is ±2%, and the calibration gas uncertainty is ±1%. Injection rate uncertainty is ±0.5% with good mixing, and typical air infiltration variation errors of ±5% are typical.

Multiple Tracer Measurement System (MTMS) Method

Lawrence Berkeley Laboratory's multiple tracer measurement system (MTMS) injects a unique tracer gas into each zone [5]. One injection and one sample tube are required for each zone, and both have continuous flow. Air sampled from each zone is introduced sequentially into a residual gas analyzer (RGA, that is, a quadruple mass spectrometer), which measures the intensity of selected peaks that uniquely identify and quantify the concentration of all the tracers in each zone. At present five tracer gases have been used successfully, and a capability of eight has been demonstrated in the lab. In order to keep concentrations within acceptable limits, MTMS attempts to keep the concentration of each gas at a constant value in the zone in which it is injected. Since (in contrast to the CCTG system) the analysis is not dependent on holding constant concentration, the control is optimized for stability rather than fast response, using basically the same algorithm as that employed by the CCTG.

MTMS Analysis—The analysis of the data uses the full multizone continuity equation, which includes both interzonal flows and uses the time derivative of the concentration. The matrix of continuity equations is integrated over a user-selected time constant and then is solved for the individual flow rates. Next, any flow rates which are physically impossible are adjusted to minimize the disallowed terms. The uncertainties then are calculated. This procedure is repeated consecutively to produce time-series data. The accuracy of the RGA is approximately 0.05 ppm with a linearity of better than 1%. The mass flow controllers are calibrated to approximately 0.5% of full scale. The combined instrument error is approximately 2%, but the estimated flow rates from any of such tests are rarely that good because of incomplete mixing. The uncertainties in the concentration and flow rates associated with the mixing in the room will dominate the error and will be the same for all the techniques. In this four-zone study, each of the 16 concentrations was measured every 4 min. The time constant in the analysis was set to 30 min.

Perfluorocarbon Tracer Measurement Techniques (PFT) Method

The ventilation measurement technology employed by the Brookhaven National Lab (BNL) involves the release and measurement of multiple perfluorocarbon tracers (PFTs). The PFTs are emitted at a steady rate by miniature permeation sources with a different PFT being emitted into each well-mixed zone of the building. Three methods currently are available for measuring the PFT concentrations in the building zones:

1. Passive adsorbent tubes known as CATS (capillary adsorption tube sampler).
2. BATS (Brookhaven atmospheric tracer sampler), a programmable, pumped device which automates the collection of air onto 23 adsorbent tubes.
3. A real-time instrument which both collects and analyzes sampled air for PFTs with a resolution of about 5 min.

Samples collected using either CATS or BATS are returned to the laboratory where they are analyzed using gas chromatographic separation and electron capture detection. A more detailed description of these measurement techniques can be found elsewhere [6,7]. All three of these sampling devices were used for this intercomparison with both the BATS and the real-time analyzer collecting samples every 15 min and the CATS collecting integrated samples over the entire 6-h test. The results reported in this paper for the test period are from samples collected on the BATS.

PFT Analysis—The BNL ventilation flows were computed by inserting the measured tracer concentrations and the known emission rates into a multizone model consisting of N^2 mass balance differential equations and $2N + 1$ flow balance equations, where N is the number of well-mixed building zones. Derivatives within the mass balance equations were evaluated using a five-point numerical technique around the point of interest. In cases where there were known changes in building ventilation (windows shut, doors opened, etc.), derivatives were computed using a five-point technique which projects forward or backward from the time of the ventilation change. Errors on the computed flows were estimated using a first-order error analysis technique. These error estimates are not presented in this paper. A further description of the techniques used by BNL to generate ventilation flows and their errors can be found elsewhere [8].

System Comparison Planning

The decision as to the number of tests and when to test attempted to take into account such factors as the number of tracers available and the concentration levels employed. In the case of the perfluorocarbon tracers we are talking about concentrations of the order of 1×10^{-12}, yet with the LBL mass spectrometer approach, gas concentrations were parts per million, or six orders of magnitude higher. The Princeton constant-concentration approach using sulfur hexafluoride was operated at the parts per billion level, or roughly the halfway point of the two other systems. Because of such a spread in concentration levels, the BNL team deployed their system early in the test period to obtain information prior to the presence of high concentrations of other tracer gases so as to evaluate possible tracer interference. Indeed, the real-time measurements of low-concentration perfluorocarbon tracers were influenced by the high concentrations of other gases. However, the passive sampler and programmed sampler techniques using the more sophisticated gas chromatographic analysis were able to overcome such interference problems.

To test the response of the three systems, deliberate changes were made in the ventilation in the test apartments. At the start of the test, all windows were closed, and the door between Zone 2 (bedroom/bathroom) and Zone 3 (living room/kitchen) was placed slightly ajar (opened only 8 cm). About 2 h into the test, at precisely 17:10, a living room window was opened. Then, at 18:25, the door between the two zones was fully opened. Finally, at 19:40, the apartment was returned to its original conditions by closing the window and again placing the door 8 cm ajar. The only other known change in ventilation occurred when, shortly after 16:00, workmen left the mechanical services room and closed its outside doors. The mechanical exhaust fan then was able to create a greater draw on the adjacent test apartment and storage room, which was evident from the tracer results.

Discussion of Results

Results from the measurements in the comparison testing will first be discussed using time histories during and prior to the test period, 24 Feb. 1988, covering the hours between approximately 13 to 14:00 and 19 to 20:00. All systems were operational during the majority of this period except as noted. Following the test period an additional period, lasting for a number of days, allowed comparison between the CCTG and PFT.

Measured Infiltration into Zone 2 (Living Room/Kitchen, Basement Apartment)

The air infiltration into Zone 2 is characterized by two distinctly different periods as shown in Fig. 2: an initial period in the ~40 to 100 m³/h range, followed by a window opening at 17:10 hours, and then rapidly increased air infiltration to the ~150 to 300 m³/h level. The actual values of airflow depend on which measurement system is used. The first period finds the air infiltration measurements in good agreement (criss-crossing values, ±20% maximum

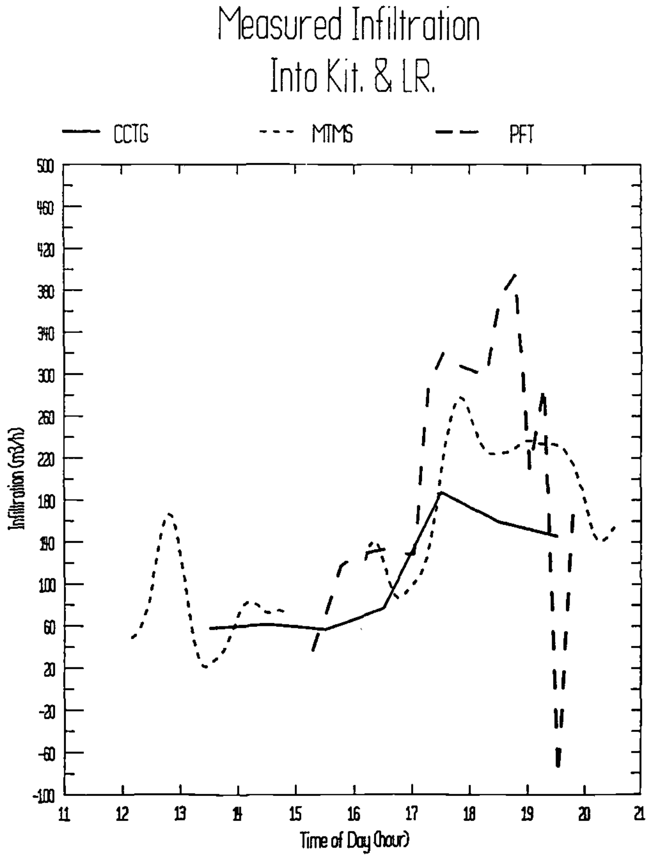

FIG. 2—*Three airflow measurement systems evaluating the air infiltration into Zone 3, kitchen and living room. Airflow changes have been introduced at several time intervals.*

disagreement); but the second period finds the CCTG predicting approximately 170 m^3/h and PFT-BATS and MTMS averaging approximately 240 m^3/h (i.e., the CCTG values are 29% lower).

The fluctuations in the PFT-BATS result from 18:25 to 19:40 were because the door between the two zones was opened, causing the two different tracers used in the two zones to become intermixed (and no longer representing a separate zone), which causes the multiple differential equation solution to become ill-defined. This is demonstrated by the PFT results in Table 3 listed for each 15-min measurement period. Note that in the living room/kitchen zone, before the window was opened, the infiltration rate was about 130 ± 16 m^3/h. After the window was opened, the rate immediately jumped up 300 to 320 ± 44 m^3/h, with a standard deviation of still less than ±15%.

However, after the door was opened and the two zones became intermixed, the infiltration rates in this zone (Zone 3) as well as the bedroom/bathroom zone (Zone 2) were calculated with a high degree of uncertainty, with standard deviations of ±100% and more, which means the values are meaningless. Averaging methods in the MTMS and CTGG procedures tend to mask the flow variations.

When the two zones are calculated as a single zone (Fig. 3), that is, the whole test apartment, for the five 15-min periods with the door open, the infiltration rates are quite

TABLE 3—*Effect of high interzonal mixing on determination of individual zonal infiltration rates: test apartment (PFT 15-min period results with errors).*

		Infiltration Rate ± Standard Deviation, m³/h		
Period Start Time	Action[a]	Bed/Bath (Zone 2)	Liv/kit (Zone 3)	Test Apt (Zones 2 and 3)[b]
15:10	Door ajar and windows closed	30 ± 12	38 ± 37	68 ± 39
15:25		31 ± 9	76 ± 18	108 ± 20
15:40		25 ± 9	118 ± 18	143 ± 20
15:55		23 ± 7	128 ± 15	152 ± 17
16:10		17 ± 6	131 ± 15	148 ± 16
16:25		15 ± 5	134 ± 16	149 ± 16
16:40		14 ± 5	129 ± 17	143 ± 18
16:55		20 ± 5	129 ± 17	149 ± 18
17:10	LR window opened	40 ± 18	291 ± 42	331 ± 46
17:25		12 ± 21	321 ± 44	333 ± 48
17:40		11 ± 18	310 ± 43	320 ± 47
17:55		19 ± 22	304 ± 44	323 ± 50
18:10		10 ± 22	299 ± 46	308 ± 51
18:25	Door opened	−67 ± 317	374 ± 343	300 ± 42
18:40		−62 ± 973	396 ± 1098	317 ± 44
18:55		91 ± 356	210 ± 452	317 ± 45
19:10		18 ± 246	291 ± 318	303 ± 44
19:25		423 ± 761	−83 ± 827	324 ± 46
19:40	Door ajar and windows closed	9 ± 27	169 ± 34	177 ± 44
19:55		12 ± 22	163 ± 32	175 ± 38

[a]Door was between Zones 2 and 3; window opened at 17:10 was in living room.
[b]Test apartment rate was the addition of Zones 2 and 3 infiltration rates except when the door was opened, which requires separate zone reduction calculation.

TABLE 4—*Comparison of hourly average infiltration rates: test apartment.*

	Infiltration Rate, m³/h					
	Zone 2			Zone 3		
Hour	CCTG	MTMS	PFT	CCTG	MTMS	PFT
13	30	38	...	59	58	...
14	19	26[a]	...	62	72[a]	...
15	28	86[a]	...	58	144[a]	...
16	14	19[a]	17	78	133[a]	131
17	36	39	20	189	305	277
18	32	46	−19[b]	160	303	335[b]
19	28	54	129[b]	147	244	143[b]

[a]The system was restarted three times between 14:50 to 16:10. The data during this time are subject to greater error.
[b]Door between Zones 2 and 3 open from 18:25 to 19:40. Large errors for individual zone rates during this time but reasonable for two zones combined into one (see Table 6).

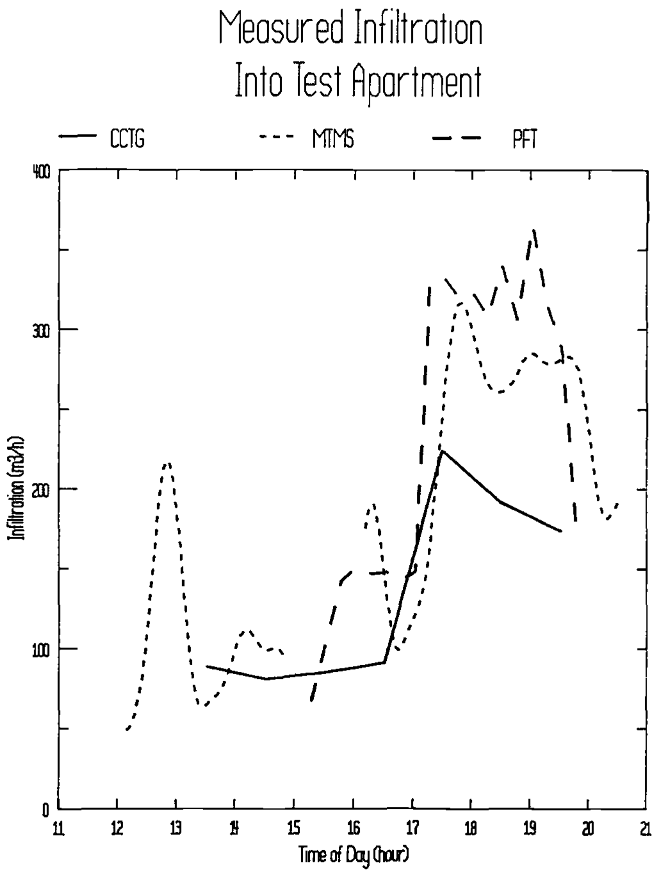

FIG. 3—*Three airflow measurement systems evaluating the air infiltration into the test apartment which comprised Zones 2 and 3.*

constant at 300 to 320 m^3/h and are in perfect agreement with the rates from the five previous periods (see Table 3). Note that the standard deviations for the combined test apartment results are now less than ±15%, and therefore, they are meaningful. The total infiltration into the test apartment determined by the three methods is shown in Fig. 3. Before the window was opened at 17:10, all three gave results of about 80 to 130 m^3/h. With the window open, the PFT-BATS and MTMS tracked each other quite well, with the former about 10% higher than the latter. And when the window was closed, both systems returned to about the same level, 160 to 180 m^3/h. The CCTG results seemed to be about two-thirds of the PFT-BATS results, both before and after the window was opened.

Measured Infiltration into Zone 3 (Bedroom/Bath Basement Apartment)

Similar to the Zone 2 data, Zone 3 indicates good agreement of the three air infiltration measurements through hour 18:25 (their values were in the 20 m/s range) (Fig. 4). After that point, with the door opened, the PFT-BATS measurements become very scattered because of the previously mentioned interzone mixing problem. After initial close agreement during hours 14 through 18, CCTG measurements indicate a slightly decreasing trend in air infiltration, while MTMS points out a slightly increasing air infiltration rate beyond 17:10.

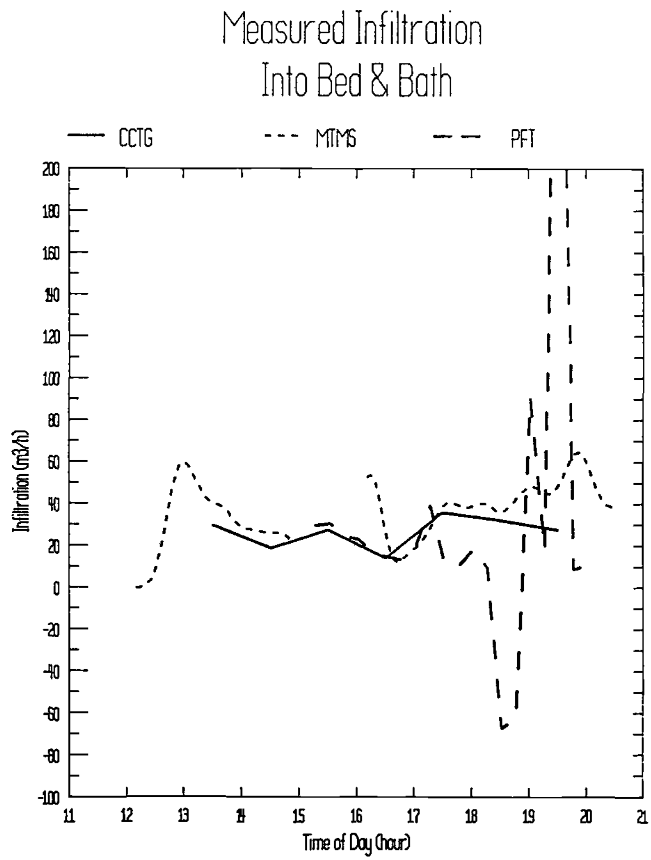

FIG. 4—*Three airflow measurement systems evaluating air infiltration in Zone 2. Evidence of incorrect zone assumptions is shown in the PFT readings.*

Again, this appears to be due to a problem of zones influencing each other, not a problem with a measurement method. Two zones become one and, especially for the PFT-BATS, a separate calculation such as illustrated in Fig. 3 should be performed to avoid the flow fluctuations.

Measured Infiltration into Zone 1 (Apartment 1B)

The air infiltration rate for Zone 1, which is the two-story apartment, is illustrated in Fig. 5. The measurement systems indicated that this zone is isolated from the others. The air infiltration, as characterized by all three systems, consists of two peaks approximately at hours 16 and 19. However, the level of infiltration is different for each measurement system with MTMS exhibiting the highest values, PFT the middle, and CCTG the lowest range of infiltration values.

Measured Infiltration in Zone 4 (Basement Storage)

Measured air infiltration in the basement storage area is shown in Fig. 6. The trend for all measurement systems is a generally rising infiltration rate over time, gaining almost 200

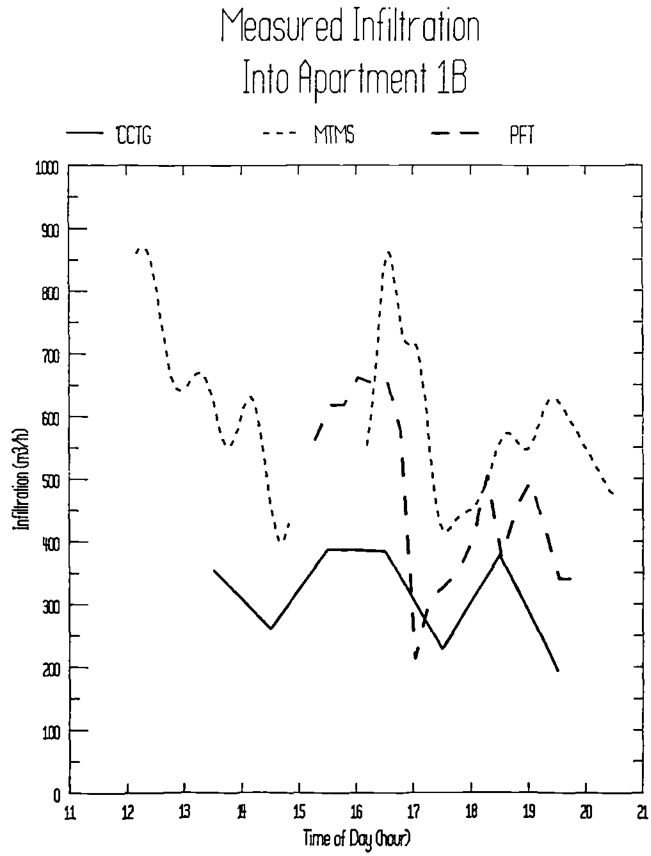

FIG. 5—*Three airflow measurement systems evaluating air infiltration in the occupied apartment (Zone 1). CCTG airflow readings are the lowest of the three.*

m^3/h from hours 16 to 19. The general level of the CCTG airflow predictions is noticeably less than those using PFT-BATS or MTMS.

Interzone Flows

As shown in Fig. 7, values of the airflow rates between Zones 2 and 3 are near zero prior to the window opening at 17:10; and the window opening shows little effect based upon hour 18 readings. In contrast, the opening of the door between the zones at 18:25 does result in an immediate increase in air exchange between the zones. The two methods of measurement predict similar air exchange between the zones at the low exchange levels in the plot on the left. However, there is a greater difference at the high airflow levels which follow the door opening with unrealistic values recorded (see plots on the right, where 3500 m^3/h using PFT and 1000 m^3/h using MTMs are shown). Closing both door and window at 19:40 drops the interzone flow rates back to near the zero reading.

Tables of Airflow

Looking at the tables, the following observations are made. When the MTMS was free of restarting incidents and flow rates were less than 100 m^3/h, values of air infiltration matched

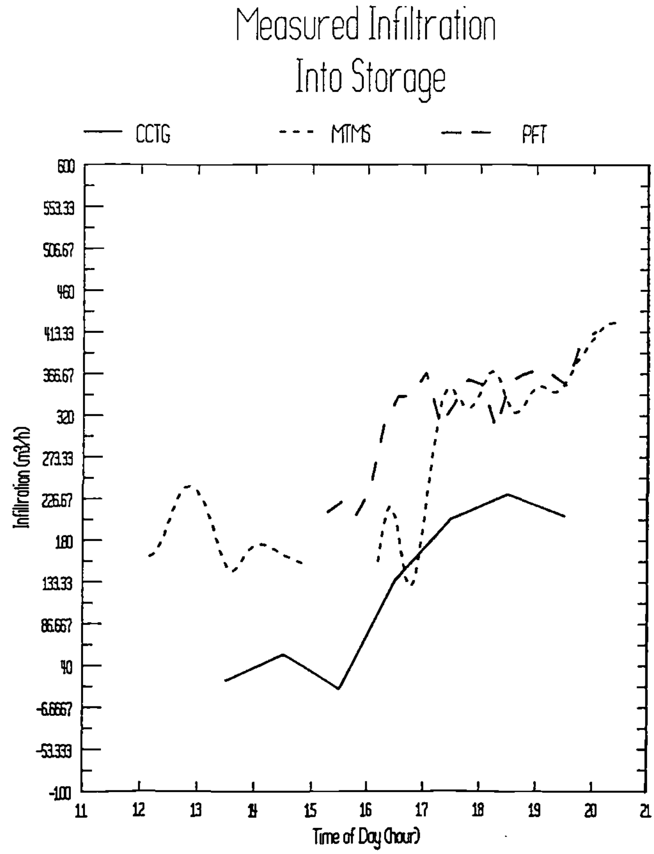

FIG. 6—*Three airflow measurement systems evaluating Zone 4, the storage room. Again, CCTG readings are noticeably less than MTMS and PFT-BATS.*

the CCTG values closely (±10%, ±5%, and ±1% of mean flow rate, e.g., Tables 4–6). When higher flow rates prevailed (following the window opening), the CCTG readings were observed to fall below the MTMS and PFT-BATS values (although the PFT-BATS values were fluctuating due to the interzone mixing previously discussed).

Table 5 tabulates the data for the occupied apartment and the storage room; at higher flow rates CCTG appears to be reading low. In Zone 4, hours 17 to 19, PFT-BATS and MTMS agreement is good.

In Table 6, during the periods when the MTMS was working properly, there is good agreement with CCTG (±1 to 2%, hours 13 and 17). PFT-BATS appears to be the high reading in hour 17 (+30%). The last two hours, again, point to CCTG reading below those of the other two systems for the higher flow rates.

Table 7 provides further information on interzone flows including Zones 2 and 4, as well as Zones 2 and 3 described in Fig. 7. Except for the question of two zones becoming one, general agreement between MTMS and PFT-BATS is good.

Table 8 describes the period following the three system tests where, in this case, a six-day comparison took place between CCTG and PFT-CATS measurement systems. At the higher flow rates, the CCTG measurements averaged less than the PFT readings, and at low flow rates the reverse was true. The percentage differences are listed in Table 8.

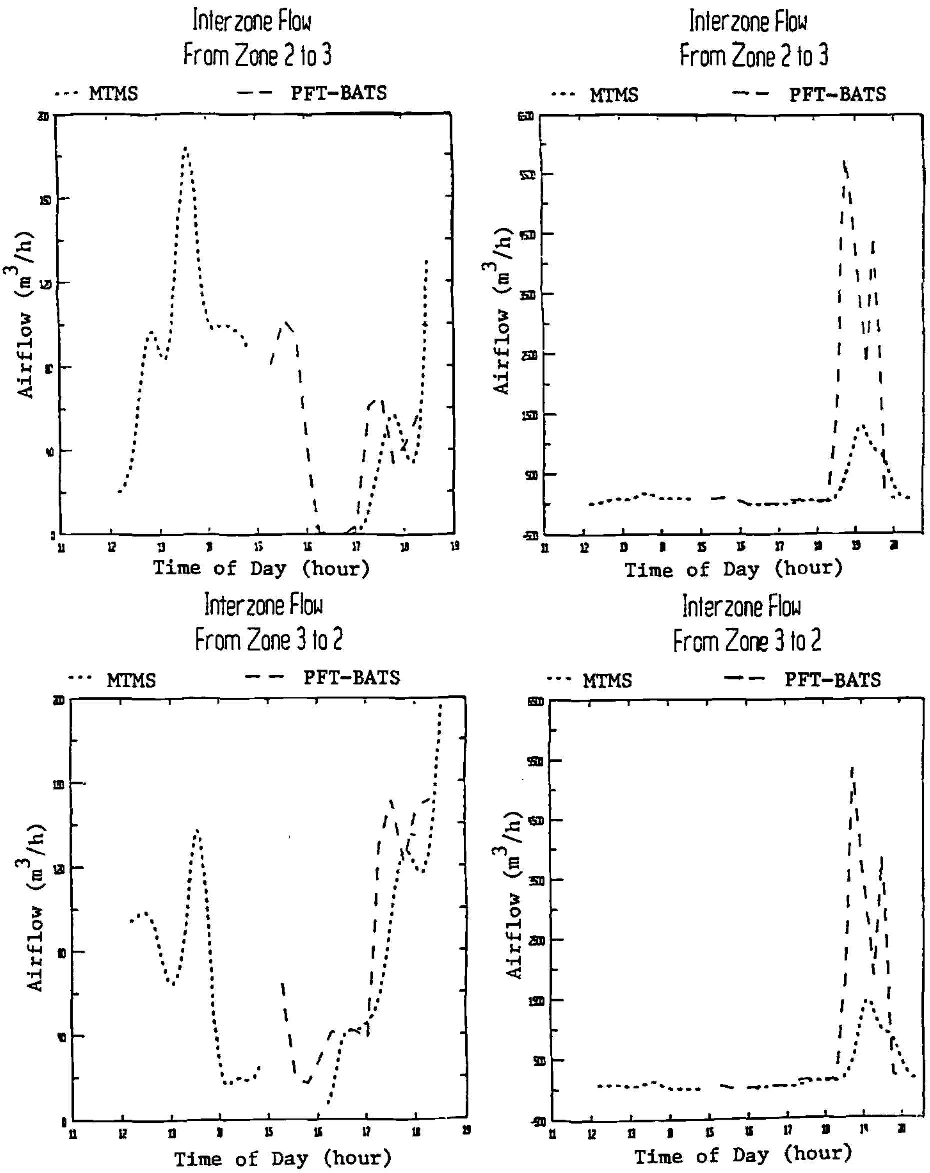

FIG. 7—*Interzone flows between Zones 2 and 3 (bedroom/bath and living room/kitchen) evaluated by MTMS and PFT-BATS.*

Conclusions

Aside from the fact that cross comparisons of airflow measurement systems in a field test situation do not provide an absolute standard for comparison, the advantages are that "real effects" are constantly taking place which force each measurement system to make constant, and hopefully consistent, adjustments. The test period points out just how much the opening of a window or door can influence air infiltration and the air movement between zones of the building. All three systems were shown to respond quickly to such changes.

TABLE 5—*Comparison of hourly average infiltration rate: Zones 1 and 4.*

	Infiltration Rate, m^3/h					
	Zone 1			Zone 4		
Hour	CCTG	MTMS	PFT	CCTG	MTMS	PFT
13	356	598	. . .	64	193	. . .
14	262	758[a]	. . .	53	207[a]	. . .
15	390	585[a]	. . .	14	194[a]	. . .
16	386	902[a]	602	137	237[a]	233
17	230	367	318	205	328	343
18	380	528	625	233	303	349
19	196	571	389	208	375	379

[a]See Table 4.

TABLE 6—*Comparison of hourly average infiltration rate: combined test apartment.*

	Infiltration Rate, m^3/h		
Hour	CCTG	MTMS	PFT
13	89	92	. . .
14	81	100[a]	. . .
15	86	121[a]	. . .
16	92	141[a]	148
17	225	227	297
18	192	273	323
19	175	278	271

[a]See Table 4.

Varying complexities of the tracer gas systems allow similar measurements to be made with various compromises. The perfluorocarbon tracer, PFT, systems allow elimination of plastic tubing to each measurement zone since PFT sources and samplers can be placed readily in each space. However, if such BATS or CATS sampling is employed, the airflow measurements must await subsequent laboratory analysis. If immediate readings are desired, a real-time PFT analyzer can be utilized, but then a single plastic tube to each zone is necessary for sampling. The variety of individual PFT tracer gases allows interzone measurements to be made at the same time air infiltration is being determined.

Where one desires primarily air infiltration data in many rooms or zones of the building, the constant concentration tracer gas (CCTG) system offers a means of analyzing ten (or even more) zones. Sampling and injection tubes are required for each zone. Air infiltration readings are immediately available and are updated with each survey. To perform CCTG interzone measurements, the system operation becomes more complex, since it is based on depriving zones of tracer gas and observing tracer gas concentration variations in that zone and surrounding zones [*9*].

The multiple-tracer mass spectrometer (MTMS) system provides immediate measurements of air infiltration and interzone flow in up to five zones. Again, two tubes to each zone are required, and because of detection requirements, higher tracer gas concentrations are necessary. Although it is the most complex of the three systems tested, the measurement unit can be readily transported to the test site.

TABLE 7—*Comparison of hourly average interzone rates: between Zones 2 and 3 and Zones 2 and 4.*

Hour	Flow Rate, m^3/h							
	Zone 2 to 3		Zone 3 to 2		Zone 2 to 4		Zone 4 to 2	
	MTMS	PFT-BAT	MTMS	PFT-BATS	MTMS	PFT-BATS	MTMS	PFT-BATS
13	131	...	91	...	7	...	26	...
14[a]	94	...	22	...	0.0	...	56	...
15[a]	69	...	39	...	0.1	...	61	...
16[a]	3	3.6	29	39	7	13	33	0.3
17	30	45	88	120	28	46	0.5	0.0
18[b]	274	2254	349	2134	55	82	1.0	0.9
19[b]	930	2458	1060	2088	46	−10	0.5	−0.1

[a]See Table 4.
[b]Door between Zones 2 and 3 open during part of these periods.

TABLE 8—*Comparison of 6-day, 4-Zone measurements: CCTG and PFT.*

Zone	Room	PFT			CCTG		
		Average Infiltration, m^3/h	Standard Error, m^3/h	%	Average Infiltration, m^3/h	Normal Standard Deviation	Difference, %
1	Apartment 1B	236	29	12	193	0.30	20
2	Bed/bath	9.5	2.8	30	12.4	0.50	−26
3	Kitchen	135	15	11	112	0.23	19
4	Storage	262	29	11	201	0.28	26

The importance of the data analysis technique chosen was demonstrated with the PFT analysis of Zones 2 and 3 when the door was opened between the zones. The very evident data scatter was not a reflection of the measurement technique, but rather pointed out that the proper interpretation of data for that case required a single zone analysis once the zones were actively communicating with each other. The characteristic pattern of the data is indicative of when the separate zone assumption should be altered.

Looking at the 5-h test data, it is clear that the CCTG air exchange measurements were never higher than the PFT-BATS or MTMS. This observation does not prove these measurements were incorrect, however, subsequent testing of the CCTG and MTMS systems in a Princeton radon test house pointed to tracer contamination from MTMS as the source for reduced readings on the CCTG. Although the tracer gases are different, at 1000 times the concentration levels of the SF_6, the freons were found to alter the SF_6 peak readings.

PFT results would appear to be compromised by high interzonal flows especially when it is rapidly changing. The response time using the PFT-BATS approach, however, was very rapid due to the 15-min sampling, where the MTMS analysis used a half-hour time constant and a weighted measurement algorithm (using a degree of influence of past measurements).

The entire range of instrumentation choices, subjected to a series of tests from rapidly changing air infiltration conditions during the test period, interzone testing, and multiday average airflow measurements, should be viewed as an introduction to the research and building monitoring communities of just what air exchange measurement tools are currently available. These measurement techniques were shown to be capable of meeting challenges in both interzone and multizone situations with rapidly changing airflows.

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DISCUSSION

P. Lagus[1] *(written discussion)*—Why do you think that other tracer gases affected the response of your constant concentration measurement? If you are measuring SF_6 chromatographically, there should be *no* interference with the other tracers.

D. T. Harrje (author's closure)—The concentration of tracer gases used by the MTMS system was on the order of 1000 times that of the SF_6 used in the CCTG. Although peaks are displaced between the gases, there can still be interference from the tail of the previous gas chromatograph trace (using electron capture). This could result in the CCTG interpreting gas concentrations that were falsely high because of the incorrect baseline, and thus concluding that air infiltration was less than that actually present. Why this would have been the case at higher flow rates versus lower flow rates is difficult to explain. As stated in the text, these problems were evident in a radon home test where CCTG and MTMS systems were running simultaneously for many hours. There was also cause for concern that a small leak in the intake to the CCTG, operating in the higher gas concentration environment of the MTMS, may have been a factor. Again, this should not have been a question of flow rate levels.

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Peter L. Lagus[1] *and Kyoon-Haeng Lie*[1]

A Numerical Investigation of the Constant Tracer Flow Technique

REFERENCE: Lagus, P. L. and Lie, K-H., "**A Numerical Investigation of the Constant Tracer Flow Technique,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067*, M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 21–30.

ABSTRACT: One of the techniques to be included in the upcoming revision of ASTM Standard E 741 is the so-called constant flow technique. This technique is effected by injecting tracer into a room or structure at a constant rate and measuring the resulting tracer concentration. For steady-state conditions, this resulting concentration can be interpreted in terms of an equivalent air leakage rate, assuming the source injection rate is known. An increasingly popular variant of this technique entails the use of passive injectors and samplers to obtain an estimate of long-term average air leakage rate.

We have undertaken an examination of numerical solutions to the first-order differential equation governing the concentration. To simplify our considerations, all calculations are based on a single well-mixed zone. Instantaneous and time average concentration histories are generated using measured air exchange data. These histories are then examined for their utility in predicting actual air leakage rates.

The passive long-term average technique appears to underpredict the actual air leakage rate for the limited data considered. Values of air leakage inferred from instantaneous measurements are also provided for comparison with actual air leakage rates.

KEY WORDS: tracer measurements, constant flow technique, passive technique, numerical calculation

One of the techniques to be included in the upcoming revision to the ASTM Test Method for Determining Air Leakage Rate by Tracer Dilution (E 741-83) is the so-called constant injection technique. As opposed to the tracer decay technique, the constant injection technique is effected by injecting tracer into a room or structure at a constant rate and measuring the resulting tracer concentration. For steady-state conditions, this resulting concentration can be interpreted in terms of an equivalent air leakage rate, assuming the source injection rate is constant. An increasingly popular variant of this technique entails the use of passive injectors and samplers to obtain an estimate of long-term average air leakage rate.

Unfortunately, most real world measurements do not afford the attainment of steady-state conditions necessary for the simple interpretation of resulting concentrations in terms of air leakage. In this paper we have undertaken a series of numerical calculations in order to demonstrate explicitly the effect of a changing air exchange rate on concentration histories. In the course of this we will examine the ability of both a discrete (instantaneous) and a time average concentration sample to predict actual air leakage rates within a single well-mixed zone.

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Calculations

We'll begin with the familiar first-order differential equation governing the tracer concentration within a well-mixed volume.

$$V \dot{C}(t) + Q(t)\, C(t) = F(t) \tag{1}$$

where

V = volume, m^3,
$C(t)$ = concentration as function of time, vol/vol,
$Q(t)$ = air leakage as function of time, m^3/s, and
$F(t)$ = source injection rate, m^3/s.

So long as the source term and the airflow rates remain constant, this equation possesses a relatively simple solution [*1*].

$$C = C_0 e^{-\frac{Q}{V}t} + \frac{F}{Q}\left(1 - e^{-\frac{Q}{V}t}\right) \tag{2}$$

For long time periods, *i.e.*, time periods such that the exponential terms are insignificant, Eq 2 reduces to

$$C = \frac{F}{Q} \tag{3}$$

In actual practice, this relationship is rearranged since F is known or measured and the resulting concentration, C, is also measured, then

$$Q \doteq \frac{F}{C} \tag{4}$$

In the passive variant of the constant injection technique, a diffusion type sampler is used to measure the time averaged concentration, C_{Av}, over a long time period [*2*]. Combined with a knowledge of the injection rate, the (long-term) average flow rate is given by

$$\left(\frac{1}{Q}\right)_{AV} = \frac{C_{AV}}{F} \tag{5}$$

For the case where the source term is constant (*i.e.*, constant injection), but Q is a time-varying function (such as due to changing meteorological conditions), analytical solutions to Eq 1 do not, in general, exist. However, numerical integration of this equation for any known $Q(t)$ can be easily performed.

Even in the ideal case, where both $F(t)$ and $Q(t)$ are constant in time, the transient portion of Eq 2 requires a finite amount of time to decay. Accordingly, in Fig. 1 we present concentration histories for a simple steady-state source injection in which the air exchange rate, Q/V, is varied parametrically. This plot demonstrates that steady-state conditions are not attained very rapidly for air exchange rates which might commonly be encountered. For instance, with an air exchange rate of 0.25, steady-state is not attained for approximately 12 h. Accordingly, the interpretation of isolated concentration data points (before at least 12 h have elapsed), in terms of an air leakage rate, could lead to substantial errors. Con-

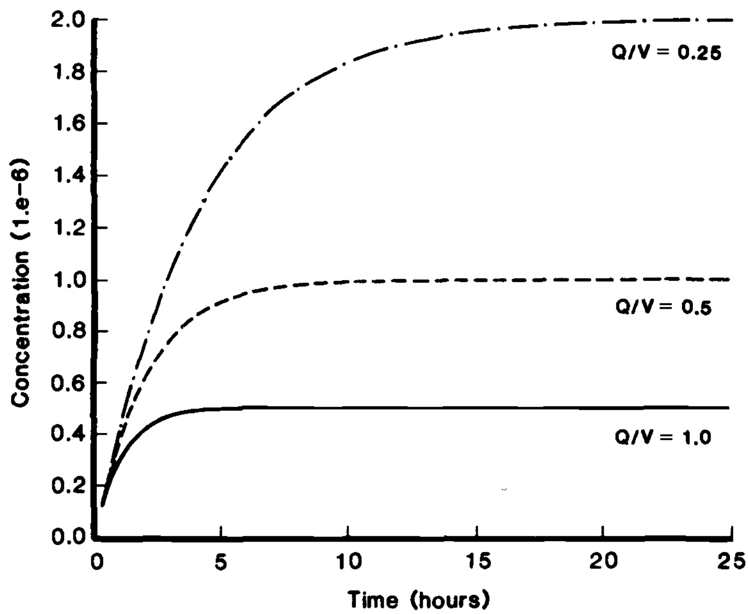

FIG. 1—*Concentration profile for three air exchange rates.*

centration data points taken after 12 h would provide a correct estimate of air leakage rate, so long as flow conditions *do not change.*

In experimental practice, one begins a test by initiating a constant injection of tracer into a structure. Often an attempt is made to homogenize the tracer concentration by means of HVAC fans, external mixing fans, or merely waiting for diffusion mixing to occur. After this, the experimenter either waits an extended period prior to collection of an integrated average concentration (passive) sample or takes discrete measurements and attempts to interpret the resulting data in terms of a leakage rate. In either case, knowledge of the injection rates, F, is assumed. This, of course, assumes that Q has not changed. If it has, then the experimenter has to wait until the effects of this change have manifested themselves. By taking an average instead of an instantaneous concentration measurement, an attempt is made to "smooth out" the effects of any variation in C and, hence, the inferred Q.

To illustrate this point, in Fig. 2 we show the concentration response to a step change in air leakage rate from 0.5 to 1 ACH at time equal to 2 h. For the step increment in Q, we see different responses for the instantaneous (shown as a dashed line) and time averaged (shown as a solid line) measurements. The increasing curves to the left of the 2-h line are a result of starting the calculation at time $t = 0$ with an air exchange rate of 0.5 ACH. Prior to time $t = 0$, the injection concentration was taken to be zero.

We have plotted the quantity $\Delta = 1 - F/Q \cdot C$ for both the instantaneous and average values of Q and C. The quantity, Δ, is useful in looking at the departure from steady-state, *i.e.,* how far off we would be from the "true" leak rate if we naively form the ratio of F and C and assume that this represents the leakage rate. When $\Delta = 0$, the use of *Eq* 4 is exactly satisfied. By plotting results in this format, the departures from steady-state conditions can be easily visualized.

For the simple step change situation, the average concentration measurement does not provide a good estimate of the new leakage rate. An instantaneous concentration mea-

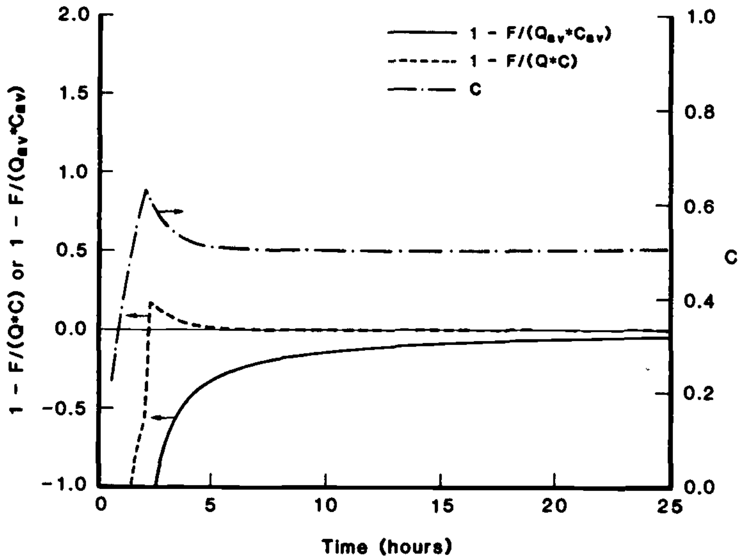

FIG. 2—*Response to step change in air leakage rate.*

surement, on the other hand, would provide a correct leakage rate after about 3 h. Thus, for this case, neither measurement is particularly useful for determining the air leakage rate, unless one is willing to wait and Q doesn't change anymore.

In order to further illustrate the difference between the instantaneous and the time average measurements of air leakage rate, a series of numerical calculations was performed for five sets of measured air leakage rate data. Two of the sets were obtained in experimental chambers specifically designed to study air leakage rate effects, while three sets were obtained in actual residential structures. Air leakage rate data were either measured or known at discrete intervals for all five sets.

The first data set explored was published in conjunction with a laboratory study of the passive measurement technique [*3*]. Experiments were performed in a 34 m^3 chamber. Temperature and humidity were precisely controlled. Good air mixing was ensured by providing an air recirculation rate of 60 ACH. Fresh air exchange rates were varied from 0.6 to 1.64 ACH.

Instantaneous and time-averaged concentration histories were calculated to compare with experimental data over a 69-h experiment. Average concentration was calculated from

$$C_{Av} = \int_0^T C(t)dt \tag{6}$$

where T is the elapsed time. The results are presented in Fig. 3. Note that very soon after the onset of the testing, Δ crosses zero from negative to positive, attains a value of approximately 0.15, and maintains that throughout the remainder of the experiment. The actual $Q(t)$ for these calculations is also plotted in Fig. 3 for comparison.

Also plotted in Fig. 3 is a point representative of the *measured* average concentration over the entire 69-h test, along with error bars corresponding to three standard deviations. The calculated Δ lies above the measured plus three standard deviation error bar by approximately 15%. This may indicate a systematic error in the measured concentration data. What is clear in this figure is the systematic departure of Δ from zero for the Q_{Av} calculation,

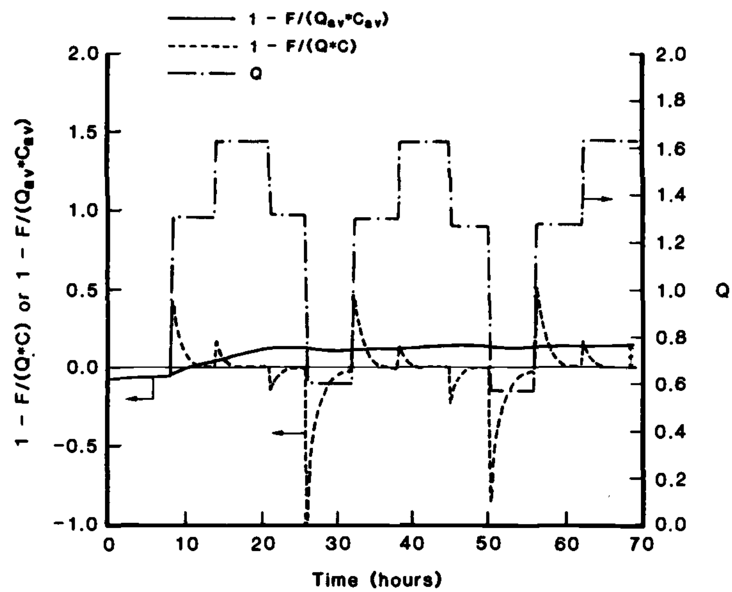

FIG. 3—*Passive sampler test data (after Leaderer).*

i.e., the nonattainment of equilibrium during the experiment, has resulted in a bias of the data away from zero. In fact, this calculation is consistent with an underprediction of Q [underprediction of $\left(\frac{1}{C}\right)_{Av}$] of approximately 15%. Note that measurement of instantaneous concentration values could lead to significant over- or underprediction, or agreement depending on *when* the measurement was taken.

A similar calculation was performed utilizing approximately 72 h of data from the Mobile Infiltration Test Unit (MITU) test facility of Lawrence Berkeley Laboratory. MITU is a fully instrumented air infiltration test chamber with a volume of approximately 30 m^3. In the course of experimental investigation with MITU, extensive air exchange data were measured by a slow-update constant concentration technique that took into account the capacity of the trailer. However, no average concentration histories were measured. Again, for these data the volume is well mixed for tracer measurements.

The resulting Δ values, as a function of time, are presented in Fig. 4. Note that Δ for the average concentration data becomes positive and remains so, suggesting that the average infiltration, again, is underpredicted by the average concentration measurement. Q, as a function of time, is also provided on the Δ plot. What is apparent from this graph is that the average concentration technique would be in error by approximately 35% by the end of the calculation (test). Again, the instantaneous concentration measurement does not predict the measured flowrate at all well.

It is apparent from both Figs. 3 and 4 that the Δ calculated from the instantaneous concentration varies wildly as the driving Q varies. Thus, even for these ideal cases (good mixing, single zone), inference of the correct Q from an instantaneous measurement of C would only be fortuitous.

The discrepancy in Q between agreement (Δ = 0), and what actually results from both of the above calculations, is consistent with error estimates provided by previous investigators [*4,5*]. We should point out that the calculations have been performed for experimental situations in which the assumptions (*i.e.*, good mixing, homogeneous concentration, precisely

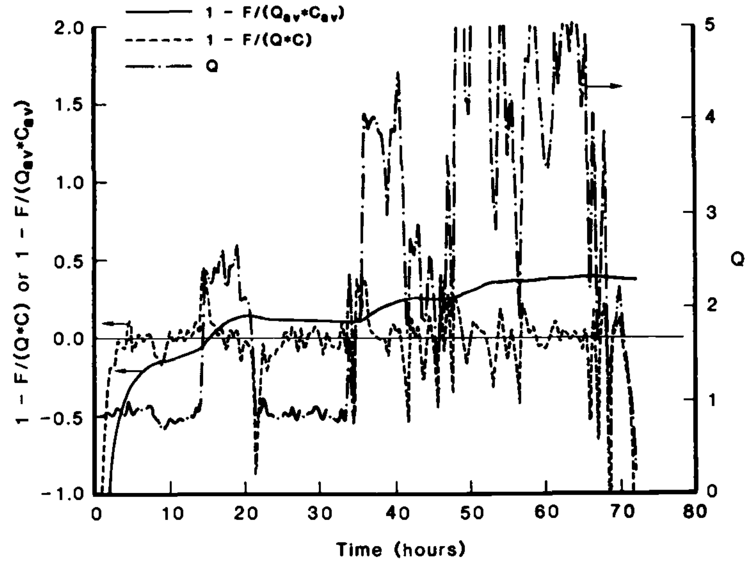

FIG. 4—Δ *versus time for the LBL MITU chamber.*

known air exchange rate) should have been very well satisfied. In real world situations, mixing is often imperfect, resulting in nonhomogeneous concentrations, and knowledge of the actual air exchange rate may be less than ideal.

In order to provide a comparison in actual structures, data were obtained on the Geomet Test House from Dr. Roy Fortmann at Geomet and on two test houses in Canada from Dr. David Wilson. Concentration histories were again calculated, and Δ, as a function of time, was generated. The resultant Δ histories are presented in Figs. 5, 6, and 7. For the Geomet

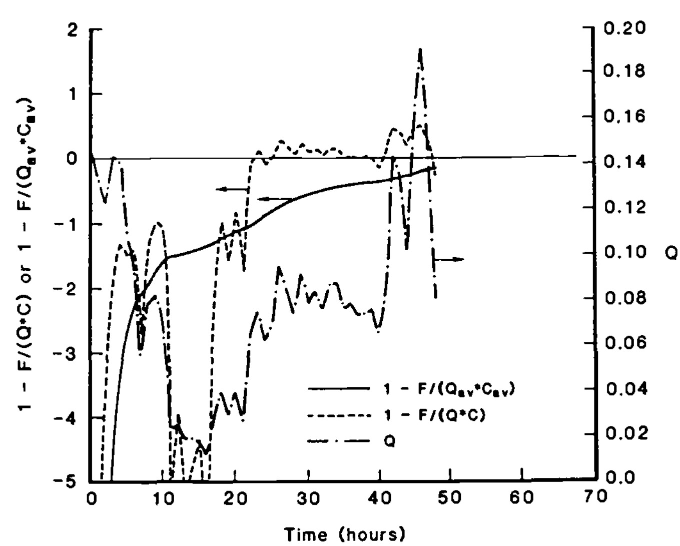

FIG. 5—Δ *versus time for the Geomet House.*

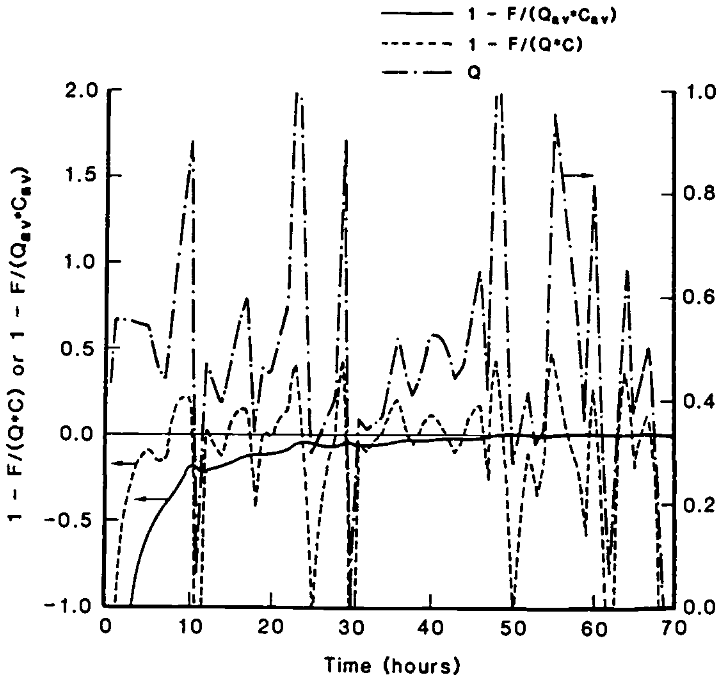

FIG. 6—Δ *versus time for the Canadian House No. 3.*

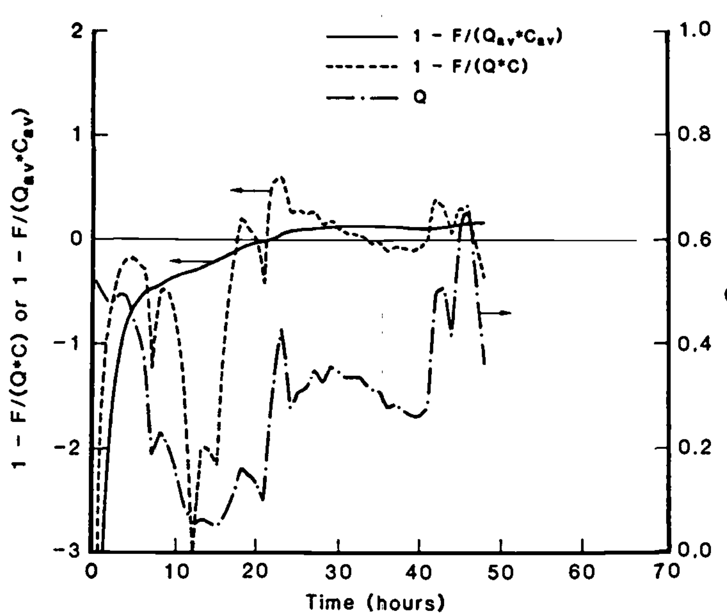

FIG. 7—Δ *versus time for the Canadian House No. 5.*

data and the Canadian House No. 3, the systematic underprediction of air leakage does not occur until significantly after the time plotted in the figures. For the Geomet data, consistent underprediction begins to occur at approximately 80 h and eventually reaches a value of approximately 5%. For the Canadian House No. 3, consistent underprediction does not occur until an elapsed time of approximately 400 h and reaches a value of roughly 5%. These two plots underscore the effect of a relatively low air exchange rate and low variability on the lengthening of the time before a steady-state underprediction occurs. For the Canadian House No. 5, where the air exchange rate is somewhat greater and more variable, Δ tends to a positive value of approximately 15% within 24 h of test initiation.

Also provided on these three plots is Δ as a function of time for instantaneous concentration measurements. As is apparent, a single or even several measurements of instantaneous concentration would be essentially worthless in predicting the air leakage by means of Eq 4. Thus, for these cases also, the instantaneous concentration measurement is unlikely to provide an accurate estimate of the air leakage rate.

One might naturally ask, when, if ever, is the constant injection technique of use with an instantaneous concentration measurement? As is apparent from Eq 1, such a measurement is useful when $\dot{C} \approx 0$. Experimentally, such a situation can occur whenever the effects of *changing* air leakage is negligible. This can occur during periods of unchanging meteorological conditions (steady wind and temperature) or within structures which possess forced ventilation [*i.e.*, negative or positive pressure (constant volume HVAC systems)] of sufficient intensity as to overpower, or at least severely attenuate, meteorologically induced changes.

As an example of real data in which the conditions necessary to use Eq 4 were reasonably satisfied, we present concentration data taken from the force-ventilated (negative pressure) industrial building in Fig. 8 [*6*]. Note that these data represent measurements over an approximate 4-h span and illustrate that, to within $\pm 5\%$, a constant concentration had been obtained. From these data it was possible to interpret resulting concentration in terms of an equilibrium leakage rate. However, even for these data it was necessary to obtain a number of concentration measurements and display them graphically to ensure that concentration values were not changing during the period over which the air leakage was calculated.

Conclusions

In the five sets of numerical calculations based on experimental data, we have seen that the average concentration (passive) technique appears to systematically underpredict actual air leakage. We have also seen that an instantaneous concentration measurement, combined with a knowledge of tracer injection rate, is not likely to yield a reliable estimate of air leakage for situations in which air leakage is dominated by changing meteorological conditions. Thus, great care and experimental judgement must be exercised when attempting to apply either of these techniques to residential scale measurements.

Finally, we have seen experimental concentration data from a constant flow test in a mechanically ventilated industrial facility. For these data, the steady-state was attained and the concentration values could be combined with the source injection rates to provide an apparently reasonable estimate of air leakage.

Acknowledgments

It is a pleasure to acknowledge the cooperation of Dr. Max Sherman of Lawrence Berkeley Laboratory for useful discussion along with the MITU data, Dr. Roy Fortmann of Geomet who provided infiltration data on the Geomet Test House, and Dr. David Wilson who

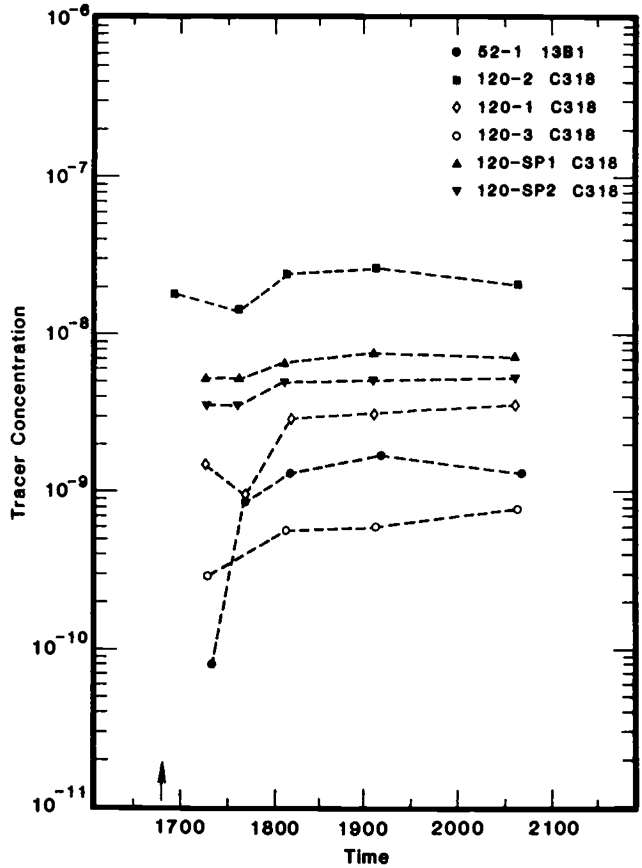

FIG. 8—*Tracer concentration profiles for industrial building.*

provided infiltration data on several test houses in Alberta. Computer time for this work was provided by S-CUBED Division Internal Funding.

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DISCUSSION

D. Harrje[1] *(written discussion)*—With the constant injection system, and especially in those cases where one is attempting to confirm the ventilation of mechanical systems, wouldn't it considerably improve measurement times by using an initial tracer pulse to quickly bring the tracer concentration to a level close to an anticipated final value.

P. Lagus (author's closure)—Yes, assuming you have some idea what the ventilation rate is. You also will have to wait for any transient to die out, but if your guess as to the pulse size is fairly accurate, the *amplitude* of the transient will be smaller.

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Measuring Airflow Rates with Pulse Tracer Techniques

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ABSTRACT: New tracer gas techniques for measuring airflow rates in HVAC ducts and buildings airflow systems are described. These pulse tracer techniques are based upon the application of integral mass balance equations to the tracer gas concentration response of an airflow system to pulse injections of tracer. For building airflow systems, or portions of them, the airflow system is first idealized by an appropriate multi-zone model, pulse injections of tracer are applied to each zone independently, and the concentration response of each of the zones is measured. The multi-zone integral mass balance equations are formed and solved to determine the airflow rates between the zones. The airflows that are determined and the accuracy of these determinations are dependent not only upon the air exchange characteristics of the building, but also on the appropriateness of the system idealization employed.

This paper presents the theoretical basis of the pulse techniques for measuring airflows in ducts, and for studying single-zone and multi-zone building airflow systems. Procedures for formulating appropriate multi-zone idealizations of building airflow systems are described and practical details of pulse testing outlined. A series of field studies are reviewed, providing examples of procedures used to formulate system idealizations, experimental techniques employed to conduct the tests, and airflow rate measurement results.

KEY WORDS: air exchange, airflow, infiltration, measurement, multi-zone, tracer gas, ventilation

Indoor air quality and energy use in buildings are both closely related to airflow into, out of, and within a building system. Consequently, indoor air quality and building energy analysis both critically depend upon obtaining complete and detailed information about these airflows. In most cases these airflow rates will be unknown due to uncertainties in envelope infiltration and the performance of the HVAC system, and due to the inherently complex nature of inter-zone airflows. One may attempt to determine these flows by using network flow analysis methods [*1,2*] or, for existing buildings, by using tracer gas measurement techniques. Perera [*3*] and Lagus [*4*] provide comprehensive reviews of existing tracer gas techniques for measuring airflows in buildings. This paper presents an alternative to these existing techniques, the pulse-injection tracer techniques.

Tracer gas techniques attempt to determine building airflow rates from the measured tracer concentration response of building airflow systems to carefully controlled injections of tracer gases. Mass balance relations are used to relate measured tracer concentrations to these airflow rates, and tracer techniques can be classified by both the injection strategy employed and the form of the mass balance equations. Three different injection strategies commonly are used: *decay,* in which a suitable amount of tracer gas is injected to establish

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an initial condition of uniform concentration throughout the space; *constant injection,* in which the injection rate is constant; and *constant concentration,* in which the injection rate is controlled in an attempt to maintain a constant tracer concentration throughout the building system. The mass balance relations may be formulated in either an instantaneous form, which, for the multi-zone case, leads to systems of ordinary differential equations, or an integral form that accounts for tracer mass conservation over a given interval of time. While most researchers historically have tended to use instantaneous mass balance relations in the development of tracer gas techniques, a few have explored integral formulations of concentration response data [*5–9*].

In principle, a unique tracer technique may be developed for each injection strategy using either instantaneous or integral mass balance formulations. For the three injection strategies outlined above we may consider an array of six basic tracer techniques, as shown in Table 1. Furthermore, it is useful to distinguish single-zone techniques (SZ) from multi-zone techniques (MZ). The tracer techniques based upon instantaneous formulations have been applied with varying degrees of success. The tracer techniques based upon the integral formulations have been largely ignored until recently and have yet to be studied thoroughly.

The decay technique may be used to determine effectively infiltration airflows in buildings that behave as a single zone and is the subject of the ASTM Test Method for Determining Air Leakage Rate by Tracer Dilution (E 741-83). It has also been applied to determine the details of infiltration, exfiltration, and zone-to-zone flows in buildings that behave as multi-zone systems. Several multi-zone decay techniques based upon instantaneous formulations have been considered [*3,5,8,10–12*]. Difficulties in measuring the first-time derivative of the concentration response have limited the success of some of those approaches. Others appear to result in poorly conditioned systems of mass balance equations. Most multi-zone decay techniques rely on data collected very soon after the tracer gas injection. For this data to be reliable, the tracer gas concentration must be uniform in each of the building zones immediately after injection. This is a difficult initial condition to achieve, and the accuracy of the results will be degraded by deviations from these assumed initial conditions.

The constant injection technique may be applied to single and multi-zone situations to determine the details of infiltration, exfiltration, and zone-to-zone flows. The constant injection technique based upon an instantaneous formulation tends, however, to significantly underestimate infiltration airflows as commonly implemented (that is, using average concentrations measured over relatively long time periods as in the so-called perfluorocarbon tracer (PFT) method [*13*]) [*14–15*]. An integral formulation of the constant injection tech-

TABLE 1—*Classification of tracer techniques.*

Tracer Injection Strategy	Mass Balance Formulation: Instantaneous	Mass Balance Formulation: Integral
Decay	SZ:[a] yields infiltration MZ:[b] yields all flows	(See pulse injection)
Constant injection	SZ:[a] yields infiltration[c] MZ:[b] yields all flows[c]	SZ:[a] yields infiltration[d] MZ:[b] yields all flows[d]
Constant concentration	SZ:[a] yields infiltration MZ:[b] yields only infiltration	SZ:[a] yields infiltration[d] MZ:[b] yields only infiltration[d]
Pulse injection	(See decay)	SZ:[a] yields infiltration MZ:[b] yields all flows

[a]SZ = single zone.
[b]MZ = multi-zone.
[c]Tends to underestimate.
[d]Presently under consideration.

nique provides a means to mitigate this shortcoming and is presented in Axley [*16*]. The constant concentration technique is a reliable technique for single- and multi-zone situations, providing accurate determinations of outdoor airflow rates into each of the building zones [*17*], but does not provide any information regarding zone-to-zone airflows. It is believed that the integral formulation of the constant concentration technique, presently under consideration by the authors, will provide a means to implement this technique without the need for the careful control that is required in the instantaneous formulation.

In this paper we shall consider the *pulse injection technique* that was presented by Walker as the *decay integral method* [*8*] and further developed by Afonso and his colleagues [*18–20*]. This technique is based upon an injection strategy of separate, short-duration, pulse injections of tracer into each zone of the building system and the application of integral mass balance equations to the reduction of the measured concentration response data. Although decay techniques have employed pulse injections to establish initial concentrations, they have not used data collected during the time interval of the pulse injection to solve for airflows. Nor have they used integral mass balance equations in analyzing the concentration response data. It is for these reasons that we distinguish the pulse injection techniques from traditional decay techniques. This paper will first consider the simplest case, the application of pulse injection techniques to the determination of flows in ducts, then move on to building applications involving both single-zone and multi-zone building idealizations. We shall then discuss experimental procedures and the results of the application of these techniques to the study of airflows in a large office building.

Duct Pulse Technique

The application of the pulse-injection technique to the measurement of airflow rates in ducts provides a straightforward introduction to the pulse techniques. Measuring airflow rates in ductwork in building ventilation systems is difficult using traditional airflow rate measurement techniques (for example, pitot tubes and hot-wire anemometers), due to insufficient lengths of straight ductwork for the establishment of fully developed flow profiles. Constant injection tracer gas techniques have been used to measure these airflow rates [*4*], but they require one to wait for equilibrium and to measure very low tracer gas flow rates. The duct pulse technique is a quick and simple alternative for measuring these quantities in even the most complex duct configurations.

Theory

Consider the duct segment illustrated in Fig. 1. Air flows into the duct from the left at a time-varying mass flow rate of $w(t)$. We inject a short duration tracer pulse at a rate $G(t)$ into the duct and measure the time variation of tracer concentration $C(t)$ at the exit. Assuming that the tracer injection results in only trace concentrations and, therefore, does not contribute significantly to the air mass flow rate, then the exit air mass flow rate will equal $w(t)$.

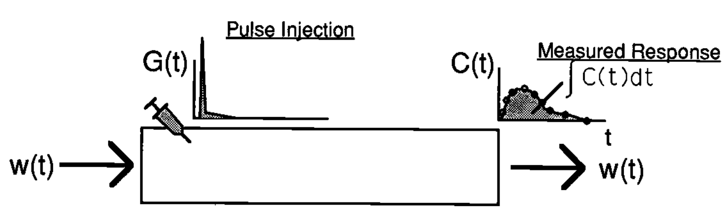


FIG. 1—*Duct pulse injection technique.*

Furthermore, if the exit concentration measurement is a flow-averaged concentration (for example, the concentration is well mixed across the section) then the mass flow rate of tracer exiting the duct will simply be equal to the product of the flow rate and the exit concentration, $w(t)C(t)$, where concentration is expressed in terms of the mass fraction of tracer relative to air. Recognizing that after some time, say t_2, all tracer is purged from the duct, we may account for tracer mass conservation through the use of the following integral mass balance:

$$\int_{t_1}^{t_2} w(t)\, C(t)\, dt = \int_{t_1}^{t_2} G(t)\, dt \; ; \; w(t) \geq 0 \tag{1}$$

which simply asserts that the tracer mass leaving the duct segment equals the amount injected. t_1 is a point in time before the tracer gas injection.

We may apply the *integral mean value theorem* to the expression on the left, as the concentration variation does not involve a sign change, and simplify to obtain the governing equation for the duct pulse injection tracer technique:

$$w(\xi) = \left[\int_{t_1}^{t_2} C(t)\, dt\right]^{-1} \int_{t_1}^{t_2} G(t)\, dt \; ; \; t_1 \leq \xi \leq t_2 \tag{2}$$

In words, the air mass flow rate that occurred at some time, ξ, during the time interval (t_1, t_2) is the ratio of the mass of tracer injected to the integral of the concentration response downstream from the injection point. Clearly, if the air mass flow rate is constant, the determination will yield this constant value. If the air mass flow rate changes very little during the interval, then $w(\xi)$ will be a good estimate of the average flow rate during that interval.

Experimental Procedures

In applying the duct pulse technique there are several practical experimental considerations. The most important issues are knowing the mass of tracer that is injected and obtaining an accurate determination of the concentration integral. Since one only requires the integral of $G(t)$, the actual injection profile is irrelevant. It is only important to know the injection mass. This mass can be measured before or during the injection, but it is crucial that all of the tracer gas is injected into the duct.

The duct pulse measurement technique requires the determination of the integral of the concentration at the downstream measurement point, not the concentration time history. The determination of this integral relies on more than just accurate measurement of tracer gas concentrations. This integral must be based on a cross-sectional average concentration, or the concentration at the point of measurement must vary only along the length of the duct, not across the duct cross section. A multi-point injection across a duct cross section will assist in achieving a uniform concentration at the concentration measurement point.

Because the concentration response will be relatively short-lived, it will be difficult to determine the concentration integral from numerical integration of real-time concentration measurements unless one's concentration measuring equipment has a high sampling frequency and covers a wide range of measurable concentrations. Therefore, it is advantageous to determine the concentration integral through the measurement of the average tracer gas concentration at the measurement point. This average concentration can be determined by filling an appropriate air sample container, beginning well before the pulse is injected and continuing until the pulse is completely purged from the duct. The concentration integral simply equals the average concentration multiplied by the length of time over which the sample container is filled.

In applying this technique to a particular system, there will be some initial uncertainty in the amount of tracer gas that should be injected into the duct work and in the appropriate length of time for averaging. The primary requirement is that the average concentration in the air sample container is in the accurately measurable range of one's tracer gas concentration measurement equipment. Meeting this requirement depends on choosing an appropriate combination of injection mass and concentration averaging time. In general, there may be some trial-and-error in determining these quantities. Since each measurement requires only a few minutes, it is not difficult to find appropriate values for these quantities. An estimate of the airflow rate obtained with a traditional measurement technique, such as a pitot tube, can be used to estimate the injection mass and the concentration averaging time. Because the time required to make a measurement is so short, an airflow measurement can be repeated several times, thereby providing an estimate of the repeatability of the results.

Measured Results

Some preliminary applications of the duct pulse technique have been conducted in the HVAC system of an office building. A comparison between the results of these duct pulse measurements and the airflow rates measured by hot-wire traverse is shown in Fig. 2. These results lie in three distinct regions, depending on the type of duct that was studied.

In the ducts corresponding to the two lower airflow rates, a premeasured amount of tracer gas (sulfur hexafluoride, SF_6) was injected by hand. Plastic syringes were filled with SF_6, and the gas was injected into a hole in the duct. In the measurements corresponding to the higher airflow rates, the tracer gas was injected through a calibrated flow meter. The injections lasted no more than 1 min. In all of these tests, the concentration integral was based on an average concentration determined by filling an air sample bag with a battery-operated pump over a period beginning at least 1 min before the injection and lasting several minutes after the injection was compete. The air sample was taken from the duct as far downstream from the injection point as possible in order for the SF_6 to have the opportunity to mix with the air. In these tests, the injection mass and sampling period were varied to examine the sensitivity of the results to these variables, and the measurements were repeatable to within about 5%. The sampling times ranged from 3 to 10 min.

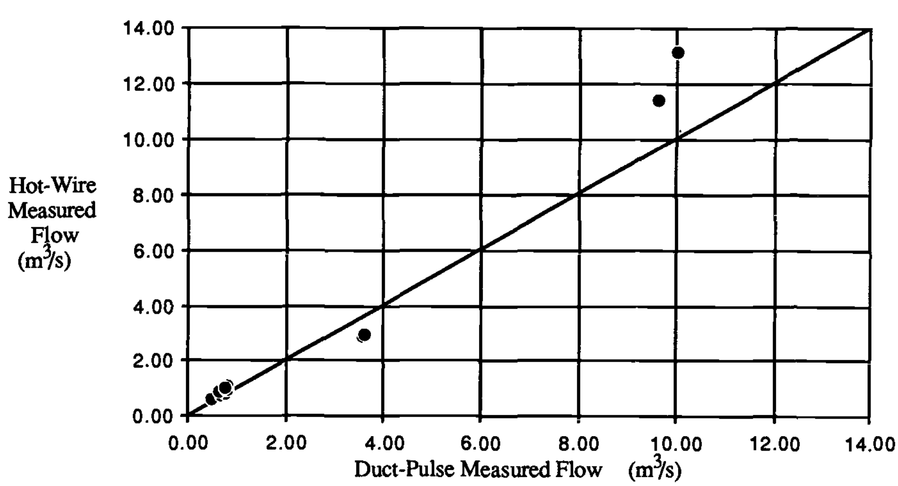


FIG. 2—*Comparison of duct-pulse and hot-wire measurements.*

The agreement between the duct pulse results and the results of the hot-wire traverses are encouraging given the uncertainties in the flow profile at the duct walls and the errors in the hot-wire readings and the inside area of the duct. A detailed laboratory study of the duct pulse technique is still necessary to provide a rigorous validation of the technique. The duct pulse technique provides a rapid and convenient means to measure a wide range of airflow rates in ducts. It is, however, based on the assumption that there is no leakage of air into or out of the duct, which in many cases is not true. However, the technique could be used to quantify duct leakage by employing a series of injections and samples at various points along the length of the duct.

Single-Zone Pulse Technique Theory

Consider the single-zone idealization illustrated in Fig. 3. Air flows into the zone at a mass flow rate of $w(t)$ and is assumed to be instantaneously and uniformly mixed within the zone. A short-duration tracer pulse is injected into the zone, and the zone concentration response to the pulse, $C(t)$, is measured.

Again we assume that the tracer injection rate is small relative to the air mass flow rate so that the exit air mass flow rate is practically equal to the inlet rate. We may write an instantaneous mass balance relation for this single-zone idealization, with M equal to the mass of air within the zone, as:

$$w(t)C(t) + M\frac{dC(t)}{dt} = G(t) \ ; \ w(t) \geq 0 \tag{3}$$

where we have assumed the tracer concentration outside the zone to be zero. In words, at any instant in time, the mass flow rate of tracer out of the zone, $w(t)C(t)$, plus the accumulation of tracer within the zone, $M\, dC/dt$, is equal to the rate of generation (i.e., injection) of the tracer, $G(t)$.

We may also demand that tracer mass be conserved over any arbitrary time interval, say (t_1, t_2), by directly integrating Eq 3 over the time interval to obtain:

$$\int_{t_1}^{t_2} w(t)C(t)\, dt + M\Delta C = \int_{t_1}^{t_2} G(t)\, dt \tag{4}$$

where $\Delta C \equiv C(t_2) - C(t_1)$.

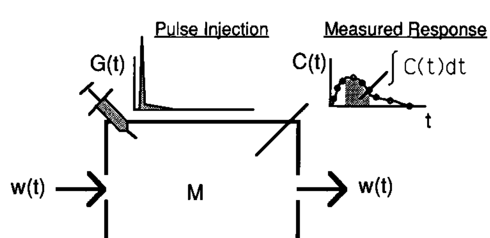


FIG. 3—*Single-zone pulse injection technique.*

We apply the integral mean value theorem to the first integral and simplify to obtain the governing equation for the single-zone pulse injection tracer technique:

$$w(\xi) = \left[\int_{t_1}^{t_2} C(t)\, dt\right]^{-1} \left[\int_{t_1}^{t_2} G(t)\, dt - M\Delta C\right] ;\ t_1 \leq \xi \leq t_2 \tag{5}$$

For single-zone systems, we may determine the air mass flow rate that occurred at some time, ξ, during the time interval (t_1, t_2) by simply computing the ratio of the mass of tracer injected, corrected by the amount of tracer accumulated $-M\Delta C$, to the integral of the concentration response within the zone. Again, if the air mass flow rate is constant the determination will yield this constant value. If the air mass flow rate changes very little during the time interval, then $w(\xi)$ will be a good estimate of the average flow rate during that interval.

By explicitly accounting for the accumulation of tracer, we are able to consider any time interval we desire; we do not require complete purging of the tracer as before. This widens the possible experimental options as discussed below. We may consider a time interval sufficiently long to allow complete purging, or short time intervals that in the limit approach an instant in time, which would in principle provide instantaneous determinations of airflow rates.

Afonso et al. [*18–19*] report the results of single-zone pulse tests conducted in a laboratory test facility in which the airflow rate into the zone was measured with nozzles. Four tests were conducted at four different supply airflow rates into the zone. The measurements of the space air exchange rate generally were repeatable within 3%, and the agreement with the supply airflow rates measured with the nozzles ranged from 10 to 17%. The values calculated from the pulse tests were always less than the measured airflow rates, perhaps due to air leakage from the supply ducts. In these experiments, the room mass, M, was treated as an unknown and was solved for by evaluating Eq 5 both before and after the tracer gas injection.

Multi-Zone Pulse Technique Theory

The development of the theory of the multi-zone pulse technique that follows is presented for the technique as currently proposed and is specific to this case. A more general development of multi-zone tracer gas theory in general, and the pulse technique in particular, is contained in Axley [*16*]. In the multi-zone case, we have to consider systems of equations and, consequently, the solution for airflows involve matrix, rather than scalar, algebraic operations. As a result, the issues of *singularity* and *conditioning* of the resulting equations become a central concern and will largely determine the success or failure of any pulse test.

Consider a multi-zone idealization of a building airflow system, with the air within each zone being instantaneously and uniformly mixed. This idealization consists of n well-mixed building zones and a well-mixed exterior (that is, outdoor) "zone," with single flow paths linking each of these zones to all others. The exterior zone is designated as Zone 0 and the building zones are 1 through n. The mass of air in the exterior Zone 0 is considered infinite, and we assume that airflow from zone-to-zone is practically instantaneous. A three-zone example of such an idealization is illustrated in Fig. 4.

The dispersal of tracer in this multi-zone idealization may be described by the following instantaneous mass balance equations (see Refs *21–22* for complete details):

$$[W]\{C\} + [M]\frac{d\{C\}}{dt} = \{G\} \tag{6}$$

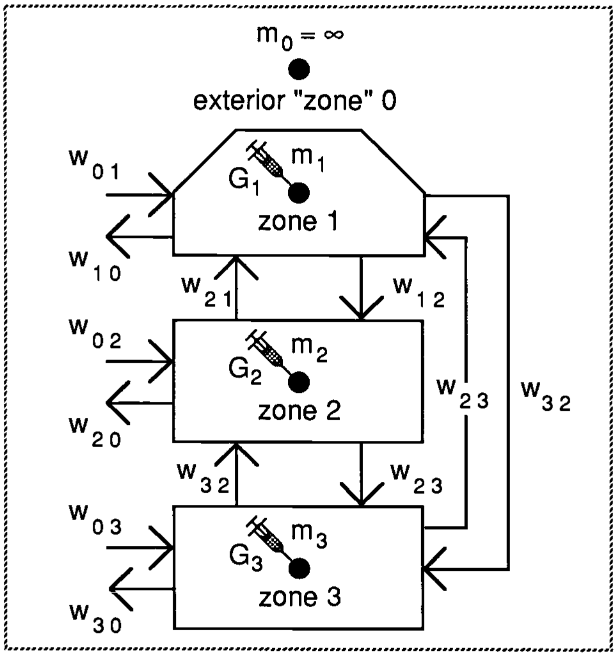


FIG. 4—*Three-zone building idealization.*

where

$\{C\}^T = \{C_0, C_1, C_2, \ldots C_n\}$, where C_i is the tracer gas concentration in Zone i,
$[M] = \text{diag}\{m_0, m_1, m_2, \ldots m_n\}$, where m_i is the mass of air contained in Zone i,
$\{G\}^T = \{G_0, G_1, G_2, \ldots G_n\}$, where G_i is the tracer mass generation rate in Zone i, and
$[W]$ = the *system mass transport matrix:*

$$[W] \equiv \begin{bmatrix} \left(\sum_{j=0;\ \neq 0}^{n} w_{0j}\right) & -w_{10} & \cdots & -w_{n0} \\ -w_{01} & \left(\sum_{j=0;\ \neq 1}^{n} w_{1j}\right) & \cdots & -w_{n1} \\ \cdots & \cdots & \cdots & \cdots \\ -w_{0n} & -w_{1n} & \cdots & \left(\sum_{j=0;\ \neq n}^{n} w_{nj}\right) \end{bmatrix} \quad (7)$$

where

w_{ij} = the air mass flow rate from Zone i to Zone j.

We admit only positive values for w_{ij}, and it should be noted that the diagonal terms are equal to the total air mass flow rate out of each zone.

The injection and measurement strategy used for the multi-zone pulse injection technique is illustrated in Fig. 5 for a three-zone case. We first subject one zone to an individual, short-duration tracer pulse and measure the tracer concentration responses in all zones. A second zone is excited and, again, we measure the response in all zones. The process of excitation and response measurement is continued until all zones have been independently pulsed. These independent zone pulses may be done in series using a single tracer, simultaneously using multiple tracers, or as a series of multiple-tracer pulses.

As in the single-zone case, we require that tracer gas mass is conserved over any arbitrary time interval, say (t_1, t_2), by integrating Eq 6. Applying the integral mean value theorem for an injection into Zone i yields:

$$\{\int C_0, \ldots \int C_i, \ldots \int C_n\} \, [W([\xi])]^T = \{(-m_0\Delta C_0), \ldots (\int G_i - m_i\Delta C_i), \ldots (-m_n\Delta C_n)\} \quad (8)$$

where we have introduced the shorthand notation:

$$\int C_i \equiv \int_{t_1}^{t_2} C_i dt \; ; \; \int G_i \equiv \int_{t_1}^{t_2} G_i dt \; ; \; \Delta C_i \equiv C_i(t_2) - C_i(t_1)$$

Here, we must consider a separate unknown time, ξ_{ij}, for each element of the mass transport matrix $[W]$.

The $\int C_i$'s, $\int G_i$'s, ΔC_i's, and ξ_{ij}'s depend on the nature of the measured data and constitute a data set. To distinguish one data set from all others, we use a superscript i as follows:

Integral data set i:

$$\{\int C_0^i, \int C_1^i, \ldots \int C_n^i\}, \{\Delta C_0^i, \Delta C_1^i, \ldots \Delta C_n^i\}, \int G_i^i, [\xi^i]$$

Since the exterior zone, which will be involved in all building idealizations, cannot be excited by tracer injection (due to its practically infinite volume), it must be handled differently. For this zone we use the requirement of the conservation of total air mass flow. This may be realized by recognizing that the mass concentration for air in all zones is unity and unchanging, that is:

$${}^{air}C_i = 1 \; ; \; {}^{air}G_i = 0$$

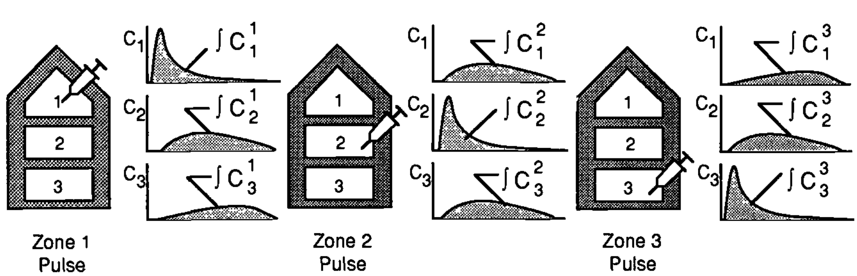


FIG. 5—*Multi-zone building idealization.*

and, thus the integral data set for air alone is:

$$\int^{air}C_i = 1\Delta t \; ; \; \Delta^{air}C_i = 0 \; ; \; \int^{air}G_i = 0$$

Designating this data set as Set 0 and substituting these values into Eq 8, we obtain the integral mass balance relation corresponding to the conservation of total air mass flow:

$$\{1, 1, \ldots 1\}[W([\xi^0])]^T = \{0, 0, \ldots 0\} \tag{9}$$

The formation of the first term of the right side of Eq 8, $-m_0\Delta C_0^i$ $(i \neq 0)$, corresponding to the exterior environment, presents a problem since the mass of air in the exterior zone, m_0, is considered infinite. We derive this term by requiring conservation of tracer mass for each injection, concluding that:

$$m_0\Delta C_0^i = \int G_i^i + \sum_{k=1}^{n}(-m_k\Delta C_k^i) \tag{10}$$

That is to say, the infinitesimal change in tracer concentration in the exterior zone is simply equal to the net generation of tracer in Zone i less the net accumulation tracer in all zones of the building.

Based on the n injections into the n zones and Data Set 0, we obtain $n + 1$ integral data sets. From these data sets, $n + 1$ separate, underdetermined systems of algebraic equations may be formed:

$$\begin{aligned}
\{1, 1, \ldots 1\}[W([\xi^0])]^T &= \{0, 0, \ldots 0\} \\
\{0, \int C_1^1, \ldots \int C_n^1\}[W([\xi^1])]^T &= \{(-m_0\Delta C_0^1), (\int G_1^1 - m_1\Delta C_1^1), \ldots (-m_n\Delta C_n^1)\} \\
&\ldots \\
\{0, \ldots \int C_i^i, \ldots \int C_n^i\}[W([\xi^i])]^T &= \{(-m_0\Delta C_0^i), \ldots (\int G_i^i - m_i\Delta C_i^i), \ldots (-m_n\Delta C_n^i)\} \\
&\ldots
\end{aligned} \tag{11}$$

These equations can be assembled into a single-determined system of algebraic equations if the following condition is satisfied:

$$[W([\xi^0])] \cong [W([\xi^1])] \cong [W([\xi^2])] \cong \ldots [W([\xi^n])] \equiv [\overline{W}] \tag{12}$$

The resulting system of equations, after substitution of Eq 10, is the basis of the multi-zone pulse injection technique:

$$[\int C][\overline{W}]^T = [\int T] \tag{13a}$$

where

$$[\int C] = \begin{bmatrix} \{1 & 1 & \ldots & 1\} \\ & & \vdots & \\ \{0 & \int C_1^1 & \ldots & \int C_n^1\} \\ \{0 & \int C_1^i & \ldots & \int C_n^i\} \\ & & \vdots & \\ \{0 & \int C_1^n & \ldots & \int C_n^n \end{bmatrix} \tag{13b}$$

$$[\int T] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ \left(\sum_{k=1}^{n-} m_k \Delta C_k^1 - \int G_1^1\right) & (\int G_1^1 - m_1 \Delta C_1^1) & \cdots & (-m_i \Delta C_i^1) & \cdots & (-m_n \Delta C_n^1) \\ \vdots & \vdots & \vdots & \vdots & & \vdots \\ \left(\sum_{k=1}^{n} m_k \Delta C_k^i - \int G_1^i\right) & (-m_1 \Delta C_1^i) & \cdots & (\int G_i^i - m_i \Delta C_i^i) & \cdots & (-m_n \Delta C_n^i) \\ \vdots & \vdots & & \vdots & \vdots & \vdots \\ \left(\sum_{k=1}^{n} m_k \Delta C_k^n - \int G_n^n\right) & (-m_1 \Delta C_1^n) & \cdots & (-m_i \Delta C_i^n) & \cdots & (\int G_n^n - m_n \Delta C_n^n) \end{bmatrix} \tag{13c}$$

It must be emphasized that the formulation of Eq 13 critically depends on the algebraic condition imposed by Eq 12, that is, the values of each w_{ij} are essentially the same at each value of ξ_{ij}. In practical situations we expect the system airflow rates to vary with time. If all airflows in the system do not vary greatly over the time period spanning all pulse tests, then this condition will essentially be met. If the variation of these airflows about their mean values is of relatively small amplitude, high frequency, or a combination of the two, then we should expect that the condition of Eq 12 will also be met. For these cases, the mass transport matrix will correspond to a mean flow condition in the system, thus, we have chosen to use the overbar (signifying a mean value) notation, $[\overline{W}]$, above.

It is conceivable that other special cases of airflow variation will also satisfy the condition of Eq 12, thus, strictly speaking, Eq 13 is not limited to the determination of a mean flow condition. From a practical point of view, however, it is best to attempt to determine airflows for a mean flow condition, thus, tracer injection and data collection strategies should be employed that may be completed rapidly. Both the pulse injection strategy and an integral constant injection strategy [*16*] can meet this objective. The use of multiple tracers will enable the test to be completed even more quickly.

It may be shown [*16*] that if the air mass flow rates are steady and the pulse injections are of short duration relative to the integral time intervals, then the integral concentration matrix $[\int C]$ will be nonsingular. Therefore, the pulse injection technique as proposed will, in principle, lead to equations that may be solved to determine airflow rates (that is, with infinite precision computation and data sets without error). These equations may, however, be expected to be ill-conditioned (that is, especially sensitive to data errors) and, therefore, in some cases the flows that result from the solution of these equations may be overwhelmed by error. The use of independent injections (such as, the pulse injection strategy) in each building zone, for an appropriate multi-zone idealization of the building, will tend to minimize the ill-conditioning of the system and provide a near-optimal determination of the air flows for the given idealization. The ill-conditioning will be further minimized by idealizations and injection strategies for which the rows of $[\int C]$ are characterized by large values of $\int C_i^i$ relative to the rest of the $\int C_i$'s. In those cases where ill-conditioning (as measured by the condition number of the system of equations, discussed below) remains a problem, the analyst should consider alternative idealizations of the building airflow system.

Solution of the Inverse Analysis Equations and Error Evaluation

Errors in the estimation of airflows by tracer techniques may be attributed to an inappropriate idealization of the building system being investigated, uncertainties introduced via flow variations, and/or error introduced via measurement error. The idealization of a given building airflow system may, to a great extent, determine the success or failure of the application of tracer techniques to the determination of airflows in the building. For example, the idealization of a very well-mixed portion of a building system as a collection of multiple zones will, in itself, result in a poorly conditioned system of inverse equations that will tend to amplify measurement error. Although we attempt to provide some guidance in this paper, the process of system idealization remains an art that requires experience and skill.

In the single-zone case, flow variation can result in very large errors in the estimation of mean airflows [*16*]. It must be expected that even greater errors will result in multi-zone cases due to the numerical phenomena of ill-conditioning that is intrinsically associated with the inverse problems being considered here. It is the primary responsibility of the analyst to attempt to conduct a given tracer test in such a way that the underlying assumptions of the tracer technique are satisfied. With this done, numerical techniques exist to deal with solution errors resulting from measurement error.

Equation 12 must be solved with special care to avoid unnecessary amplification of data errors due to ill-conditioning. Conventional elimination or iterative equation solving techniques may be expected to fail for very ill-conditioned problems and, thus, the analyst is well-advised to employ numerically more stable algorithms. *Singular value decomposition* has become the method of choice for solving ill-conditioned problems and is recommended here [*23*]. (Solution techniques based upon Cramer's rule are computationally inferior to the elimination and iterative techniques and should not be considered.)

Furthermore, as the degree of ill-conditioning that might be associated with any given problem will not, in general, be evident, the analyst is well advised to not only compute the solution, but also to compute and report a measure of the error associated with the solution. D'Ottavio [*24*] and Walker [*8*] have discussed error analysis techniques relating to the solution of both the constant injection technique and the pulse injection technique (Walker's *decay integral method*), and their results apply here as well. Three error estimation techniques are offered: (*a*) error estimation based upon perturbation analysis of systems of linear equations involving vector and matrix norms; (*b*) error estimation based upon Monte Carlo error analysis; and (*c*) error estimation based upon first order error analysis using Taylor expansions.

The perturbation analysis approach provides an upper-bound error estimation, but is sensitive to the scaling of the inverse equations. D'Ottavio employed *optimal scaling* of the equations based upon scaling individual equations by the inverse of their row Euclidean norm to provide a (near) minimum of this upper bound error estimation. Central to perturbation analysis of systems of linear equations is the so-called *condition number*, which, in simple terms, provides an upper bound estimate of the ratio of the maximum relative solution error to the maximum relative data error (that is, an error amplification factor). Thus, reporting the condition number of the integral concentration matrix $[\int C]$ provides one means of characterizing the error associated with the solution of a given problem. In the studies considered below, the solution was achieved using the robust and stable numerical method known as singular value decomposition [*23*]. The condition number of the system is obtained as a by-product of the singular value decomposition.

Application of the Pulse Injection Technique

The pulse injection techniques provide powerful tools for the determination of building airflow rates: however, to realize their potential they must be part of a systematic building investigation. Such an investigation involves: (*a*) the qualitative analysis of the building airflow system required to form an idealization of the building airflow system and to plan the experimental procedures; and (*b*) the quantitative tasks of conducting the tests, reducing the data, and analyzing the results. In this section we discuss the investigative approach we have taken, the experimental procedures used to make these airflow rate measurements, and the results of several field applications.

Investigative Approach

The successful application of the pulse injection techniques demands a clear understanding of the building being studied and its airflow systems. Based on this understanding, the analyst/experimentalist develops an idealization of the building as a series of well-mixed zones and formulates an appropriate pulse injection strategy in order to determine the airflow rates between these zones. Forming this idealization is a crucial step, determining not only the injection and sampling strategies and consequently the experimental effort and cost, but also affecting the conditioning of the system of mass balance equations and, thereby, the accuracy of results. To the extent possible, the analyst/experimentalist should attempt to formulate an idealization and related injection strategy that will allow testing that satisfies the condition of Eq 12 (practically speaking, to design a test that can be completed in a minimum of time). Thus, in general, simple idealizations will be preferred and multiple tracers may be advantageous.

An idealization of a building airflow system consists of a series of well-mixed zones connected by airflow paths, but need not include every airflow and every zone in the building. In fact, such an all-inclusive model of a building will generally be unmanageably complex from an experimental point of view and involve the determination of more airflow rates than are necessarily of interest. In many cases, several distinct building zones can be considered as a single zone with no degradation in the accuracy of the results if a tracer gas injection strategy can be employed that results in these separate zones having the same integral response to the tracer gas injections. In certain circumstances, a selected subsystem of the building can be investigated, providing useful information without consideration of the rest of the building. In this situation, the rest of the building is being combined with the outdoors to form Zone 0.

The development of a multi-zone idealization begins with a qualitative analysis of the building layout and the ventilation system equipment and zoning to identify the major zones and system airflow paths of the buildings. In addition to the air handler zoning and physical layout, the multi-zone idealization can be based on an interest in airflows between particular portions of the building, or other aspects of the building's air exchange performance. In the process of forming an idealization, the existence of unexpected or undesired airflows due to envelope leakage, poor system performance, or inadequate separation between zones are investigated. A qualitative airflow diagnosis, using handheld instrumentation (for example, anemometers), smoke sticks, or tracer gas pulses, can serve to elucidate such building airflow characteristics. For example, exhaust airflows may be verified as such or shown to be not flowing in the expected direction. Specific airflow rates may be shown to be zero and need not be included in the idealization.

Once the building idealization has been developed, tracer gas injection and air sampling strategies are defined. The injection strategies include the manner in which the tracer will be delivered to each zone, the mass of tracer to be injected and a means for determining this mass, and the timing of the injections into the various zones. The air sampling strategies include the number and location of air sampling points in each zone, and the manner in which they will be sampled. Specific issues regarding injection and sampling are discussed below. Once the data are collected they are converted into the form of Eq 13, which is then solved for the unknown airflows and analyzed to provide an evaluation of the error.

Experimental Procedures

In addition to the use of an appropriate multi-zone idealization, a pulse measurement requires careful injection and sampling procedures. To a large degree, these procedures relate to the important assumption that each zone is well mixed, more specifically, that the value of $\int C_i$ is uniform throughout each zone. The appropriateness of this assumption is increased by injecting the tracer gas as uniformly as possible throughout the zone. The gas can be released directly into the zone itself using a multi-point injection scheme or by moving the injection outlet through the space during the release. Such a "within-the-space" injection can be difficult in a large or complex zone, in which case the gas can instead be injected into the supply air distribution system serving that zone, if one exists. Using the air distribution system to inject the tracer can provide a uniform dispersal of the tracer gas, but one must be sure that all of the gas gets to the space (that is, the supply duct work does not leak). In many systems this assumption cannot be justified, but, as discussed below, one can still use the supply air system for injection in this situation but not include the injection period in the concentration integral. The injection should last a short period of time relative to the airflow system time constants in order to approach the ideal post-injection conditions of a nonzero tracer gas concentration in the injection zone and zero concentrations in all other zones. Postinjection conditions of this type tend to minimize the ill-conditioning of $[\int C]$.

As with the duct pulse technique, one only needs the integral of the tracer gas concentration in each zone. This can be determined with real-time monitoring or with an average air sample taken during the integration period. Real-time monitoring must be conducted with consideration given to the sampling frequency of the tracer gas monitor and the transport of air samples from the zones to the monitor. Since the pulse technique employs the assumption that the integral of the concentration response is uniform throughout each zone, the tracer gas concentration must be sampled at several locations in each zone in order to verify this assumption.

The time interval over which the integral is determined need not include the tracer gas injection, nor need it last until the tracer gas concentration goes to zero. If the integral includes the tracer gas injection, then the injection mass must be known precisely and be well dispersed throughout the test space. If the injection period is not included in the integral, then the injection mass need not be known, though it needs to be controlled such that the concentration within the zone is in the measurable range of the tracer gas detector. In this case, $\int G_i$ will equal zero, but the value of $-m_i\Delta C_i$ will be large and positive due to the significant tracer gas concentration at $t = t_1$.

The duration of the integration period involves a balance between one's ability to measure accurately low concentrations and one's knowledge of the zone masses, m_i. Towards the end of the concentration response, the tracer concentrations will be very low and may be difficult to measure accurately. One can avoid this source of error in the integral by choosing t_2 to be a time when the concentrations are still within a range that can be determined accurately. In this case, the $m_i\Delta C_i$ terms may be significant, and if they are, an accurate knowledge of the m_i will be important. The importance of knowing m_i accurately depends on the relative magnitudes of the $\int G_i$ and $-m_i\Delta C_i$ terms.

In some cases, the concentration response in the injection zone will be very short-lived, corresponding to a high air exchange rate. In these cases, one should employ an average concentration to determine the integral. This averaging should begin well before the tracer gas injection and continue until the concentration within the zone has decreased to essentially zero. One can determine the air exchange rate of a single zone with such an average, but must be certain that the tracer gas concentration is zero at $t = t_2$. If it is not, then an air sample taken at t_2 is needed to compute the $M\Delta C$ term. This approach enables the low-cost determination of single-zone air exchange rates with on-site air sampling and off-site tracer gas concentration analysis.

Field Tests Using the Pulse Techniques

The integral pulse techniques were applied to two multi-zone idealizations of a 15-story office building. This building has four separate air handlers serving the 15-story tower section, two for the 14th and 15th floors, and two more serving Floors 1 through 13. These air handlers run on 100% outdoor air and are located in a penthouse mechanical room. The air from the building is exhausted through a relief air system directly to the outdoors, with no provision of the recirculation of return air. On each floor, air from the supply air shafts is forced into an unducted ceiling plenum by booster fans. This supply air enters the occupied space through diffusers in the suspended ceiling as shown in Fig. 6. Based on an on-site inspection of the building and its systems, it was noted that there were significant amounts of supply air leaking from the pressurized ceiling plenum directly to the relief air shafts, to other service shafts, and presumably through the exterior envelope, without reaching the occupied space below the suspended ceiling. This leakage led to the question of how much of the supply air was actually reaching the occupied space on the floors. In addition, strong airflows were noted in the two stairways in the building, flowing up to the penthouse mechanical room. These airflows and other flows into the penthouse from the building led to the question of what were the airflow rates between the building zones and the penthouse.

Based on the inspection of the building and its systems, two different idealizations of the building were investigated with pulse tests. As shown in Figs. 7 and 8, one idealization is of the whole building, and the second is of an individual floor. In the first idealization, the tower is modeled as three zones, based on the air handler zoning and the observed importance of the penthouse. Zone 1 consists of the penthouse mechanical room, Zone 2 is the 14th and 15th floors modeled as a single zone, and Zone 3 includes Floors 3 through 13. The lower two floors were left out of Zone 3 because they did not respond to the tracer gas injections and were therefore considered part of Zone 0. The second idealization models an individual floor as two zones, a supply zone and an occupied zone, and is an example of a building subsystem that enables the investigation of specific aspects of a building's air exchange characteristics. The supply zone includes the supply air distribution system for a floor, and the occupied zone includes the space below the suspended ceiling. The supply

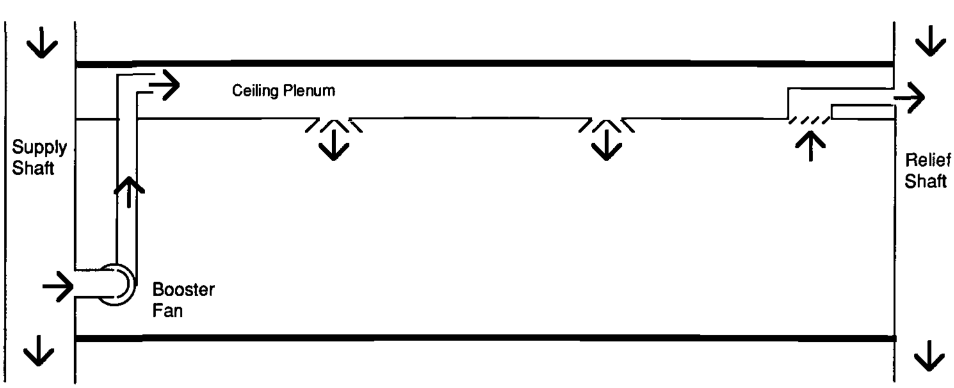


FIG. 6—*Simplified section of an individual floor of tower.*

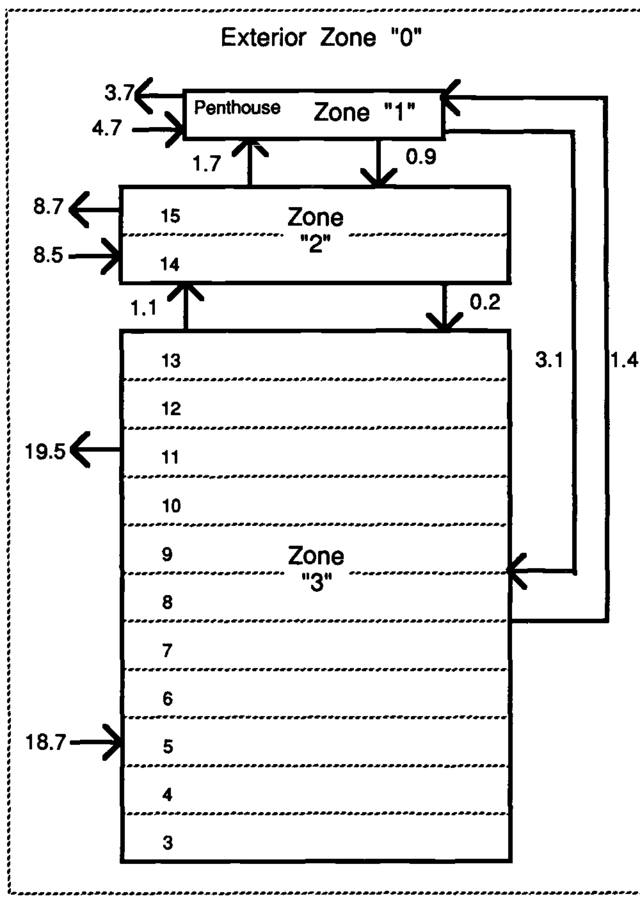
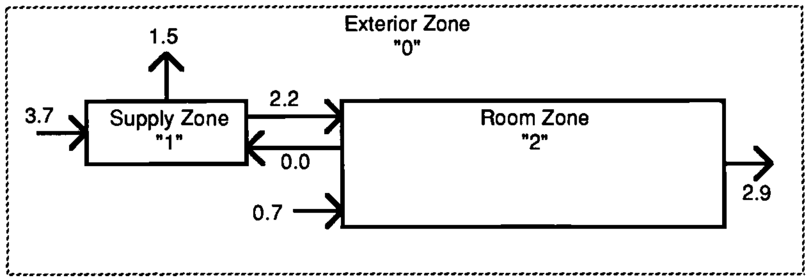


FIG. 7—*Three-zone idealization and results for 12/1/87 (all flows in m*^{3}*/s).*

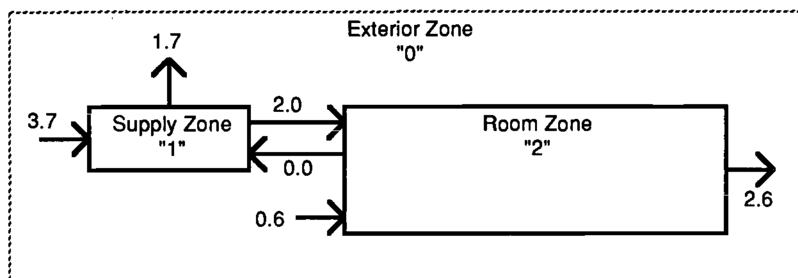
zone is a conceptualization, not a physical zone contained within well-defined boundaries. Therefore, the mass of the supply zone cannot be used in analyzing the data. The first idealization is intended to determine the airflow rates between the main air handling zones, the penthouse and the outdoors. The second idealization is intended to determine how much of the floor's supply air actually reaches the occupied space.

The tower model depicted in Fig. 7 was investigated using successive pulse injections of sulfur hexafluoride (SF_6) into the penthouse (Zone 1), the 14th and 15 floors (Zone 2), and Floors 3 through 13 (Zone 3). A premeasured amount of SF_6 was injected into the penthouse by hand while walking throughout the space over a period of about 2 min. The injections into the other two zones were made by injecting SF_6 into the air handlers serving these zones through flowmeters at a known rate for a known length of time (about 1 min). The concentration response to the penthouse pulse was measured every 5 min in the penthouse and on Floors 7, 11, 14, and 15. Only two floors in Zone 3 were monitored because the Zone 3 response to the penthouse injection was minimal, and in order to enable more frequent sampling of the short-lived penthouse response. The concentration responses to the Zone 2 and Zone 3 pulses were measured every 10 min in the penthouse, on Floors 14 and 15, and on the odd-numbered floors from 3 to 13. The penthouse concentration was



Test A Results

Condition Number = 3.2



Test B Results

Condition Number = 3.4

FIG. 8—*Floor idealization and results for 12/17/87 (all flows in m*^{3}*/s).*

based on a mixture of air from two locations in the penthouse. The individual floor concentrations were based on a mixture of air from four locations on each floor. It must be emphasized that the floors in Zones 2 and 3 behaved as single well-mixed zones in these tests, i.e., they responded with practically uniform concentration integrals for this particular injection strategy. For other injection strategies, these floors will, in general, behave differently.

Because the penthouse injection was released directly into the zone and because the penthouse concentration response was very short-lived, the tracer gas injection period was included in the concentration integral. Because of leakage in the supply air distribution system serving the building, the injection periods were not included in the integrals of the concentration response to the injections in Zones 2 and 3.

The results of one of the tower pulse tests are shown in Fig. 7. The airflow rates from the outdoors (Zone 0) into Zones 2 and 3 include intentional outdoor air intake through the air handlers and air infiltration through leaks in the exterior envelope of the building. Due to leaks in the supply air distribution system, not all of the outdoor airflow through the air handlers necessarily reaches the space and therefore only a fraction of the outdoor air intake will contribute to the measured airflow rates from the outdoors to Zones 2 and

3. The airflow rate through the air handlers serving Zone 2 is about 7 m^3/s, as measured with a duct pulse test, but not all of this supply air gets to the zone due to leaks in the supply air system. The difference between the measured airflow rate from the outdoors to Zone 2, 8.5 m^3/s, and the measured airflow rate through the air handlers is a lower limit on the infiltration airflow through leaks in the building envelope into Zone 2, that is, 1.5 m^3/s or about 0.5 air changes per hour. Similarly, the airflow rate through the air handlers serving Zone 3 is about 20 m^3/s. Only 18.7 m^3/s of outdoor airflow into Zone 3 was measured, and therefore no estimate of the minimum infiltration rate into that zone can be made. The measured airflow rates from the penthouse to Zones 2 and 3 were larger than expected, possibly due to airflow down elevator shafts and large openings on the negative pressure side of the air handling systems within the penthouse. Two additional pulse tests were conducted on the idealization in Fig. 7 and the resultant airflow rates and condition numbers of all three tests are similar. In two of the tests, a small negative value was obtained for the airflow rate from Zone 2 to Zone 3. In as much as negative flows violate the assumption of the underlying theory, we must conclude that these values have resulted from data measurement errors amplified by the ill-conditioning of the system and are probably a manifestation of the data and analysis errors discussed earlier. More specifically, we may, by perturbation analysis, place an upper-bound error estimate on all flows equal to the product of the condition number, the relative data error, and the maximum flow determined. Representative values for these three quantities were 4, 1%, and 20 m^3/s, thus a reasonable upper-bound error estimate would be ± 0.8 m^3/s, a value on the order of the negative flows obtained.

The floor model depicted in Fig. 8 was investigated with a pulse test in order to determine the amount of supply air that was bypassing the occupied space of the floor. In this idealization of a floor of this building, Zone 0 includes the outdoors and the rest of the building, Zone 1 is the supply air distribution system, and Zone 2 is the occupied space of the floor. The inclusion of the rest of the building in Zone 0 is appropriate because the floors of this building are well separated from each other in terms of airflow. During these tests the SF_6 concentration was measured on the floors above and below the floor being tested, and there was essentially no SF_6 response on the surrounding floors. The injection into Zone 1 was made by hand into the supply air ductwork, and the concentration response in this ductwork was determined by filling an air sample container to determine the average concentration. This was essentially a duct pulse test to determine the supply airflow rate to the floor. The concentration response was measured in real-time at four locations in the occupied space (Zone 2).The integral of the concentration response to the supply zone injection included the injection period in order to determine the airflow rate in the supply ductwork. The tracer gas was injected directly into Zone 2 by hand; a known amount of SF_6 was released while walking through the occupied space. Since there was no backflow from the occupied space into the supply air system, there was no need to measure the concentration response in Zone 1.

The results for a set of repeated floor-bypass tests are presented in Fig. 8 for the fifth floor of the building. These results are based upon a series of three injections; the supply zone was subjected to a single injection and the occupied space was subjected to two separate injections. The Test A results were computed using concentration data for the single supply zone injection and the first of the occupied space injections; the Test B results were computed using concentration data for the supply zone injection and the second of the occupied space injections. A comparison of these results provides an indication of the uncertainty of the computed flows. Another floor-bypass pulse test was conducted on the fifth floor of the building, and two additional floors were tested twice each. The test results were all comparable, as were the condition numbers. The fraction of supply airflow that bypassed the occupied zone ranged from about one third to one half. The airflow rate from Zone 0 to Zone 2 was generally small and in some cases assumed a small negative value, but again these negative values were not significant relative to estimates of the uncertainty in flow based on perturbation analysis.

Summary and Discussion

The pulse-injection tracer techniques provide useful tools for studying building airflow systems. The duct pulse application is a rapid and convenient means of measuring airflows in ventilation system ductwork. The building pulse applications are capable of determining the airflows in multi-zone building systems in relatively short time periods (on the order of the dominant system time constants), and can be conducted with a single tracer gas. Pulse injection determinations of airflow rates may be expected to be relatively insensitive to variations in airflow rates, and the analysis of data from field studies to date indicate that the multi-zone pulse injection technique may be expected to yield relatively well-conditioned equations. In the multi-zone pulse injection technique, as in all multi-zone tracer gas techniques, the manner in which the building airflow system is idealized as a series of interconnected zones is pivotal in obtaining a well-conditioned system of equations and, thereby, reasonable estimates of the system airflow rates.

The field tests discussed above have served as preliminary applications of the pulse injection techniques, and the process of planning and conducting the tests and analyzing the data have raised several issues. A primary factor in obtaining accurate test results is minimizing the ill-conditioning of the system of mass balance equations. The degree of ill-conditioning of this system of equations is affected by the appropriateness of the building idealization, the accuracy of the test data, and the analysis of the data to obtain the terms of the $[\int C]$ and $[\int T]$ matrices. As discussed earlier, there are two major variables in analyzing the test data, the inclusion of the injection period in the concentration response integrals and the length of the integration intervals. It has already been stated that if the tracer is injected directly into the zone and dispersed in a fairly uniform manner, then the injection can be included in the integration interval. If the tracer is sent to the zone via a supply air distribution system, it is best to begin the integration interval after the injection is complete unless one is absolutely certain that the supply air system does not leak between the injection point and the zone. Including the injection period in the injection interval will generally minimize the ill-conditioning of $[\int C]$ because the value of $\int C$ in the injected zone will generally be larger than $\int C$ in the other zones, as compared to the case in which the injection is not included.[3] Including the injection does require knowledge of the injection mass $\int G$ and that the injection is uniform throughout the zone.

An important assumption in the pulse technique is that all zones are well-mixed, that is, the integral of the tracer gas concentration response within each zone is uniform. Therefore, all of the zones should start out with a uniform concentration profile, and the beginning of the integration interval should be delayed until the injection has mixed sufficiently to realize these conditions. If these initial conditions cannot be achieved by a well-distributed injection, even if the tracer in injected directly into the zone, then the injection should not be included in the integration interval. If the injection is not included, it is advisable to delay the start of the integration interval so that the tracer gas can mix within each zone. The longer one allows for the tracer gas to mix, the difference between the integral response, $\int C$, in the injected zone and all other zones will decrease, increasing the ill-conditioning of the system of equations.

The data collected in each of the above field tests were analyzed several times, varying

[3]Algebraically, having larger values of $\int C$ in the injected zone will ensure that the rows of $[\int C]$ will be independent and, thus, $[\int C]$ will be nonsingular while large relative differences between $\int C$ in the injected and the other zones will tend to increase the orthogonality of the rows of $[\int C]$ and, thereby, reduce the ill-conditioning of $[\int C]$.

the inclusion of the injection period in the integration interval and varying the length of this interval. The airflow rates calculated with these various data sets from the same test were compared. It was found that some of the calculated airflows rates were quite insensitive to which data set of a particular test was used, while others varied significantly for different data sets. For some tests, all of the calculated airflow rates varied by only 5 to 10% as the length of the injection interval and the inclusion of the injection was varied. For other tests, some airflow rates were insensitive to these variations while others were not. Including or not including the injection in the integration interval for Zone i generally had a lesser effect on the airflows involving zones other than Zone i than on the airflows involving Zone i. It is not clear whether these differences in the sensitivity of the data from an individual test is due to the quality of the test data or to some other effect.

The pulse injection techniques are relatively new, and there have been only limited applications in the field. Additional study in both the laboratory and the field is needed to more completely examine sources of errors and to better establish experimental procedures for their practical application. Several specific items are proposed for additional study including a laboratory study of the duct pulse technique designed to assess the experimental errors associated with the procedure. A laboratory investigation of the multi-zone technique employing a facility in which inter-zonal airflows could be modulated and measured would enable the verification of the airflow rate determination by the pulse technique and an examination of the errors associated with data analysis and solution of the system of the mass balance equations. Additional field applications of the pulse technique are also appropriate at this time, using experimental procedures that are refined based on the experience discussed above and employing new building idealizations.

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DISCUSSION

P. Lagus[1] *(written discussion)*—What happens if the $w(t)$ in the duct is decaying (i.e., if there is duct leakage)? How do you interpret the concentration profile? Can you infer anything about duct leakage with this technique?

A. Persily (author's closure)—The duct pulse technique as described in the paper does assume that the airflow rate into the duct is the same as the airflow rate out, i.e., there is no duct leakage. However, as noted in the paper, the technique could be modified to indeed quantify the amount of leakage by employing a series of injections and samples at various points along the length of the duct.

J. T. Reardon[1] *(written discussion)*—What do you mean when you state that for a zone to be considered a single zone it must provide the same (i.e., a uniform) *concentration*

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integral response (CIR) throughout its spatial extent? The example cited was a multistory portion of a large building supplied by a single air handling system in which floors were well sealed in that there was very little direct communication between floors. Did you impose, by measuring the concentration integral response in this one air handling system, a uniform CIR, or was a CIR measured from several of the floors to establish that a uniform CIR did exist within the single zone?

A. Persily (author's closure)—In order for a volume or space to be idealized as a single zone in the integral pulse technique, it must have the same integral concentration response to each tracer gas injection that occurs in the measurement procedure. This requirement can be fulfilled even if the zone is not well mixed given appropriate airflow circumstances and tracer gas injection strategies. In the measurements cited in the paper, the concentration was monitored on every other floor of the building and the integral of each floor's concentration was calculated. The values of these integrals were very close to each other, verifying that the idealization of these various floors as a single zone was appropriate.

Stephen N. Flanders[1]

Air Change Measurements of Five Army Buildings in Alaska

REFERENCE: Flanders, S. N., "**Air Change Measurements of Five Army Buildings in Alaska,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 53–63.

ABSTRACT: The air change rates of five buildings (four barracks and one vehicle maintenance garage) were measured, using the tracer gas dilution technique. The median air change rate for all zones measured was close to 0.5 air change per hour (ACH). The range of air change rates was between 0.05 and 1.75 ACH. Most of this range was attributable to variation in the effectiveness of the buildings' ventilation systems. Outdoor temperatures were between −15 and −20°C (5 and −4°F). The wind was calm for all but one barracks measurement. The maintenance facility, a large single-zone building, permitted good results from the tracer gas technique. The barracks, multi-zone buildings, varied in the ease with which the tracer gas technique could be applied. The barracks ventilation systems were in operation when air change measurements were made. These systems incorporated air-to-air heat exchangers with intakes and exhausts mounted in rooftop penthouses.

KEY WORDS: air change rates, Alaska, Army buildings, infiltration, tracer gas, ventilation

The purpose of this study was to determine how to use tracer gas techniques to measure air change rates in typical Army buildings in Alaska. There is little information available to the engineering profession in Alaska about actual air change rates in military buildings, yet the military constitutes a significant fraction of the work of architecture/engineering firms in that state. Typical Army buildings are difficult to assess because they comprise many rooms, usually locked, with sometimes rudimentary mechanical ventilation.

Tracer gas techniques measure air change as a result of the prevailing weather conditions and the operation of the building. Three tracer gas techniques are available [*1*]: dilution, constant emission, and constant concentration techniques. The ASTM Standard Test Method for Determining Air Leakage Rate by Tracer Dilution (E 741) is not specific about the building types it applies to, but ASTM E 741 does require good mixing of the tracer gas such that concentrations do not vary by more than 5% from place to place.

Previous work on military hangars by Ashley and Lagus [2], using the tracer dilution technique, achieved good mixing in large, single-zone buildings with fans. Their tracer gas concentrations varied between 6 and 16% of the mean measurement value, above the ASTM E 741 limit criterion. The air change rates agreed within a standard deviation (SD) of 6% of their mean value. Their work suggested that air change behavior of large, single-zone buildings can be monitored at a few sampling locations.

In a complex building, typical of the military, the dilution technique is simplest to employ if uniform concentration can be established prior to measurement. The constant emission technique requires either automated equipment that precisely dispenses tracer gas at known

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rates, or a large number of passive sources for emitting the tracer gas throughout the building. One such passive source, the perfluorocarbon tracer (PFT) gas emitter [3], dispenses gas at a known rate without mechanical control. The current PFT technique is suitable primarily for single-family homes and is difficult to adapt to a large building with many locked rooms, such as a typical military barracks. The constant concentration technique would be difficult to employ in a large, complex building unless the sampling and injection took place in the ventilation system. Constant emission techniques require fairly frequent sampling to avoid underestimating air exchange in the presence of changing conditions [4].

Large office buildings have been subject to air change measurements using the tracer gas dilution technique [5]. The measurements took place with the building unoccupied and the ventilation shut off from outside and with the building in full operation. Data from an office building in Anchorage had a low correlation between infiltration and the difference between indoor and outdoor temperatures (ΔT) for ΔTs ranging from 5 to 40 K (9 and 75°F). The reported infiltration rates ranged from 0.25 to 0.5 ACH, indicating a fairly tight building envelope. At lower ΔTs, the ventilation system operated at about 1.3 ACH, indicating a properly functioning system.

Procedure

The Buildings

The study included four barracks (666, 668, 3417, and 3419) and one vehicle maintenance shop (750). All buildings were of reinforced concrete slab and frame construction with concrete masonry block infill walls. These buildings represented a balance of cases: (1) updated ventilation systems versus outmoded systems; (2) occupied versus unoccupied; (3) multi-zone versus single-zone; and (4) two Alaskan climatic regions. Three buildings were at Fort Richardson,[2] near Anchorage, and two barracks were at Fort Wainwright[3] in Fairbanks. The barracks, except for 3417, were occupied during the measurement; the shop was vacant during the measurement. The barracks (Figs. 1 and 2) each had a volume of 12.9×10^3 m^3 (0.456×10^6 ft^3), served by a variety of ventilation systems. Each ventilation system incorporated an air-to-air heat recovery coil housed in a rooftop penthouse.

The maintenance shop (Fig. 3) had a vehicle exhaust evacuation system that was not running during the night the measurements took place. The maintenance shop (Building 750) was 122 by 19 by 7 m (400 by 63 by 23 ft), divided in half. The study encompassed only one half of the building, with a volume of 16.4×10^3 m^3 (0.579×10^6 ft^3).

Equipment

The equipment included a gas chromatograph (GC), set up in a building near the test sites, and five sequential gas samplers. The electron-capture GC is designed for sulfur hexafluoride (SF_6) tracer gases in concentrations of 10^{-9} to 10^{-12}. The GC has a cycle time of about 5 min between samples. The sequential gas samplers each have twelve polyethylene, 30-cm^3 syringes. The syringes extend to their full capacity at programmed intervals.

An experiment determined that the syringes retain the sampled concentration for up to five days. Twelve syringes were extended simultaneously in a building that contained a well-mixed SF_6 tracer gas. Over five days the syringes were randomly selected for injection in the GC. During that period, the determinations of the natural logarithm of the concentration varied by a standard deviation of 1.64% of the mean.

[2]Heating degree-days: 5957 K (10722°F). 97.5% design temperature: 246 K (−27°C, −16°F). Mean winter wind speed: 2.1 m/s (4 knots).

[3]Heating degree days: 7969 K (14345°F). 97.5% design temperature: 229 K (−49°C, −47°F). Mean winter wind speed: 1.5 m/s (3 knots).

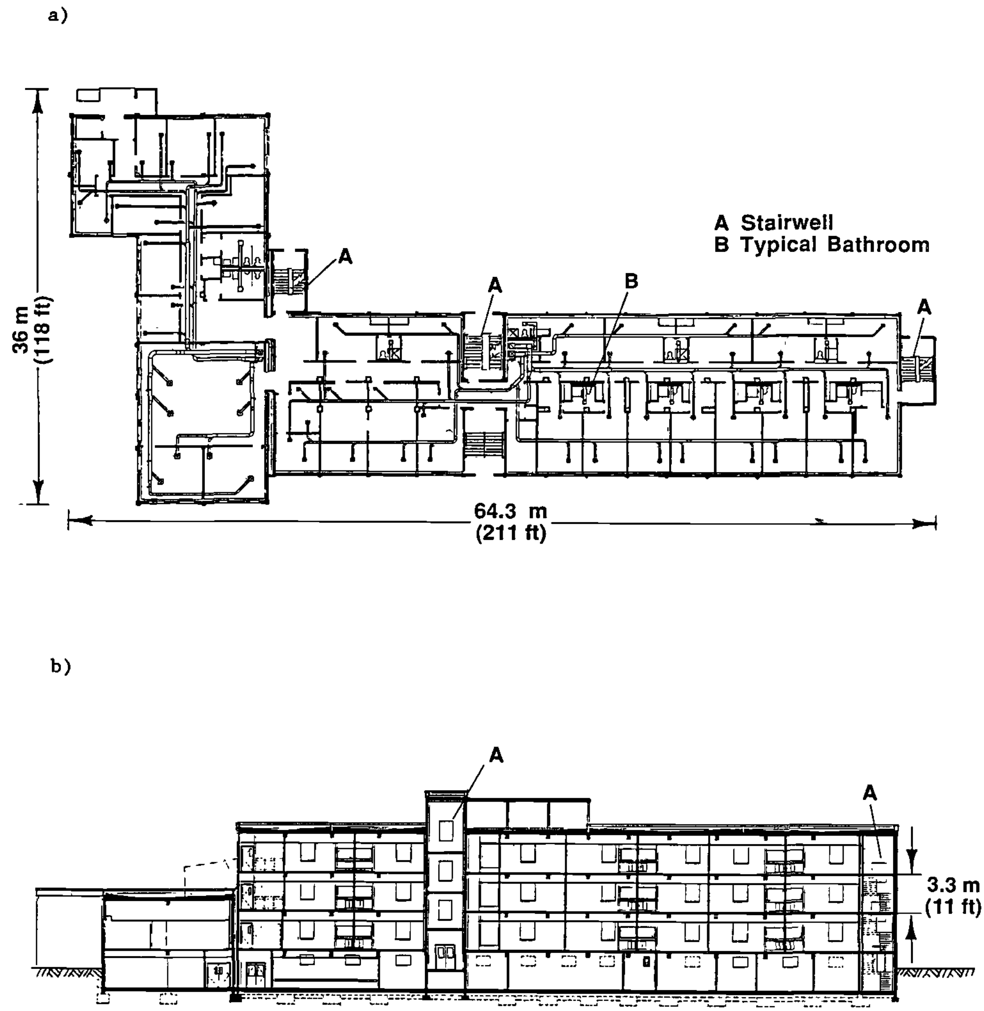

FIG. 1—*Typical barracks,* (a) *plan,* (b) *section.*

Sampling and Analysis Techniques

Vehicle Maintenance Shop—The five sequential gas samplers were placed at approximately even intervals around the perimeter of the large space. The twelve syringes of each sampler were set to collect samples at 60-min intervals, starting 1 h after an 8.2-cm^3 volume of pure SF_6 was injected in half the building by slow release.

Barracks—The ventilation systems were allowed to function normally in each case. Ten cm^3 of SF_6 was released in the air inlet of the barracks ventilation system penthouse and 3 cm^3 in either the ventilation penthouse for the wing of the building (Building 668) or directly into the occupied space of the wing. The five sequential gas samplers were placed in the building, such that each of the following areas received a sampler: Floors 3, 2, 1, and basement, and the first floor of the building wing. Testing a barracks with the ventilation shut down and sealed was not an available option. The operation of individual bathroom

FIG. 2—*Typical barracks, exterior view.*

FIG. 3—*Building 750 at Fort Richardson, a motor vehicle maintenance shop.*

vent fans could not be verified because they were behind locked doors. However, the fans and bathroom lights were assumed to be off at night.

No flow measurements were obtained from the ventilation systems of the buildings.

Gas Concentration Analysis—Both the sequential gas samplers and their syringes were chosen for analysis according to a randomized plan. Such randomization helps avoid autocorrelation effects, such as sample time spent in the syringe, etc. For each sampler, 10-cm^3 replicates of the first syringe were injected into the GC to determine the scatter of the gas concentration analysis process and to confirm the correct setting of sensitivity of the apparatus. Replicates were also made when the performance of the GC was in doubt because of variations in results from sample to sample. The remaining samples were injected using the full 30 cm^3 of the syringes.

Interpretation of the Data—The SF_6 concentrations for each zone were plotted as natural logarithms against time for each sampling period, as specified in ASTM E 741. When the logarithmic data fall on a straight line, the slope represents a constant rate of air exchange, expressed in air changes per hour (ACH).

A single-zone model [6] was applied to an abstract building with similar attributes to the barracks, as determined by a standard procedure for determining leakage areas and their distributions [1]. The model differed from the actual building because it did not attempt to represent the internal resistances to flow from zone to zone or the parallel and series paths for flow from indoors to outdoors via the stairwells and ventilation ducts. The model runs compared the effects of air exchange of different wind and temperature scenarios in cases with the area of the ventilation intakes included or excluded.

Results

Air change rates in the buildings studied were between 0.05 and 1.75 ACH. The median air change rate for all zones measured was close to 0.5 ACH. Table 1 summarizes the air change rates obtained for each building by zone, based on choosing portions of the data that represented reasonably straight lines in the natural logarithm versus time plots. Building 750 had air change rates of about 0.25 ACH. The barracks had air change rates that ranged from 0.24 to 1.74 ACH in the dormitory portions of the buildings (Floors 1 to 3) with the fan systems operational.

The ΔTs for the five measurements ranged from 40 to 50 K (72 to 92°F). The average standard deviation (SD) of the mean ΔTs was 4.3% of the mean. In all cases, except for Building 3417, the wind was essentially calm. For Building 3417, it came from the east at between 1.5 and 5.1 m/s (3 and 10 knots).

TABLE 1—*Air change rates (FR = Fort Richardson, FW = Fort Wainwright). The buildings are presented in order of measurement. The design ACH for Building 668 are based on as-built drawings for a renovated ventilation system. As-built drawings were not available for the ventilation systems of the other buildings.*

Building	Use	Floor	ACH	ΔT (K)	Design ACH
FR 750	Vehicle maintenance (SDs of above mean value)	Ground	0.25 (±7%)	43.3 (±2.6%)	
FR 668	Barracks	3	0.33	47.8 (±5.1%)	1.25
		2	0.35		1.25
		1	0.30		1.12
		Basement	0.66		2.56
		Wing	0.46		1.02
FR 666	Barracks	3	0.33	43.4 (±4.7%)	
		2	0.24		
		1	0.77		
		Basement	0.057		
		Wing	0.56		
FW 3419	Barracks	3	No data	45.7 (±8.6%)	
		2	1.74		
		1	0.23		
		Basement	0.15		
		Wing	0.74		
FW 3417	Barracks	3	0.49	39.9 (±0.52%)	
		2	1.05		
		1	0.29		
		Basement	0.37		
		Wing	Not mixed		

Figures 4, 5, 6, 7, and 8 represent the tracer gas concentrations for each building, plotted as natural logarithms against time.

The model assumed that the ventilation openings were 9 m^2 (27 ft^2) and that the sum of the crack areas in the other construction elements was 1.3 m^2 (14 ft^2). The ventilation openings were further assumed to be on the roof, as they are on the actual buildings. Table 2 shows a summary of the effects of temperature, wind, and the presence of rooftop ventilation openings. In windless conditions the presence of these ventilation openings increased the air change rate by a factor of 2.7 over what the air change rate would be with no mechanical ventilation system. In the ΔT range of 40 K (72°F), the presence of a 5-m/s (10-knot) wind almost doubled the air change rate in the case with the ventilation openings.

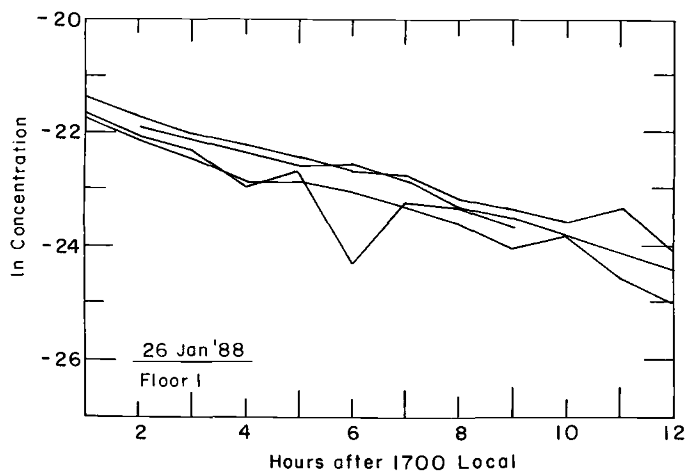

FIG. 4—*Building 750: natural logarithm of measured SF_6 tracer gas concentrations.*

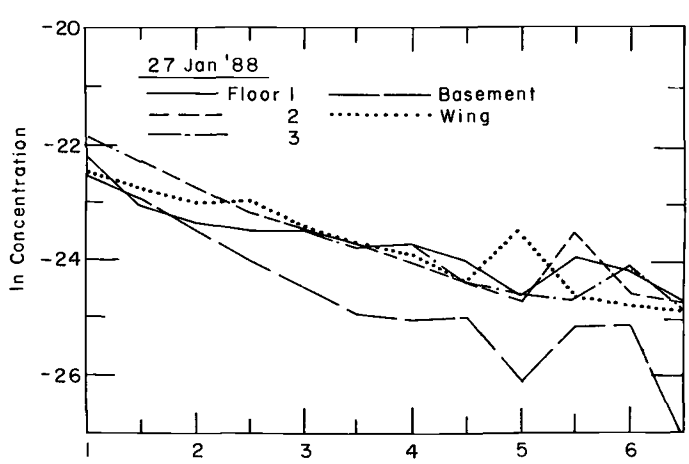

FIG. 5—*Building 668: natural logarithm of measured SF_6 tracer gas concentrations.*

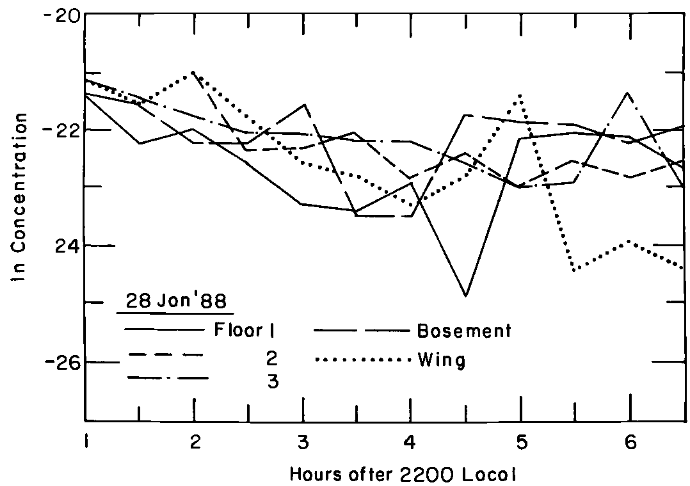

FIG. 6—*Building 666: natural logarithm of measured SF_6 tracer gas concentrations.*

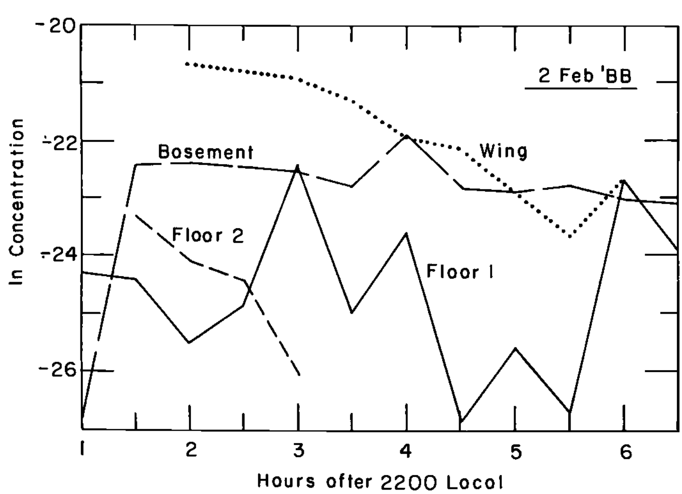

FIG. 7—*Building 3419: natural logarithm of measured SF_6 tracer gas concentrations.*

Discussion of Results

General

The desired result of tracer gas dilution test for air change is exemplified in Fig. 4. The natural logarithm of the concentrations form a fairly straight line. The concentrations are approximately the same in this large, reasonably well-mixed, single-zone maintenance building. As explained in Ref *1* and other sources, the slope of this log-normal line represents the ACH in the measured space.

Data from the barracks buildings are not so well behaved (Figs. 5 to 8). These buildings comprise many separate cells. Each floor has many separate dormitory rooms. Each barracks has significant differences in its heating and ventilation system, compared with the other

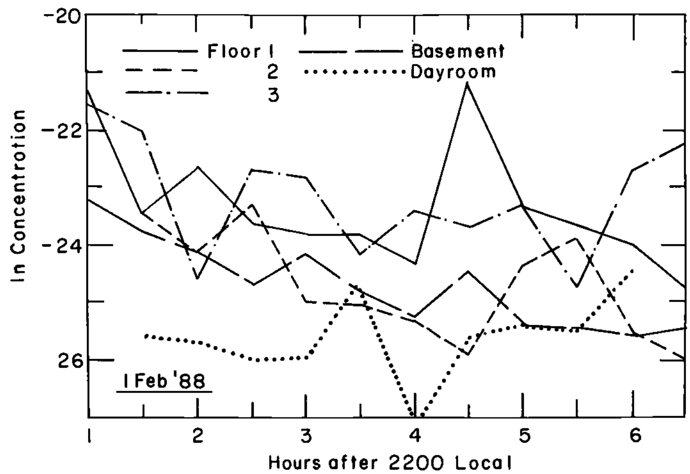

FIG. 8—*Building 3417: natural logarithm of measured SF_6 tracer gas concentrations.*

TABLE 2—*Air change rates for a typical barracks building without its wing, treated as a single-zone model* [6]. *Note: A temperature difference of 40 K = 72°F and a wind speed of 5 m/s = 10 knots.*

Temperature Difference, K	Wind Speed, m/s	Air Changes, ACH
	No Rooftop Ventilation	
20	0	0.41
40	0	0.58
20	5	0.78
40	5	0.88
	With Rooftop Ventilation	
20	0	1.13
40	0	1.59
20	5	2.86
40	5	3.07

barracks studied, as a result of different retrofit and repair histories. Some barracks wings have separate ventilation systems. A properly functioning ventilation system should feed all zones in proportion to their volumes and air requirements, but its balance may change with varying weather conditions. The barracks are designed to provide a constant level of ventilation through heat exchangers. The data suggest that none of the ventilation systems were providing either even air distribution within the building or adequate ventilation levels.

In a multi-zone building, the behavior of the tracer gas concentration depends on the extent that the zones are in series or parallel. With zones purely parallel, the air change rates and concentrations act independently. With zones purely in series, an equilibrium of constant ratios of tracer gas concentrations among zones and with nearly equal air change rates can occur when the driving forces of wind and temperature are constant. If a zone includes a large isolated space that communicates only with that zone, that space will tend to damp variations in tracer gas concentrations as it absorbs incoming concentration levels and gives up outgoing concentration levels.

The barracks contain a combination of parallel and serial zones (Fig. 1). The stairways represent substantial parallel paths connecting the basement in series with the third floor. The doors between the main halls and the stairwells are loosely fitted in most of the barracks buildings. Often the troops leave them propped open. The ventilation duct work connects each zone with the inlet and exhaust openings on the roof. The individual floors are dead-end volumes with comparatively small leakage areas that feed laterally into the vertical conduits of both the stairs and the duct work with their ultimate exit points of doors and ventilation openings on the roof.

The stairwells and the constantly operating heat-recovery ventilation system should cause smoothly varying air change behavior. The "wild card" is the bathroom vent fan; in Building 668 these fans served eleven different ducts to the roof. The number of bathroom fans turned on and dormitory doors opened could drastically alter the rate of flow through a given floor to the roof. The actual number of fans turned on could not be verified because doors to dormitory suites were locked. Likewise, it was not practical to track the opening and closing of dormitory doors and their effect on internal resistance to air flow within the building.

Another possible source of perturbation in the data can be experimental error. When the SF_6 bottle was readied for shipment from Fort Richardson to Fort Wainwright, the room with the GC became contaminated at an unknown concentration with the tracer gas. This was evident from erratic GC readings. Consequent ventilation of the room appeared to improve the consistency of readings.The standard deviation (SD) of replicate readings from the same syringe was 0.6% of the mean concentration before the contamination event and 1% afterwards. The low SDs before and after the event do not support the hypothesis of contamination.

Discussion of Results By Building

Building 750, Fort Richardson—Figure 4 illustrates the consistent results of 0.25 ACH ± 7% SD obtained in this large, single-zone building. The building was unoccupied during the nighttime measurement period, and there was no mechanical ventilation or forced air movement. This close agreement in ACH occurred without the concentrations of tracer gas remaining within 5% of each other as required by ASTM E 741. In fact, the maximum or minimum concentrations of SF_6 differed from the mean value of concentrations at any given time by about 25% of the mean.

Building 668, Fort Richardson—Figure 5 shows fairly straight-line plots of SF_6 data that show between 0.3 and 0.66 ACH. The building had the newest mechanical system of all those surveyed. If the ventilation system were balanced during the summer, then the air change rates for Floors 1 through 3 might reflect the stack effect offsetting the forced ventilation rate. The wing was served by separate ventilation system and was isolated from the main portion of the building by closed doors. The wing was seeded with the same concentration of tracer gas as the main part of the building.

The SF_6 data plot in nearly parallel lines in Fig. 5 from 1h until 4.5 h into the measurement. Then the lines depart from straight. Because the as-built drawings for Building 668 show that all four floors are served by the same fans, the ventilation equipment probably did not cycle off after this period and thereby diminish the rate of air change. Otherwise, one would expect to see concentrations to vary at the same time on different floors as a result of a common fan system. The as-builts also show individual bathroom fans that vent directly to the roof. This could contribute significantly to the varied air changes observed early in the morning when troops might be getting up.

The concentrations were approximately equal in all zones except the basement. The as-built drawings indicate that the basement is ventilated at higher air change rates than the upper stories. Yet the data indicate much lower air change rates for the basement.

A comparison of the ACH data for FR 668 in Table 1 with that for the design ACH show that the building was operating at a much lower ACH than the ventilation system capacity. The as-built information supplied at the time of the test do not explain the control strategy for the ventilation system.

Building 666, Fort Richardson—These data (Fig. 6) would not satisfy the requirements of ASTM E 741 for consistent concentrations within the building or, in many cases, for a constant air change rate. The third floor offers several instances where a straight-line fit of three or four points is excellent. Overall, the first 5.5 h of measurement resulted in 0.33 ACH on the third floor. The wing was also comparatively well behaved. The first floor initially showed a steep slope for the first 3 h and then the concentration rose for 1.5 h. If one incorporates all the data for the measurement period, then the air change rate for the first floor is less than 0.1 ACH.

Building 3419, Fort Wainwright—The sampling unit for the third floor did not operate. The data for the second floor, the first floor wing, and the basement look well behaved (Fig. 7). The wing was closed, but SF_6 was injected into it from under the door. Only the data for the main corridor of the first floor are so scattered as to not indicate a trend.

This building was occupied and showed the highest air change rates, almost two per hour on the second floor (Fig. 7). Possibly there were windows open that were not observed. Open windows are a commonplace response to poorly controlled heating in buildings on Army bases in Alaska.

Building 3417, Fort Wainwright—This building might have been the control test for the role of occupants in allowing bathroom exhaust fans to operate during the test. It was unoccupied during the test period and no one was using bathroom vent fans intermittently. However, the wind was blowing at 1.5 to 5.1 m/s (3 to 10 knots) for this measurement. For the other buildings, the wind was calm.

SF_6 was injected in the corridors, as well as in the fan system, which was working at a very low rate. In this building, the SF_6 concentration in the main floor day room was much lower than elsewhere in the main floor hall (Fig. 8). The tendency for a rising concentration of SF_6 indicates that the distribution of the tracer gas within the building had not equilibrated between zones.

The ACH results from Building 3417 were not significantly different than those of the other barracks, despite the strong winds that prevailed during the measurement. The wind effect may have compensated for the low mechanical ventilation rate observed at the penthouse air intake and outlet.

The Model Results

The model checked computationally with the literature [5]. The single-zone model overpredicted the flow rates through a multi-zone building with interior barriers that retard flow from one part of the envelope to the other, as expected. The crack area parameters in the model were based on estimates from the *ASHRAE Handbook of Fundamental* [*1*] and the observed sizes of the ventilation openings, not on direct measurement of the actual openings of every building element; therefore, it could not be expected to represent the absolute air exchange rates of barracks buildings. Instead, it was used for comparative purposes only. The absolute air change rates of the model were about double the observed rate in the model version with no rooftop ventilation influence. With the influence of rooftop ventilation openings, the air change rates were about five times the observed rate.

Conclusions

This study offers insights both into the building air change behavior and into the technique employed. The barracks ventilation systems appear to deliver only one fourth to one half their design air change rates. The penthouse containing the heat exchanger and fans is on the roof, which creates a strong potential for air to escape the building via the duct system due to its bouyancy. This would act against the supply ventilation fan, but with the exhaust fan. Since the air intake and exhaust are at the same level, air bouyancy does not explain the diminished ventilation rate. Investigation of system filters and other impediments to flow are indicated. This was outside the scope of this study.

Tracer gas studies offer difficulties with achieving equilibrium conditions. The tracer gas must establish an equilibrium within the building through good mixing so that it will migrate only in response to air change between indoors and outdoors, not in finding zones that don't have an equilibrium partial pressure. Even in cases where good mixing has been achieved, the driving forces of wind and temperature must be fairly constant in a tracer dilution test to establish a logarithmic straight-line slope for the data.

In the barracks measured, each floor had direct air linkage to the roof via the eleven vertical ducts from the bathroom vent fans. An open dormitory door would decrease the resistance to natural air flow through a bathroom ventilation duct. With each dormitory room door open to the hall or with a vent fan turned on, the amount of air drawn from the vertical stairways would change and cause varying air change rates, as seen for the barracks in Figs. 5 through 8.

ASTM E 741 is probably too stringent in requiring concentrations to start within 5% of each other in a single-zone building. A more reasonable requirement is for the air change rates to be within 10% of each other. In a multi-story building where each floor is fairly autonomous, but connects with vertical, parallel air paths, it is unreasonable to expect a given floor to have similar concentrations or air change rates as other floors. Instead, it should be reasonable to wait for air change rates in the building to stabilize, as indicated by equal slopes of the natural logarithms of the concentrations, plotted against time.

ASTM E 741 may be too optimistic about achieving good tracer gas distribution through the ventilation system in the older barracks studied. Locked doors preclude opening spaces into each other. Malfunctioning filters, fans, and ducts may prevent balanced air and tracer gas distribution. This experience suggests that injecting an appropriately proportioned amount of tracer gas under each locked door into each space would be a more appropriate way to proceed. With a properly balanced ventilation system, placing a sampling apparatus in the exhaust air plenum in the penthouse would have given a better balanced overall measurement of air change rates in barracks.

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Air Exchange Rate Measurements

Bjorn Kvisgaard[1] *and P. F. Collet*[2]

The User's Influence on Air Change

REFERENCE: Kvisgaard, B. and Collet, P. F., **"The Users' Influence on Air Change,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 67–76.

ABSTRACT: Of the various parameters deciding the air change in a building, the influence of wind and the stack effect have in particular been focused on. Concurrently, with the increase in quality of buildings and the tightening of existing buildings, the influence of the climatic parameters is reduced, and other parameters gain a greater influence on the air change. One of the parameters having a great influence on the air change in tight buildings are the users. The air change rate is greatly influenced by the users not only in naturally ventilated buildings, but also in mechanically ventilated buildings.

On the basis of continuous measurement of the air change in 28 dwellings, the proportion between the total air change (air change in house with occupants) and the basic air change (air change in a sealed house) is discussed. The air change in each of the dwellings has been measured for a period of about one week during occupancy. The measuring principle applied is the method with constant concentration of tracer gas. The measuring equipment utilized is computerized and capable of measuring in up to ten separate rooms for periods of more than one week without supervision.

The main conclusion of the measurement was that, even though the average air change rate for occupied dwellings is higher than 0.5 times/h (which is normally recommended in Denmark), some 20% of the dwellings have an air change rate so low that indoor climate problems may easily arise. Only a small percentage of the dwellings have ventilation systems that can be adjusted to provide the recommended rate of air change. The mechanical ventilation system usually gives too high a rate of air change, while the natural ventilation system usually provides too low a rate.

KEY WORDS: air change rate, ventilation, occupant habits, measurement equipment, tracer gas method, constant concentration method

When discussing air change of buildings it is important to realize exactly which air change is being discussed: Is it the basic air change of the building? Is it the air change from the ventilation system? Is it the air change caused by the users? Or is it the total air change of the building? Since the air changes mentioned are not clearly defined, we shall give an account of the various air changes.

Basic Air Change—The basic air change is the air change caused by airflows through leaks in the building. It is measured when there are no occupants and with all doors, windows, and ventilation systems closed. The basic air change varies with wind velocity and indoor/outdoor temperature differences.

Air Change from the Ventilation System—The air change from the ventilation system is the air change from all mechanical supply and exhaust systems.

User-Influenced Air Change—The user-influenced air change is the air change caused by the opening of windows and doors. The user-influenced air change is a calculated parameter, as it cannot be measured directly.

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Total Air Change—The total air change is the sum of the basic air change, the air change from the ventilation system, and the user-influenced air change. This air change is measured in the building when it is in normal use.

Normally, the total air change is the most interesting figure for a building, but at the same time it is the figure most difficult to measure. Only during the last decade has equipment been developed for measuring total air change.

Basic air change has been measured for many years with the tracer gas decay technique, and a great deal of work has also been put into developing simplified methods for calculating this air change. However, concurrently with buildings becoming tighter and tighter, the influence of the basic air change on total air change has been reduced. In the future, the air change from the ventilation system and the occupants' behavior probably will be the greatest contributor to the total air change of a dwelling.

Measuring Equipment

The measuring equipment has been designed to be capable of automatic measurement of air changes in occupied houses. The measuring principle applied is the method with constant concentration of tracer gas.

When measuring with a constant concentration of tracer gas, a constant concentration of a tracer gas is maintained in the rooms where the air change is to be measured. The air changes then are calculated on the basis of the quantity of tracer gas injected into the rooms necessary to maintain the constant concentration. We used the tracer gas SF_6, and the concentration in the rooms was maintained at 5 ppm.

The constant concentration of tracer gas measurement method was selected because it is the only method that can be employed for continuous measurement in houses divided into several rooms. The measurement method measured how much air was supplied from the outside to each room, but it did not measure the airflow between the individual rooms of the building. The total air change of the house, therefore, was the sum of the air change rates of the individual rooms of the building weighted according to volume.

The system was controlled by a microcomputer and constructed so as to be capable of measuring the air change and humidity in up to ten separate rooms. The measurement data were continuously gathered and stored on a diskette that can hold eight days of measurements.

A photo and diagram of the air change measurement unit is given in Fig. 1. Each control box had two functions: to collect air samples from the rooms to the gas analyzer, and to regulate the dosage of tracer gas to the rooms. The calibration gas was used for a periodic control of the gas analyzer.

Setting Up the Equipment

The air change measurement unit was placed at a central location in the building. One 3-mm plastic tube for tracer gas dosage and one 4-mm plastic tube for room air collection were led from each area selected for measurement to the control box. The tubes were connected to the dosing valve and the collection valve on the control box.

The tubes were led through doors, via the keyhole, through drilled holes or possibly through a gap between door and floor. Care was taken to ensure that the doors could still be used normally for the duration of the measurement operation.

At each dosage point a small ventilator (15 W) was placed to spread the tracer gas in the air.

Special perforated dosing pipes (1 m in length with approximately ten holes) were used in the bedroom, bathroom, etc., where it was desirable to avoid noise or live leads in wet rooms.

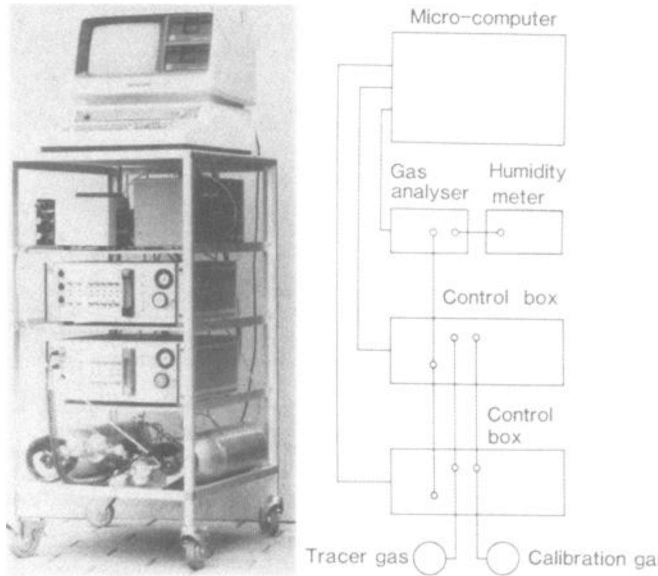

FIG. 1—*Air change measurement unit construction.*

Composition of the Measurement Group

Of the 28 dwellings in the measurement group 17 were equipped with natural ventilation, 3 with mechanical exhaust systems, and 8 with both mechanical supply and exhaust systems. In most of the naturally ventilated dwellings there were vents from bathroom, toilet, and kitchen.

Classifying the measurement according to type of building, it was seen that there were 9 measurements in apartment blocks of more than twelve stories, and 19 measurements in housing units of one or two stories. No measurements were conducted in medium-rise apartment blocks.

The average size of the dwelling was 106 m^2, while the average number of occupants was 2.9, roughly corresponding to the national average for Denmark.

The mean room temperature for the measurements was 21°C, the outdoor temperature was 2°C, and wind velocity was 4.9 m/s. The outdoor temperature was slightly lower and the wind velocity higher than the average values for the heating season in Denmark.

Measurement Results

Figure 2 shows the size of the total air changes measured. The difference between the total air changes in the individual dwellings was quite large, from an air change of 0.2 times/h in the least ventilated dwelling, to an air change of 1.56 times/h in the best ventilated dwelling. The average of the total air changes in the 28 dwellings was 0.67 times/h.

If the dwellings are grouped according to ventilation system, it can be seen that the mechanically ventilated dwellings have a considerably larger total air change than those with natural ventilation. The two ventilation systems are compared in Fig. 3.

The average total air change was 0.51 times/h for the naturally ventilated dwellings, and 0.93 times/h for the mechanically ventilated dwellings.

Even though the naturally ventilated dwellings on average have a total air change rate close to the 0.5 times/h recommended in Denmark, the variation in the values was so great

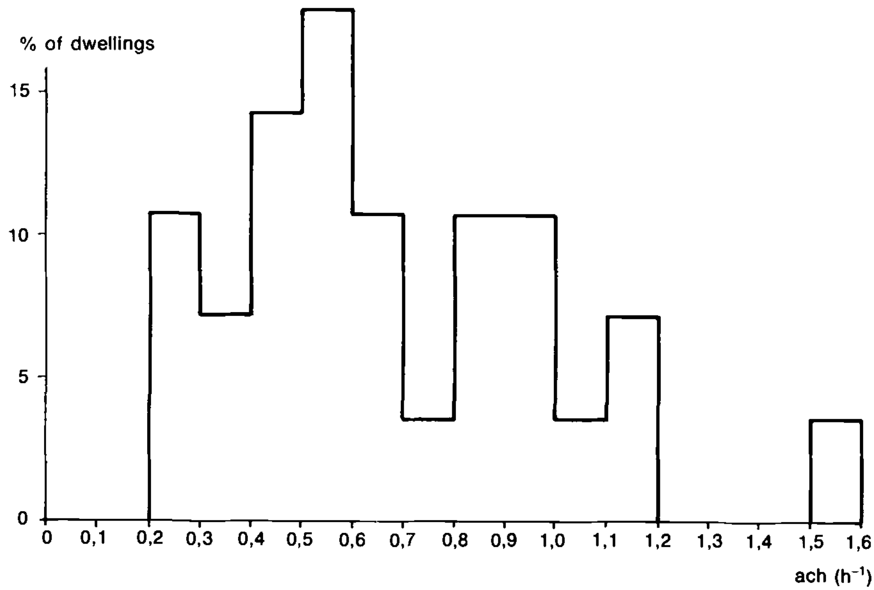

FIG. 2—*Total air change for the 28 dwellings. The value for each dwelling is obtained from one week's measurements.*

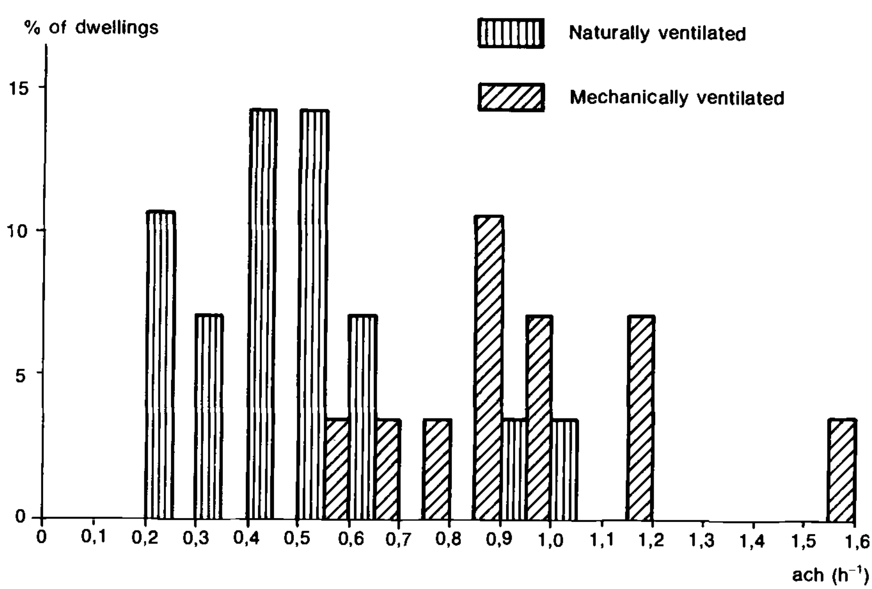

FIG. 3—*Total air change for the 17 naturally ventilated dwellings and the 11 mechanically ventilated dwellings. The value for each dwelling is obtained from one week's measurements.*

that the air change in many of the dwellings is unacceptable. Over 25% of the naturally ventilated dwellings have a total air change rate of less than 0.4 times/h, and, in a climate such as Denmark's, this normally will lead to problems with moisture.

Influence of the Occupants

By looking at how the total air change varies according to time in a single dwelling, the occupants' influence on the air change clearly can be observed. An example is shown of the variation of the air change for a one-family house with natural ventilation (Fig. 4), and an example of a mechanically ventilated one-family house is shown (Fig. 5).

As it was not possible to measure the basic air change and total air change rate at the same time, the basic air change rate was only measured once in each dwelling. The basic air change rate was measured for approximately 2 h.

Figure 6 is an attempt to illustrate the variation in basic air change rate as a function of the outdoor climate. The total air change rate is the same as in Fig. 4, but the variation in basic air change rate has been calculated from a simple one-zone model of the house, taking into consideration the wind velocity and the outdoor temperature, but not the wind direction. As can be seen from the figure, the model used has been too simple.

Figure 7 shows the influence of the users on the air change in 16 naturally ventilated dwellings. If the size of the basic air change and the user-influenced air change in the 16 naturally ventilated dwellings in Fig. 5 are compared, it can be seen that 63% of the total air change is caused by the behavior of the occupants.

Also, in the mechanically ventilated dwellings, the behavior of the occupants has a great influence on the air change. Mechanical ventilation systems are normally dimensioned to provide all of the air change required. In addition to this, there will always be a basic air change which depends on the tightness of the dwelling, influences from the climate, and the ventilation system, as well as air change influenced by the behavior of the occupants.

Calculated on the basis of the seven dwellings where the dimension values for the ventilation system are known, the total air change is 65% higher than what was projected.

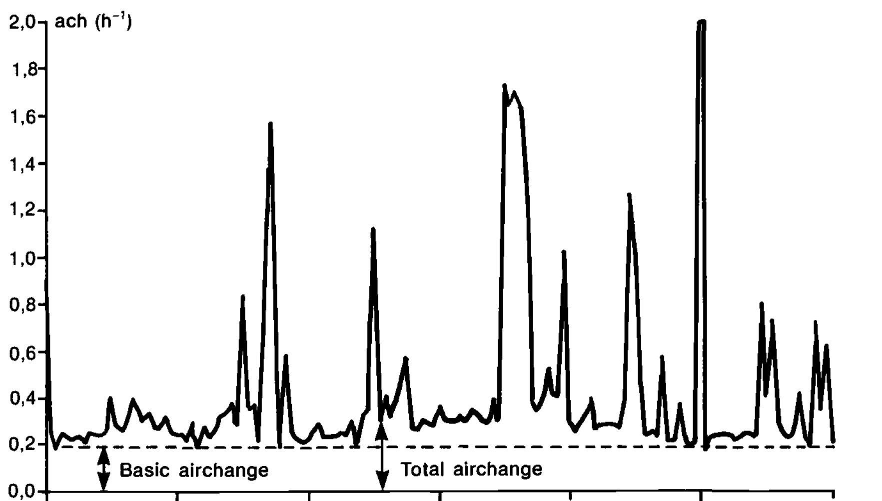

FIG. 4—*The total air change rate as a function of time for a one-family house with natural ventilation. The size of the measured basic air change rate is shown on the figure.*

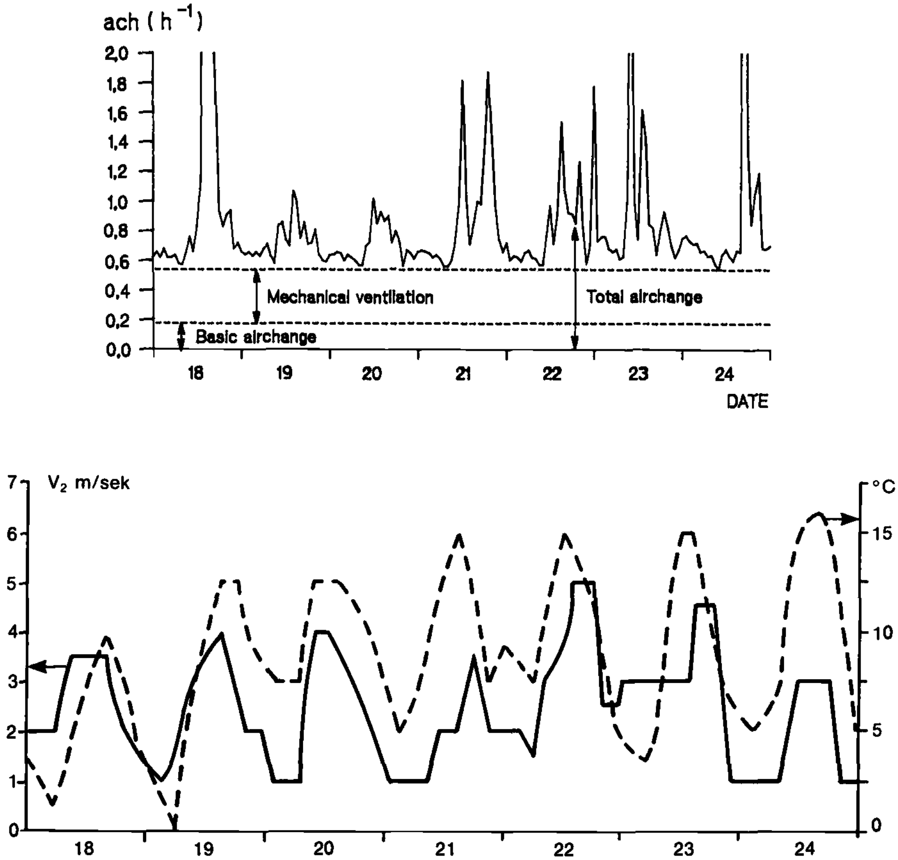

FIG. 5—*The total air change rate as a function of time for a one-family house with mechanical injection and exhaust systems (upper diagram). The size of the measured basic air change rate and the performance of the ventilation system is shown on the figure. The outdoor temperature and the wind velocity can be seen in the lower diagram.*

The Behavior of the Occupants

As can be seen from Fig. 7, there is a considerable difference in the total air change between the individual dwellings. As the basic air change is fairly similar, it is the behavior of the users which caused these large differences.

In order to get an idea of what influences the occupants' habits regarding ventilation and what is irrelevant, the following four hypotheses have been tested for the 17 naturally ventilated dwellings:

1. The total air change in times/h is a function of the number of occupants.
2. The total air change in m^3/h is a function of the number of occupants.
3. The total air change depends on the outdoor temperature.
4. The total air change depends on the room temperature.

In Figs. 8 and 9 the total air change can be seen as a function of the number of occupants, in Fig. 10 as a function of the outdoor temperature and, in Fig. 11 as a function of the room temperature. From Figs. 8 through 11, it can be seen that the measurement results do not

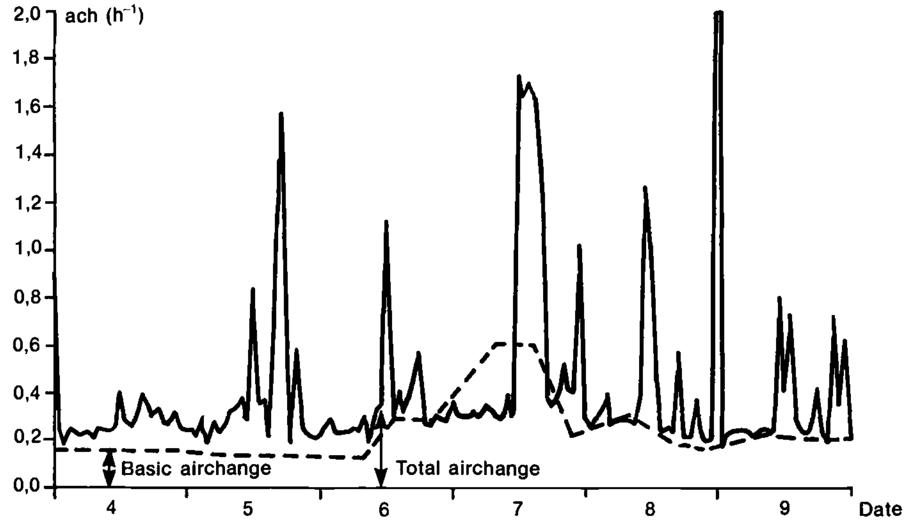

FIG. 6—*The total air change rate as a function of time for a one-family house with natural ventilation. The total air change rate graph is identical to the graph in Fig. 4. The variation in basic air change rate is calculated from a simple model, taking into consideration the wind velocity and the outdoor temperature.*

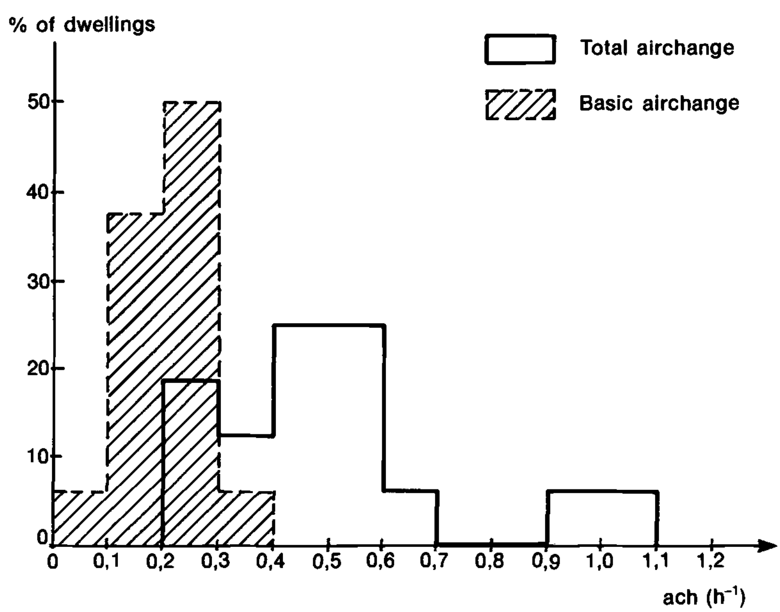

FIG. 7—*Basic air change and average total air change for 16 naturally ventilated dwellings.*

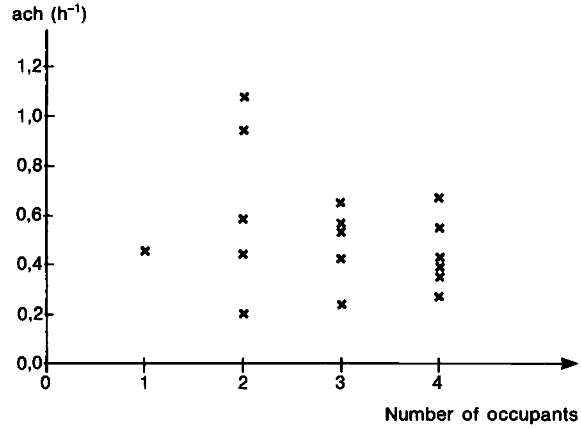

FIG. 8—*Average total air change rate as a function of the number of occupants for the 17 naturally ventilated dwellings.*

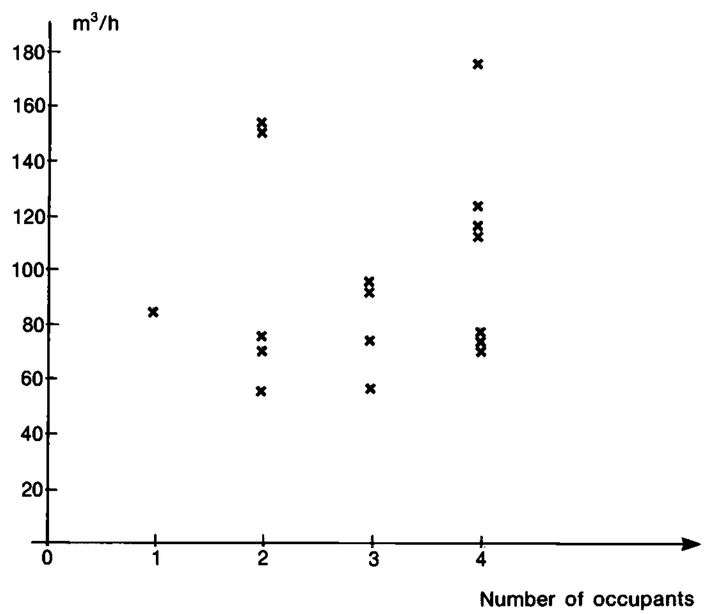

FIG. 9—*Average total air change in m^3/h as a function of the number of occupants for the 17 naturally ventilated dwellings.*

support any of the four hypotheses about conditions that influence the ventilation habits of the occupants.

It is worth noticing, however, that the group in Fig. 11 is split into two, a comfort group with an average-to-large air change or average-to-high room temperature, and an energy-saving group with low air change and low room temperature. All three members of the energy-saving group experienced considerable problems with heavy condensation of water vapor on the insider of the double-glazed windows.

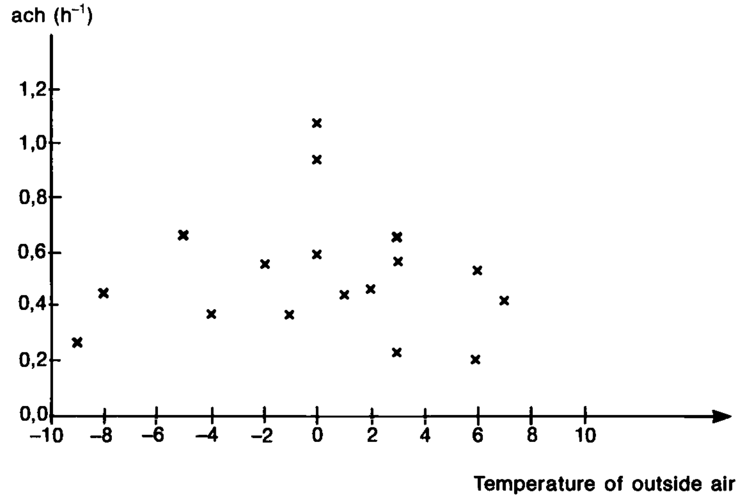

FIG. 10—*Average total air change as a function of the outdoor temperature for the 17 naturally ventilated dwellings.*

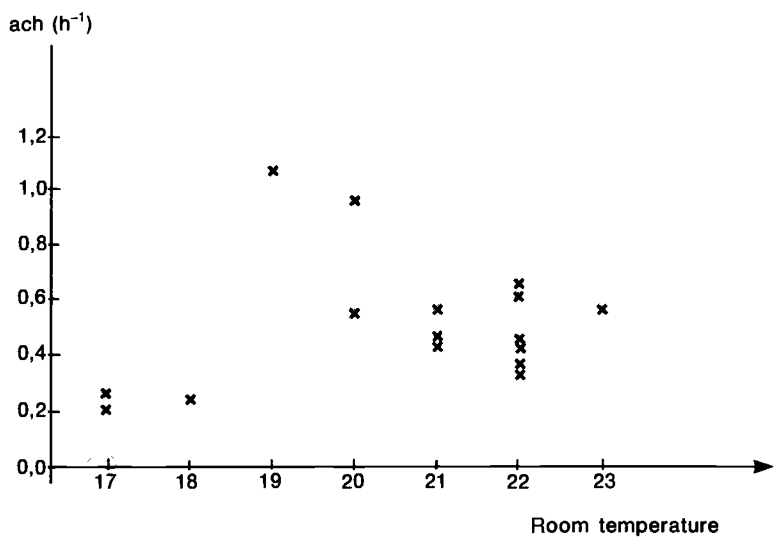

FIG. 11—*Average total air change as a function of the room temperature for 16 naturally ventilated dwellings.*

Where Does the Air Enter?

Not all rooms receive the same amount of outdoor air. In two-story dwellings, the outdoor air normally will enter the dwelling by the lowest floor and then leave from the uppermost floor.

In the 17 naturally ventilated dwellings, which have an average air change rate of 0.51 times/h, the average outdoor air change rate for the bedroom was 0.67 times/h, and the average outdoor air change rate for the living room was 0.35 times/h.

Conclusion

Measurement of air change rates in occupied dwellings showed that the occupants' behavior has a very considerable influence on the total air change rate.

In 16 naturally ventilated dwellings, the users on average provided 63% of the total air change, but in the mechanically ventilated dwellings, the user influence was also considerable.

There was a very large difference in the air change rate from dwelling to dwelling that cannot be explained by differences in the tightness of the dwellings or by the number of occupants. With the limited number of widely differing types of dwellings which have been investigated here, it has not been possible to explain the large variations in the total air change.

The average total air change rate for the dwellings measured was 0.67 times/h. Even though this rate is higher than the 0.5 times/h recommended in Denmark, 20% of the dwellings measured had a total air change rate less than 0.3 times/h, which is so low an air change rate that indoor climate problems could easily arise.

Generally speaking, the occupants do not have sufficient control of the air change rate in Danish dwellings. Often the only choice an occupant has is to either open a door or a window, or not to air the dwelling at all. Smaller ventilation openings, which can be opened by varying levels and which are placed so that they can use the stack effect, are seldom used. In the mechanically ventilated dwellings, the regulation possibilities are also limited, as the ventilation system, even set at the lowest level, normally gives a larger air change than required.

The measuring method used proved to be most suitable for continuous measurement of the greatly varying air changes found in occupied dwellings.

Bibliography

Kvisgaard, B., Collet, P. F., and Kure, J., *Research on Fresh Air Change Rate: 1,* Technological Institute, Copenhagen, 1985.

DISCUSSION

J. T. Reardon[1] *(written discussion)*—In your attempts to correlate measured air change rates with outdoor temperature, did you attempt to account for variations in building airtightness? Such variations may account for much of the apparent scatter, interpreted as an apparent failure to find a correlation. Other factors affecting the scatter may be nonzero wind speeds, which might prove more difficult to account for than building airtightness.

B. Kvisgaard (author's closure)—When calculating the basic air change rate in Fig. 6, wind velocity, indoor and outdoor temperatures, and the tightness of the buildings were taken into consideration. The inclusion of several parameters probably results in a much more precise estimation of the variation of the basic air change rate. However, it is normally difficult and time consuming to gain reliable information on the necessary parameters, such as distribution of leaks on the surface of the building, and pressure distribution on the building surfaces at different wind directions. Therefore, the quickest method often is to perform actual measurements of the air change.

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Andrew Persily[1] *and W. Stuart Dols*[1]

The Relation of CO_2 Concentration to Office Building Ventilation

REFERENCE: Persily, A. and Dols, W. S., "**The Relation of CO_2 Concentration to Office Building Ventilation,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 77–92.

ABSTRACT: Tracer gas techniques have been used to study air exchange in mechanically ventilated office buildings for many years. The analysis of the concentration of carbon dioxide (CO_2) generated by building occupants has been suggested as an alternate means of evaluating building air exchange and ventilation system performance. Various techniques for CO_2 analysis have been proposed. These include measuring the decay rate of CO_2 concentration after the occupants leave the building, analyzing real-time CO_2 concentration data in conjunction with a CO_2 mass balance equation, and using instantaneous CO_2 concentration readings to directly determine air exchange rates. Local CO_2 concentrations have also been suggested as a means of evaluating ventilation effectiveness. These techniques require specific assumptions and unique conditions in order to yield reliable information on building air exchange characteristics, and these requirements may not always be met in office buildings.

This paper examines the relationship between CO_2 concentration and building air exchange. A dataset of simultaneously measured air exchange rates, based on sulfur hexafluoride (SF_6) decay, and CO_2 concentrations obtained in three office buildings is employed to examine this relationship. The results indicate that CO_2 decay rates can provide reliable estimates of building air exchange rates, but that there may be significant error associated with the use of instantaneous concentrations to determine air exchange rates.

KEY WORDS: building performance, indoor air quality, infiltration, measurement, mechanical ventilation, office buildings, tracer gas, ventilation

Building air exchange is important as it affects energy use and indoor air quality. The study of air exchange has traditionally been done with various tracer gas techniques in which a tracer gas is injected into the building and the measured concentration response used to determine various air exchange characteristics [*1,2*]. While tracer gas measurements require specialized equipment and experienced analysts, they are the only means for actually measuring building air exchange rates and other aspects of building air exchange performance. Carbon dioxide (CO_2) concentration measurements have been suggested as an alternate means of determining air exchange rates and for evaluating the effectiveness of the building ventilation systems.

Carbon dioxide has been suggested for use in evaluating building air exchange for several reasons. First, it can be used as a tracer gas with the advantage of a built-in injection mechanism, i.e., the building occupants. Also, since CO_2 is occupant generated, its indoor level may be associated with the amount of air exchange on a per person basis. Indoor CO_2 levels do not provide an indication of the levels of nonoccupant generated pollutants within a building, but they are related to the amount of ventilation and have been suggested as a

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gross means of determining if ventilation rates are adequate [3]. CO_2 levels have also been related to odor levels within buildings and to the level of occupant satisfaction [4]. In fact, indoor CO_2 levels have been employed as an input to control systems that determine outdoor air intake levels in mechanically ventilated buildings [5,6].

Various techniques have been suggested for relating indoor CO_2 levels to building air exchange rates. The simplest is the tracer gas decay technique using occupant-generated CO_2 as the tracer. In most buildings the CO_2 concentration will build up to a level that is significantly above the outdoor concentration during occupied periods. After the occupants have left the building, the rate of decay can be related to the building air exchange rate if the usual assumptions of the tracer gas decay technique are appropriate. Alternately, during occupied conditions, it has been suggested that one use instantaneous measurements of CO_2 levels in conjunction with the CO_2 generation rate associated with people to determine the outdoor airflow rate into a building. This requires that the CO_2 generation rate is known and that the CO_2 concentration be at equilibrium or steady-state, i.e., the CO_2 generation rate due to the occupants is equal to the removal rate due to air exchange. Finally, it has been proposed that one use local CO_2 concentration measurements in conjunction with the above relation between CO_2 generation rate and outdoor airflow rate to evaluate local ventilation rates and the so-called ventilation effectiveness associated with a particular location. These various approaches have been discussed, recommended, and employed to varying degrees, but there has not been adequate theoretical consideration of the procedures nor experimental validation. This paper does both in examining the ability to use CO_2 concentration measurements to study building air exchange. The material in this paper is generally discussed with reference to mechanically ventilated office buildings, although some of this discussion is certainly relevant to other building types.

Theory of Measurement Techniques

The various techniques proposed to relate CO_2 concentration to building air exchange are based on a mass balance of CO_2 in the building. This mass balance for a single zone building is expressed as

$$V dC/dt = Q(C_o - C) + G \tag{1}$$

where

V = the building volume,
C = the interior CO_2 concentration,
t = time,
Q = the airflow rate into (and out of) the building,
C_o = the outdoor CO_2 concentration, and
G = the generation rate of CO_2 within the building.

The air exchange rate of a building is defined as the ratio of Q and V and has units of inverse time, often air changes per hour. In Eq 1 the building is assumed to be well-mixed, i.e., the CO_2 concentration of the building air is characterized by a single value. In addition, density differences between the indoor and outdoor air are ignored in using the same value Q for the airflow rate into and out of the building. Assuming that Q, G, and C_o are constant, the solution to Eq 1 is

$$C = C_{eq} + (C_{init} - C_{eq})e^{-tQ/V} \tag{2}$$

where

C_{eq} = the equilibrium concentration, equal to $C_o + G/Q$, and
C_{init} = the CO_2 concentration at $t = 0$.

One can rewrite Eq 2 in terms of C', the difference between the indoor concentration C and the outdoor concentration C_o

$$C' = C'_{eq} + (C'_{init} - C'_{eq})\, e^{-tQ/V} \tag{3}$$

where C'_{eq} equals G/Q.

If the indoor generation rate is zero, then the concentration relative to the outdoors C' will decay from its initial value to the outdoor concentration according to

$$C' = C'_{init}\, e^{-tQ/V} \tag{4}$$

Equation 4 governs the concentration decay of any nonreactive gas in a building and serves as the basis of the tracer gas decay technique for measuring air exchange rates in buildings that can be idealized as single, well-mixed zones.

The above equations are the basis of the various techniques proposed to relate indoor CO_2 concentrations to building air exchange rates. These techniques model the building as a single, well-mixed zone, which in many cases is not an appropriate idealization. Multizone approaches require one to consider a separate mass balance of CO_2 (or tracer gas) for each zone of each building, accounting for the transport of CO_2 between the zones of the building. Specific techniques for relating CO_2 concentration to building air exchange are discussed below along with the practical considerations associated with each.

Decay

Measuring the decay rate of a well-mixed tracer gas is an accepted means of determining building air exchange rates (ASTM Practice for Measuring Air Leakage Rate by Tracer Dilution, E 741-83). It will yield reliable measurements of building air exchange rates when the tracer gas concentration is uniform throughout the building. The decay technique can be used with any nonreactive tracer gas such as CO_2, and Eq 4 can be used to determine the air exchange rate as long as the tracer generation rate is equal to zero. Therefore, to use CO_2 decay to measure air exchange rates in buildings, one must wait for the occupants to leave and then monitor the decay in concentration. The CO_2 concentration will begin to decrease as soon as occupants begin leaving the building, and if the occupants leave over an extended period of time, as is the case in most office buildings, the CO_2 level may already be quite low when the generation rate is finally equal to zero. In this case there may be little or no opportunity to reliably determine the CO_2 decay rate. Also, due to variations in occupancy density, the CO_2 concentration may not be uniform within the building when the occupants leave, violating an important assumption of the decay technique. One cannot conduct a decay measurement under these circumstances. However, the CO_2 concentration may become uniform after a sufficiently long period of time. Decay rate measurements can be conducted under conditions of nonuniform concentration only if the concentration variation is between well-mixed zones that are isolated from one another in terms of airflow. The decay rate of such a zone will then equal its air exchange rate with the outdoors.

If there is not a sufficient level of occupant-generated CO_2 within the building, one may release CO_2 into the building to achieve the desired initial conditions, but the release must be uniform throughout the space. Equation 4 is based on a constant outdoor CO_2 concentration. If the outdoor concentration is changing during the decay, then an appropriate expression can be derived to relate the decay data to the air exchange rate. A CO_2 decay rate measurement based on the decay of occupant-generated CO_2 will generally take place at night, and therefore the measurement results will reflect the building air exchange characteristics under these particular conditions. In general, the air exchange rate at night will be different from the air exchange rate that occurs during the day when the building is occupied due to differences in building operation schedules.

CO_2 and SF_6 decay rates have been measured simultaneously in a single-family residential building and the results agreed within the experimental error associated with decay measurements [*7*]. Turiel and Rudy [*8*] made CO_2 and SF_6 decay measurements of air exchange rates in a portion of an office building, and the results were similar. Since both tracers are nonreactive, the decay rates of each should be the same under identical weather and building equipment operation. Simultaneous measurements of CO_2 and SF_6 decay rates were made by the authors in two mechanically ventilated office buildings and are discussed below.

Steady-State

Under conditions of constant CO_2 generation rate G and constant air exchange rate Q, the CO_2 concentration will eventually achieve an equilibrium value C_{eq}, equal to the outdoor concentration plus G/Q. This approach serves as a basis for determining recommended ventilation levels (ASHRAE Standard, Ventilation for Acceptable Indoor Air Quality, 62-1989) and has been used to estimate building ventilation rates [*9*]. In order to determine Q from the equilibrium CO_2 concentration, one must know the value of the generation rate G. When CO_2 is predominantly occupant generated, as is the case in most buildings, the value of G depends on the number of occupants and their individual generation rates. The CO_2 generation rate of a person depends on several individual characteristics including activity level, diet, and size, and a representative value for a sedentary adult is 5.3×10^{-6} m^3/s [*10,11*]. In steady-state determinations of air exchange from CO_2 concentrations, such a representative value is generally multiplied by the number of building occupants.

The determination of air exchange rates from instantaneous measurements of CO_2 concentration is sometimes used or recommended without acknowledging the assumptions about the value of the CO_2 generation rate, the constancy of G and Q, and the existence of equilibrium conditions. In most office buildings, the generation rate of CO_2 is constant for only a few hours a day. The number of people in a building may, at best, be constant from around 9 a.m. until noon, and then again from some time after 1 p.m. until about 5 p.m. In most buildings, the occupancy levels and therefore the CO_2 generation rates are not constant for even these short periods. Unless the building air exchange rate is very high, there will not be enough time for equilibrium conditions to occur. The buildup of CO_2 to equilibrium is described by Eqs 2 and 3, for constant G, Q, and C_o. The buildup of C' is plotted for various values of air exchange rate Q/V in Fig. 1. For air exchange rates of one air change per hour or less, it takes more than 3 h to approach equilibrium conditions. In many office buildings, the air exchange rates are often under one air change per hour [*12*], and therefore during typical periods of constant CO_2 generation the CO_2 concentration will never achieve equilibrium. Use of a "preequilibrium" CO_2 concentration, as if it were the actual equilibrium value, will result in the calculated air exchange rate being larger than its actual value. In order for the calculation of air exchange rates from equilibrium concentrations to be valid, the CO_2 concentration must be uniform throughout the building, or a building average value must be used. The use of the CO_2 concentration at a single location to determine a "local" air exchange rate at this location is also inappropriate since this approach ignores any sources of CO_2 other than the room occupant(s), such as airflows to and from other rooms at different CO_2 concentrations.

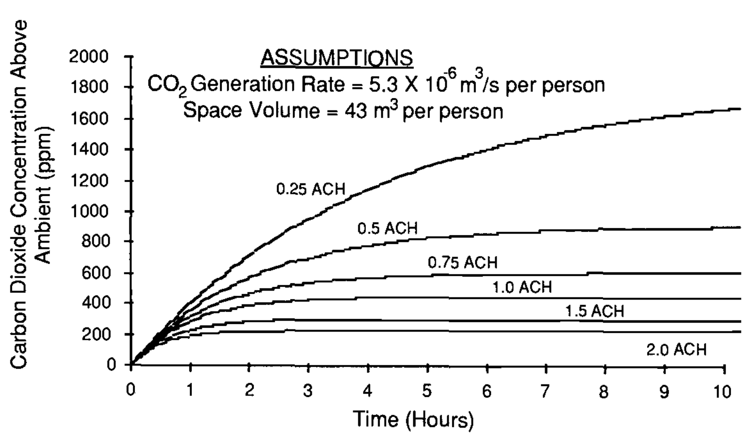

FIG. 1—*Calculated buildup of carbon dioxide.*

Therefore, it is only under very special circumstances that an instantaneous CO_2 concentration measurement can be used to determine an air exchange rate. Unless one monitors these concentrations throughout the building to be able to eliminate the possibility of interzonal airflow effects, monitors over time in order to establish that equilibrium exists, and verifies that the generation rate is constant over this period, then the approach is not valid and the air exchange rates that are determined will be in error.

Transient Analysis

One may avoid the equilibrium assumption by employing a solution to the mass balance equation, Eq 1, to relate the CO_2 concentration to Q. The solution to Eq 1 can take several different forms (e.g., Eqs 2 and 3), depending on the assumptions that are made regarding the constancy of C_o, G, and Q. Alternately, one may employ an integral form of Eq 1 to relate measured CO_2 concentrations to Q. In both cases, one must know G as a function of time to solve for Q.

Both the instantaneous solution and integral formulation approaches have been used previously. Penman [*13*] used an instantaneous solution to the mass balance equation and fit this curve to measured CO_2 concentration data in a library building. The generation rate was based on the number of occupants (recorded roughly three times an hour), and the generation rate per person was solved for iteratively. The generation rate solved for in this manner was 4.7×10^{-6} m^3/s per person. Penman and Rashid [*10*] used an integral formulation of the mass balance equation to solve for Q for a single room, in which they accounted for the transport of CO_2 from two adjoining spaces. The value of Q determined with this technique was in close agreement with the results of SF_6 decay measurements. Turiel and Rudy [*8*] also used an integral formulation to study a portion of the first floor of an eight-story office building. The value of the generation rate was based on an assumed generation rate per person (5.8×10^{-6} m^3/s) and periodic body counts. The air exchange rate determined with the integral formulation agreed well with a simultaneous SF_6 decay test under 100% outdoor air intake conditions and a CO_2 decay test under similar conditions. In another test conducted with the return air being recirculated, the CO_2 integral determination of the air exchange rate was much larger than the CO_2 and SF_6 decay determinations, although it is not clear if all of the assumptions made in these decay measurements were appropriate.

Another approach to the relation between CO_2 concentrations and air exchange rates is to employ solutions of the forms of Eqs 2 or 3, and to fit measured CO_2 concentration data to the equation using nonlinear regression techniques, treating C_{eq} (equal to G/V), C_{init}, and Q/V as unknowns. In this case one need not assume a value for G, only that it is constant during the period over which the data is analyzed. This approach is employed in this paper to estimate values of Q/V. Kusuda [13] used a simplified version of the buildup analysis approach to analyze CO_2 buildup data collected in a single school room.

Experimental Work

In order to study the above techniques, simultaneous measurements were made in three buildings of CO_2 concentrations and air exchange rates, employing the decay of sulfur hexafluoride (SF_6). These measurements were made under a range of fan operation conditions, during both occupied and unoccupied hours.

Measurement Equipment

Automated measurement equipment was used to make continuous SF_6 decay tests and monitor CO_2 concentrations. The measurement system, illustrated in Fig. 2, is made up of

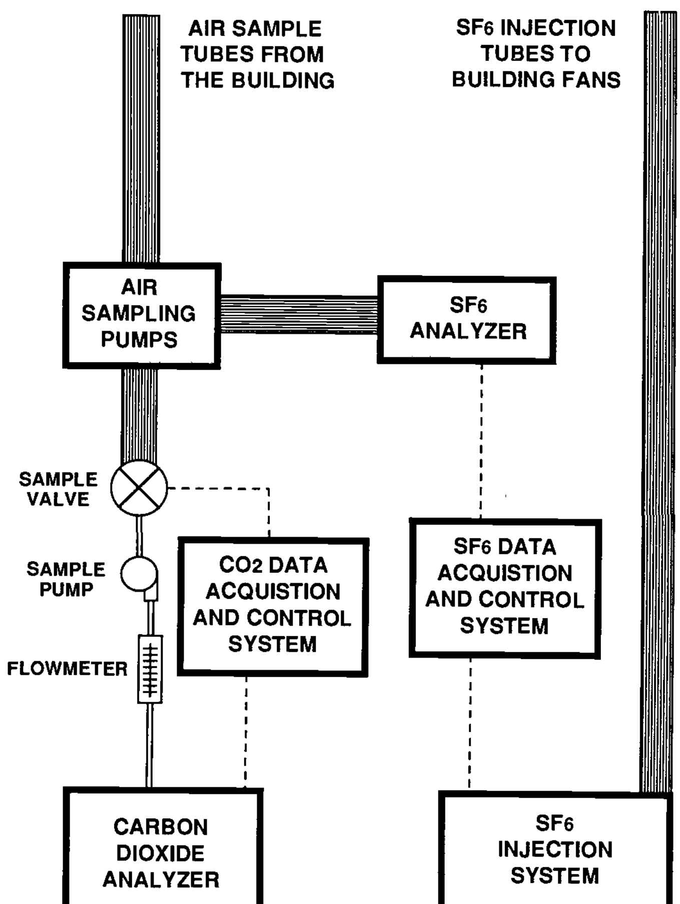

FIG. 2—*Schematic of SF_6 and CO_2 measurement system.*

two subsystems: an automated SF_6 decay rate monitoring system and an automated carbon dioxide monitoring system. Both systems are connected to a set of air sampling pumps which sample air from up to ten building locations. A network of tubing connects the sampling locations to the pump set. Building air is pulled through the tubes by the pumps, and the pump output is then split into two airstreams, one to the SF_6 system and the other to the CO_2 system.

The air exchange measurement system injects SF_6 into the building every few hours, allows the gas to mix with the indoor air, and then monitors the decay in SF_6 concentration at up to ten locations in the building. The SF_6 concentration is measured with a gas chromatograph/electron capture detector, calibrated from 5 to 300 ppb. A microcomputer controls the tracer gas injection and air sampling, records the SF_6 concentrations, and monitors and records the outdoor weather conditions, indoor temperatures, and fan operation. The system determines average air exchange rates over periods of 1 or 2 h and runs 24 h a day. Tracer is injected only when the ventilation system is operating because the fans are used to distribute the gas through the building. The air exchange rate that is determined is the sum of the airflow rates into the building through the mechanical ventilation system and through leaks in the building envelope. When the fans go off, there is often a sufficient amount of SF_6 remaining in the building to obtain a reliable decay rate measurement under fan-off conditions. This fan-off measurement determines the envelope infiltration rate alone.

The automated CO_2 sampling system consists of an infrared absorption analyzer to measure CO_2 concentrations; an electronically-activated ten-port sample valve; a microcomputer, which controls the valve and records the concentration data; and a sample pump and flowmeter. The output lines from the ten air sampling pumps are connected to the ten-port sample valve. The CO_2 sample pump provides a continuous flow of air via the valve to the sample cell of the detector. The detector compares the amount of infrared energy of a particular wavelength absorbed by the sample air with the amount absorbed by a reference gas. The energy difference, which is proportional to the CO_2 concentration, is converted to a d-c voltage which is read by the computer. The computer calculates the concentrations utilizing a linear calibration curve, records the results on disk, and switches ports on the valve every 10 min. The CO_2 monitor has a range of 0 to 2500 ppm and is accurate to within $\pm 0.5\%$ of full scale. The instrument is zeroed with nitrogen and calibrated with span gases of 350, 1029, and 2010 ppm CO_2.

Test Sites

The simultaneous SF_6 decay and CO_2 concentration measurements were made in three mechanically ventilated office buildings, designated as Buildings A, B, and C. Building A, constructed in 1974, consists of two main sections, a seven-story administration section that contains predominantly office space, and a five-story laboratory section that contains a combination of laboratory and office space. The building has an occupiable floor area of approximately 71 000 m^2 and is served by a total of about 30 supply fans, most of which operate only during occupied hours. These ventilation systems are variable air volume systems, employing economizer cycles. In the SF_6 and CO_2 measurements, the air was sampled in the building return air fans, obtaining average concentrations over large sections of the building. Therefore, the measured concentrations were representative of the interior space concentrations only when the fans were operating.

Building B is a new, seven-story office building with a one-story basement, built and occupied in 1987. The eight occupied levels have a floor area of about 46 000 m^2, and there are three main air handling systems serving the upper seven stories. These ventilation systems are variable air volume systems, employing economizer cycles. The air samples were taken in the three main return fans and at several locations within the occupied space. The air samples from the occupied space were taken about 1.5 m above the floor. Because these air samples were taken from within the occupied space, they could be used to determine SF_6 and CO_2 concentrations when the fans were off.

Building C is an office building constructed in 1969 and is divided into three main sections: a 15-story tower, a 7-story midrise, and a 4-story connecting section. The bulk of the measurements discussed in this paper were made in the tower section, which has a floor area of about 28 000 m^2. The floor area of the entire building is about 45 000 m^2. The building has seven constant volume air-handling systems, which operate on 100% outdoor air. The floors of the tower section are basically isolated from each other in terms of airflow, in part because there is no recirculation of return air. In the measurements discussed below, air was sampled in the occupied space, about 1.5 m above floor level. The existence of air sample points within the occupied space enabled the collection of concentration data when the fans were off.

Procedure

The measurements in Buildings A, B, and C included simultaneous measurements of air exchange rates using SF_6 decay and of CO_2 concentrations. The SF_6 decay measurements were based on concentration readings at ten locations within each building, each location being sampled once every 10 min. When the air handling systems were operating, SF_6 was injected into the building supply fans every 2 or 3 h and allowed to mix for about 1 h. An SF_6 decay rate was evaluated at each location over roughly 2-h periods. The tracer gas decay technique is based on the assumption of perfect mixing within the building being studied. The validity of this assumption was examined by sampling the SF_6 concentration at multiple locations within the building, and injection strategies were employed that tended to lead to uniform concentrations.

Building C was somewhat unique in that there was no recirculation of return air. This fact, in combination with other building features, led to the individual floors of Building C being well-separated from each other in terms of airflow. In this situation, the SF_6 decay rate for each floor is a measure of its air exchange rate with the outdoors.

The CO_2 measurements in each building were made at nine of the ten SF_6 measurement locations and at an outdoor location near the outdoor air inlet. Each location was sampled once every 10 min, 24 h a day. CO_2 concentrations and air exchange rates were measured in these three buildings for long periods of time throughout the year in order to examine the effects of weather conditions, building occupancy, and mechanical equipment operation on the relation of air exchange rate and CO_2 concentration.

Analysis

The SF_6 decay data were analyzed by fitting the concentration data for each sample location to Equation 4 and solving for the air exchange rate Q/V in units of air changes per hour. The exchange rates for the sample locations were generally determined for 2-h periods and were then averaged by volume to determine a building average air exchange rate. These building average rates generally had an associated error of no more than $\pm 10\%$ for air exchange rates below 0.5 per hour and $\pm 5\%$ for larger air exchange rates.

An example of CO_2 concentration data from Building A is shown in Fig. 3. This example includes the CO_2 concentration over most of a day for an outdoor location, the building cafeteria, and an average over the office space in the administration section of the building. All three locations are at the same concentration in the morning, and the outdoor concentration is relatively stable throughout the day. The concentration in the cafeteria has a strong peak during lunch, with lower peaks associated with breakfast and the morning and afternoon breaks. The concentration in the administration section starts increasing at 6 a.m., peaks at 9 a.m., decreases until around 11 a.m., and peaks again in midafternoon. This pattern

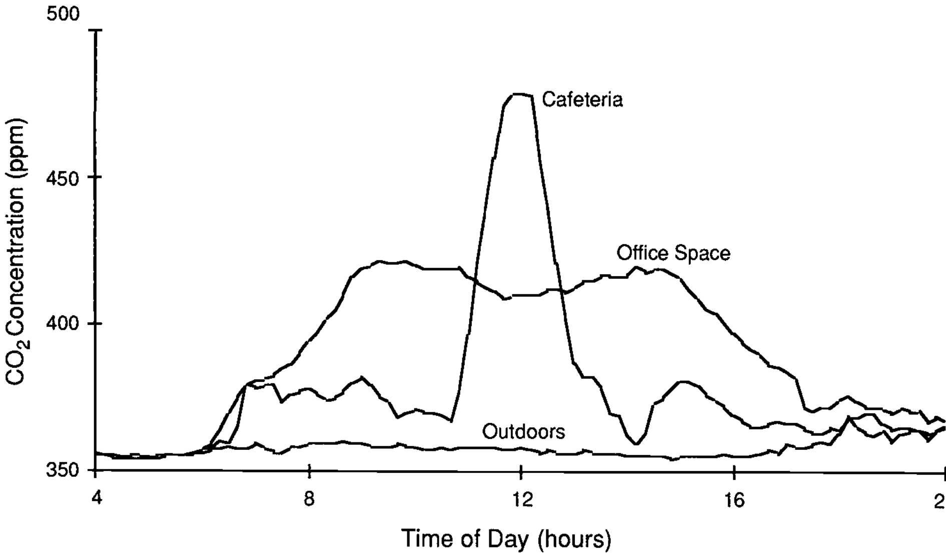

FIG. 3—*Example of CO_2 concentration data from Building A.*

is typical for office spaces in which the occupants leave for lunch. The concentration decrease in the morning, well before lunch, is presumably due to an increase in the ventilation rate to offset internal cooling loads.

The tracer gas decay measurement results take the form of 2-h average air exchange rates and the associated indoor and outdoor environmental conditions and building equipment operation status during each measurement. Several hundred such measurements were made in each of the three buildings. Figure 4 is a plot of such air exchange rate data versus indoor-outdoor temperature difference for Building B, including measurements made during the day with the fans on and measurements made at night with the fans off.

The CO_2 concentration data for the buildings were analyzed in several different ways, including the calculation of peak daily values, analysis of CO_2 buildup, and calculation of decay rates. In determining daily peak values, building average concentrations were calculated and averaged over 1-h periods. Peak values of these 1-h averages were then determined for each day and subsequently related to building average air exchange rates for those days.

The buildup of CO_2 concentrations during the day was analyzed using Eq 3 in order to determine air exchange rates. These calculations required the assumption that the CO_2 generation rate was constant during the period over which the data were analyzed. Therefore, these calculations were made over 1 or 2-h periods during the morning, after the building was fully occupied and before the occupants started to leave for lunch. The data during these periods were then fit to Eq 3 using nonlinear regression techniques, yielding values for C'_{eq} $(= G/Q)$, C'_{init}, and Q/V. These buildup calculations were made using data from each CO_2 sample port separately and for the building average CO_2 concentration.

The CO_2 concentrations recorded after the occupants left the building were fit to Eq 4 to determine air exchange rates by the decay technique. For data collected when the fans were operating, these CO_2 decay calculations could be made only while the indoor CO_2 levels were well above the outdoor concentrations. When the fans were off, the air exchange rates were significantly lower and CO_2 concentrations did not decay as rapidly, enabling the calculation of CO_2 decay rates for longer periods of time.

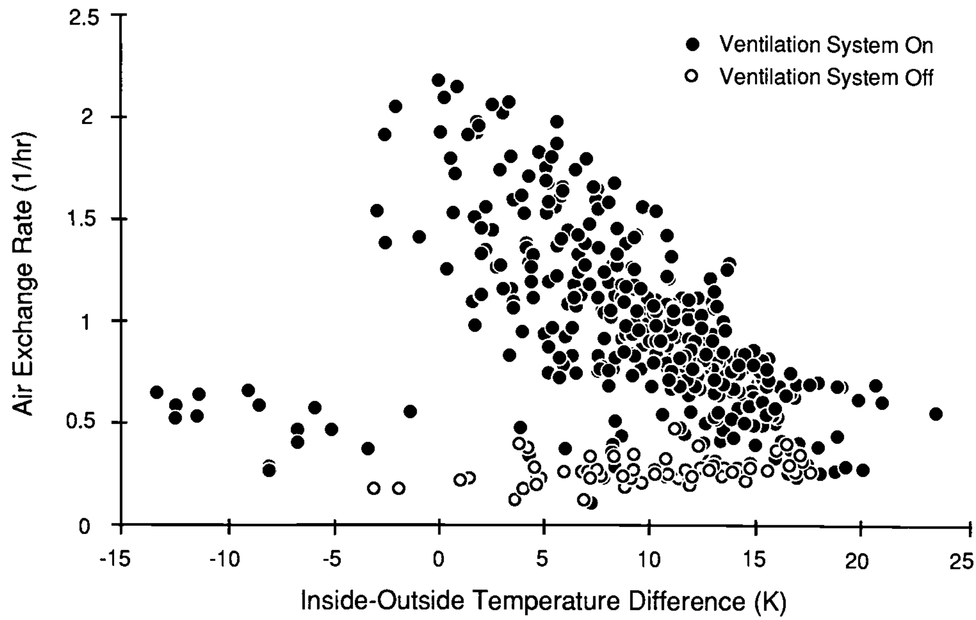

FIG. 4—*Air exchange rates for Building B.*

Results

The following section presents the results of the comparison of CO_2 concentration data and air exchange rates for the three buildings studied. Daily maximum CO_2 concentrations are first examined in relation to building air exchange rates. Two techniques for determining air exchange rates from CO_2 concentration analysis, buildup and decay, are then considered.

Peak CO_2 Concentrations

If a building is subjected to a constant generation rate of CO_2, the CO_2 concentration will eventually reach an equilibrium level determined by the generation rate G and the air exchange rate Q. If both G and Q are given in volumetric units, then the equilibrium concentration is given by

$$C_{eq} = C_o + G/Q \tag{5}$$

where C_o is the outdoor CO_2 concentration, assumed here to be constant. As discussed earlier, the amount of time required to attain equilibrium depends on Q, and in general the generation rate in buildings will not be constant long enough to reach equilibrium. The higher the air exchange rate, the closer the concentration will get to equilibrium in a given time period.

Daily peaks of the building average CO_2 concentrations were calculated for the three buildings and are plotted against the corresponding daily average air exchange rates in Fig. 5. The peak concentrations are the maximum hourly building averages that occurred during each day. The average air exchange rates were calculated over only that portion of the day during which the building was occupied, and only data for those days with a relatively constant air exchange rate are included in the plot. The lines in the plot are the equilibrium concentration as a function of air exchange rate, calculated with Eq 5. These calculations

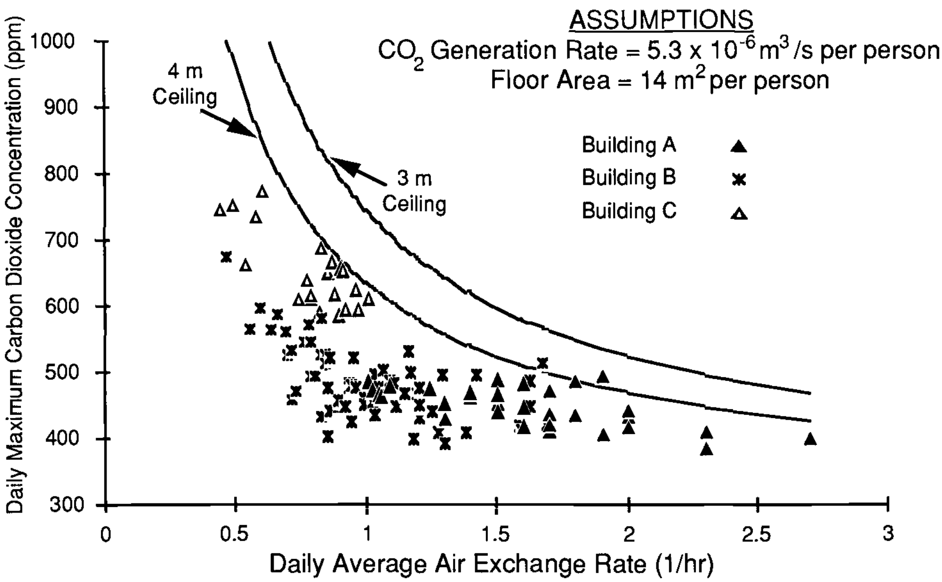

FIG. 5—*Peak CO_2 concentrations versus air exchange rate.*

were based on several assumptions, including an occupancy density of seven people per 100 m^2 of floor area, an outdoor CO_2 concentration of 300 ppm, and a CO_2 generation rate per person of 5.3×10^{-6} m^3/s. Two equilibrium curves are given, one assuming a ceiling height of 3 m (upper curve), appropriate for Building C, and one for a ceiling height of 4 m (lower curve), appropriate for Buildings A and B.

The data in Fig. 5 deviate significantly from the equilibrium curves. This is expected because the CO_2 concentrations within these buildings generally do not attain equilibrium, due to the fact that the CO_2 generation rates within the buildings are not constant for a long enough period of time. The deviations between the peak CO_2 levels and the equilibrium levels are expected to be greater at lower air exchange rates because it takes longer to reach equilibrium at these lower air exchange rates. This expected trend of larger deviations at lower air exchange rates exists for all three buildings. In addition, even at the high air exchange rates, the peak values generally fall below the equilibrium curves, suggesting that the assumed generation rates (basically the occupancy levels) may be too high.

The Building A data are relatively flat, with only a slight increase in CO_2 levels at lower air exchange rates. The deviations between this data and the equilibrium curve are greater at the lower air exchange rates, but this effect is not expected for air exchange rates between about one and two air changes per hour. The existence of these deviations can be explained by relatively short periods of constant CO_2 generation. The data for Building B are well below the 4-m equilibrium curve, perhaps due to an occupancy density that is lower than assumed. The data do show increasing peak values and greater deviations from the equilibrium curve at the lower air exchange rates, as expected. The Building C data should be compared to the 3-m curve and are well below this curve due to the CO_2 concentrations not attaining equilibrium and possibly a lower occupancy density than assumed.

Since the floors of Building C are well isolated in terms of airflow, the data from each floor can be examined separately. Peak CO_2 values and daily average air exchange rates were calculated for individual floors and compared. On some floors a strong correspondence between peak CO_2 and air exchange was evident, and on other floors no relation existed.

Variations in the activities on the floor lead to differences in the constancy of occupancy levels on the floors, and this can explain some of the difference between the floors. Figure 6 is a plot of peak CO_2 concentrations versus air exchange rate a for single floor of Building C. For this floor, and some of the other floors in the building, the data exhibit a linear relation between concentration and air exchange rate with much less scatter than the whole building average data in Fig. 5.

Calculation of Air Exchange from CO_2 Concentration

The simultaneous measurement of CO_2 concentration and air exchange rate enables the investigation of techniques for determining air exchange rates from the analysis of CO_2 concentration. Two such techniques were investigated in this study, the analysis of CO_2 concentration buildup and the analysis of postoccupancy concentration decay. The buildup technique was applied to all three buildings, while the decay analysis was conducted only for Buildings B and C. These two buildings had air sample locations within the occupied space that could be used when the air handling system was off. In addition, the air exchange rates in Building A were so large that there was not enough tracer gas remaining in the building to conduct a decay test when all of the building occupants had left.

The buildup analysis, as described above, involved fitting the CO_2 concentration data to Eq 3 during the morning buildup in CO_2 concentration. The crucial requirement for this analysis is that the CO_2 generation rate be constant during the analysis period. The results of the application of the buildup analysis were varied, with Eq 3 fitting the data very well on some occasions and very poorly on others. The analysis was carried out for individual sample locations, and while some locations generally fit the model better than others, none were characterized by consistently good fits to the model. The results for whole building average concentrations were also quite variable. Where the model fit the data well, the calculated air exchange rate from the buildup of CO_2 concentration agreed with the air exchange rate measured by SF_6 decay within 10 to 20%. The reason for the poor fit to Eq 3 in so many of the datasets is probably variation in generation rate, i.e., occupancy density, during those time periods. Figure 7 is a plot of CO_2 concentration buildup versus time for one of the datasets that fit Eq 3 very well. In this example, the SF_6 decay rate is 1.51 air

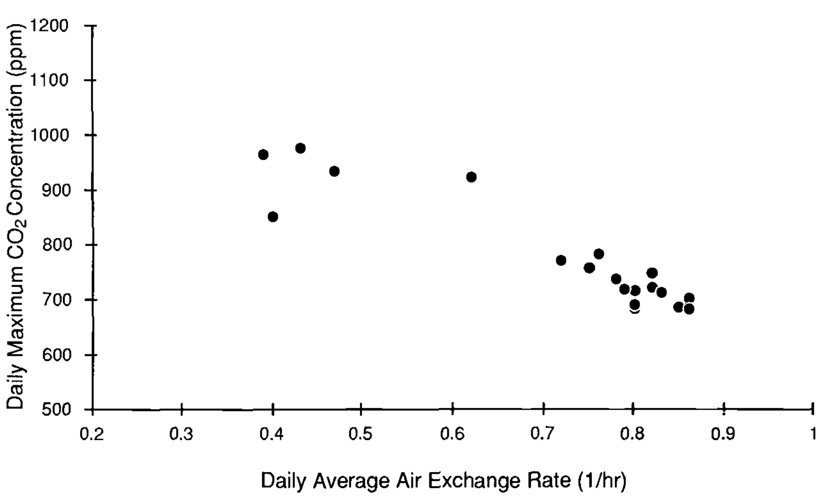

FIG. 6—*Peak CO_2 concentrations versus air exchange rate for one floor of Building C.*

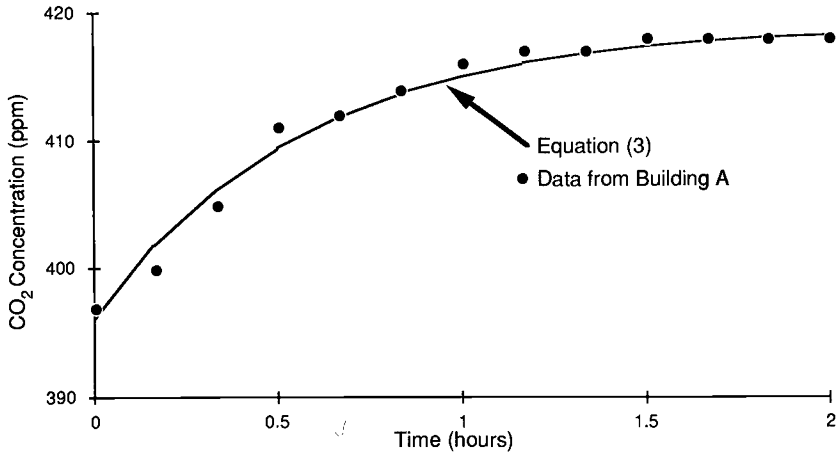

FIG. 7—*Example of CO_2 concentration buildup analysis.*

changes per hour. The CO_2 buildup analysis yields a value of the air exchange rate of 1.76 air changes per hour.

Comparison of decay rates based on CO_2 and SF_6 concentrations were made for Buildings B and C. These analyses were conducted on CO_2 concentration data collected after the occupants had left the buildings. In many cases, particularly when there were high air exchange rates, there were insufficient CO_2 concentrations within the buildings once the occupants had left, and the decay analysis could not be conducted. Because the occupancy of most buildings decreases over an extended period of time, as opposed to an instant in time, it will generally be difficult to conduct this CO_2 decay analysis when building air exchange rates are close to or above one air change per hour.

Figure 8 is a plot of air exchange rates determined by CO_2 concentration decay versus

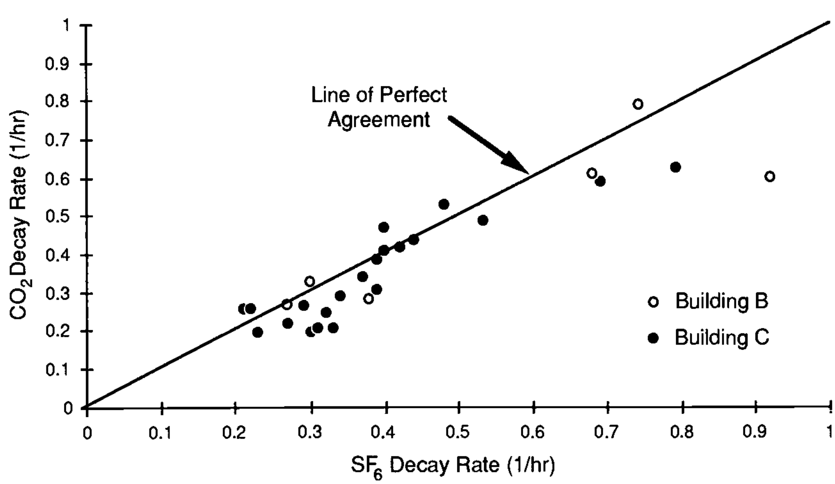

FIG. 8—*Air exchange rates: CO_2 decay versus SF_6 decay.*

the rates determined by SF_6 decay for Buildings B and C. Each point represents a 2-h decay and is an average over the whole building. The agreement between the two calculation techniques is good, with the deviations from the line of perfect agreement generally less than 0.1 air changes per hour. CO_2 and SF_6 concentrations were measured in these buildings under a wide range of weather and building operation conditions, but comparisons could be made only for air exchange rates less than 0.9 air changes per hour. As discussed earlier, this is because at higher air exchange rates there is not enough CO_2 remaining in the building when all of the occupants finally leave the building.

Summary and Conclusions

In this paper we have considered the relation between CO_2 concentrations and air exchange rates in office buildings, with the specific aim of investigating CO_2-based techniques to determine air exchange rates and evaluate office building ventilation. The theoretical basis for CO_2-based evaluation techniques were presented and discussed, and the key assumptions and practical experimental considerations of these techniques were examined. Simultaneous measurements of CO_2 concentrations and air exchange rates were made in three office buildings in order to provide a dataset to investigate three specific approaches to air exchange evaluation with CO_2. These approaches include the use of instantaneous readings of CO_2 concentration to determine air exchange rates, the analysis of CO_2 concentration decay rates after the occupants left a building, and the analysis of CO_2 buildup during periods of constant CO_2 generation.

Based on theoretical considerations and the experimental work, it is clear that instantaneous readings of indoor CO_2 levels cannot be used to determine building, or local, air exchange rates. Although this approach has been suggested as a simple means of determining air exchange rates, it is only appropriate under very limited circumstances. Specifically, only if the CO_2 concentration within a building is at equilibrium and is uniform throughout the building and the CO_2 generation rate is known can the concentration be related to the building air exchange rate. These conditions rarely exist in office buildings and many other building types, due primarily to spatial and temporal variations in occupancy levels. The comparisons of peak CO_2 concentrations and air exchange rates made for the three office buildings studied show large deviations between the measured peak concentrations and the predicted equilibrium levels, especially at air exchange rates less than about one air change per hour. These deviations exist primarily because the CO_2 generation rates, or occupancy levels, are not constant for a period of time that is long enough for the CO_2 concentration to reach equilibrium.

The analysis of CO_2 concentration decay rates to determine air exchange rates works well as long as the usual assumptions of the tracer gas decay technique are satisfied. The analysis of CO_2 decay rates after the occupants have left a building relies on the existence of a sufficiently high CO_2 concentration when all of the occupants are gone, i.e., the CO_2 generation rate is equal to zero. The amount of time it takes for the occupancy level to decrease to zero affects the applicability of this technique in any given building and the range of air exchange rates that will be able to be measured. The longer it takes for the occupants to leave the building, the lower the CO_2 concentration will be when the generation rate finally equals zero. In addition, the higher the air exchange rate, the less likely it is that there will be enough CO_2 in the building once the occupants do leave the building. For the two buildings studied in this paper, only air exchange rates less than about one air change per hour could be measured with the CO_2-decay technique.

The analysis of CO_2 concentration buildup does not appear to be a reliable technique for determining air exchange rates except in situations in which the CO_2 generation rate is known to be constant for several hours. The buildup analysis conducted in the three office buildings provided only limited agreement with the air exchange rates determined by SF_6

decay, primarily due to spatial and temporal variations in CO_2 generation rates. Analysis of CO_2 buildup data from school classrooms [*14*] fit the constant generation buildup model very well due to the constant generation rates in this building type. Previous work has shown that the analysis of CO_2 concentration data with a general mass balance equation, either in an instantaneous or integral form, works very well in determining air exchange rates as long as the CO_2 generation history is known.

CO_2 concentration analysis can provide quantitative evaluations of building air exchange, but the assumptions required for each technique must be shown to be appropriate and in certain circumstances their application may be severely limited. There are no "simple" CO_2-based measurement techniques. CO_2 concentrations are useful in providing quantitative indications of building ventilation levels per person, but this approach still requires care to avoid misinterpretation of the readings.

Acknowledgments

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DISCUSSION

D. Harrje[1] *(written discussion)*—Since many of your buildings suffered from lack of sufficient CO_2 at the end of the work day, had you considered reduced use of the mechanical ventilation to increase those CO_2 levels and aid the measurement method?

A. Persily (author's closure)—Such a reduction in the mechanical ventilation rate would certainly increase the CO_2 level at the end of the day, facilitating the determination of the CO_2 decay rate. However, we never did request such a reduction as part of our general desire to be as unobtrusive as possible when studying these buildings.

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The Northwest Residential Infiltration Survey: A Field Study of Ventilation in New Homes in the Pacific Northwest

REFERENCE: Parker, G. B., McSorley, M., and Harris, J., **"The Northwest Residential Infiltration Survey: A Field Study of Ventilation in New Homes in the Pacific Northwest,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, 1990, pp. 93–103.

ABSTRACT: A study was conducted in the Pacific Northwest region (Oregon, Washington, Idaho, and western Montana) to measure ventilation characteristics in electrically heated single-family, detached residences during the 1987–1988 and 1988–1989 heating seasons. This study generated information that will be used to develop energy conservation programs for Northwest homes. This data will be used to evaluate the cost effectiveness of various conservation measures, to establish residential building codes, and to help regional power planners in making decisions about the management of the Northwest's electrical resources.

The study was carried out under a three-way partnership. With support from the region's state energy offices, two agencies sponsored and reviewed the study: the State of Idaho's Department of Water Resources (IDWR) and the Bonneville Power Administration (BPA). Battelle Pacific Northwest Laboratories (Battelle) conducted the study under contract with these agencies.

During the first heating season 140 homes were tested in the study. These homes were built since 1980 to current building codes and practices in the region. During the second heating season, approximately 50 homes were tested that were constructed since 1986 to the proposed Model Conservation Standards (MCS). These energy-efficient MCS homes are equipped with whole-house mechanical ventilation systems.

The homes studied in the 1987–1988 heating season were selected from a list of 292 eligible residences identified in a random telephone survey. This survey was conducted in the top 43 growth counties in the region, representing approximately 90% of the regional population. The homes studied in the 1988–1989 heating season study were selected from records of new home construction in the region under utility-run incentive programs.

In the study, field technicians measured ventilation and infiltration in each home using two common techniques. The first technique was based on fan pressurization (using a blower door). Five Pacific Northwest blower door firms conducted the field work using field-evaluated orifice-type doors.

The second technique used perfluorocarbon tracer (PFT) equipment that measures the air exchange rate in the home for a two- to four-week period. A minimum of two, and maximum of three, different types of tracers were used in each home to characterize zone-to-zone air flows. Both measurements were used in analysis and evaluation of housing ventilation.

Before the ventilation measurements were taken in each home, an occupant and structure survey was conducted to determine occupant and house construction characteristics, and to identify heating and ventilation systems and their usage. During the time of the PFT measurement, the occupants kept a daily log to record activities that might influence ventilation (for example, exhaust fan usage). In addition, representative weather data was recorded for the home during the time of the PFT measurement.

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A total of 134 homes tested during the 1987/1988 heating season had valid PFT and blower door data. The mean regional season PFT air exchange rate was 0.40 ± 0.19 air changes per hour (ACH) and 0.45 ± 0.20 ACH calculated using the Lawrence Berkeley Laboratory (LBL) model and typical meterological year (TMY) heating season weather data. The mean effective leakage area was 806 ± 458 cm^2 at 4 Pa.

KEY WORDS: field study, ventilation, blower door, perfluorocarbon tracer, residential, single family, electrically-heated, random sample, indoor air quality, LBL model

This paper describes the purpose, procedures, and preliminary results of the Northwest Residential Infiltration Survey (NORIS) conducted for the State of Idaho Department of Water Resources (IDWR) by Battelle, Pacific Northwest Laboratories (Battelle). This study was carefully designed to provide information and data about the ventilation characteristics of newer homes in the Pacific Northwest.

A similar study was conducted by the Bonneville Power Administration (BPA) during the 1984/1985 heating season in over 200 new homes in the Pacific Northwest region. These homes were constructed as part of the Residential Standards Demonstration Program (RSDP). Approximately one half of the homes were constructed to the proposed Model Conservation Standards (MCS) for electrically heated homes in the Pacific Northwest region, and one half were constructed to current building practice (these were the control homes).

Both a fan pressurization test to quantify the air tightness of the home's exterior envelope and a one-time perfluorocarbon tracer (PFT) test over several consecutive weeks to measure the air exchange rate were performed in each home. Results of these measurements were analyzed in 1986.

The data showed that the PFT air exchange rates differed significantly from the air exchange rate estimates obtained using the fan pressurization test for both the MCS and control homes. These data raised concerns about the understanding of fresh air ventilation rates in homes and on the techniques for estimating those rates.

This region relies on this type of data for establishing policy and program directions. A critical environmental issue confronting new energy-efficient homes is the effect that reduced levels of ventilation may have on indoor air quality and the subsequent health of occupants.

In addition, the measurement and evaluation of fresh air ventilation in homes was necessary to decide the level of heat loss associated with the incidental infiltration of cool outside air into a dwelling (during the heating season) and the necessary fuel requirements to bring that air to an appropriate temperature.

For these reasons, it was important to investigate natural infiltration and air exchange rates in different categories of new homes and to investigate the two primary measurement techniques. The protocol and results of this study are intended to expand knowledge of these issues.

Planning and Project Oversight

During all phases of the NORIS project, guidance was received from the Project Oversight Committee (POC). The POC is made up of representatives from the regional state energy offices, BPA, the Northwest Power Planning Council (NWPPC), Brookhaven National Laboratory (BNL), Lawrence Berkeley Laboratory (LBL), Ecotope, Inc., other organizations, and individuals as designated by the IDWR.

Purpose of the Project

The purpose of this project was to determine the infiltration rates in single-family detached electrically heated homes in the Pacific Northwest region, and to investigate the relationship between fan pressurization (blower door) and PFT measurements in these homes. These homes represented two categories of homes: (*1*) those constructed to current building practice since 1980, and, (*2*) those constructed to the MCS with whole-house exhaust ventilation or build under the 1986 Super Good Cents (SGC) monitor/mitigation option.

The project was intended to provide answers to the following three questions:

1. What is the ventilation rate (air exchange rate) for a typical home of each of the two categories of homes measured by the PFT technique?
2. What are the leakage parameters [for example, effective leakage area (ELA), air exchange rate at 50 Pa pressure, flow rates, and air exchange rate] for a typical home for each of the two categories of homes using a fan pressurization measurement and the LBL algorithm for calculating these parameters from the fan pressurization results?
3. Can a method or procedure be developed to estimate the heating season average total fresh-air ventilation rate for the heating season from the fan pressurization test, and if so, what is the method or procedure?

The study focused on the first category of homes during the first year of the study (1987/1988 heating season). During the 1988/1989 heating season, the study focused on the second category of homes. This paper will focus on the first heating season study in the 1980 and newer homes.

Approach to the Sample Design and Selection

Ecotope, Inc., subcontractor to Battelle, was responsible for the sample design. Throughout the design phase, emphasis was placed on ensuring that final results were scientifically defensible with respect to both random and systematic error.

The approach to the sample design for the first heating season study is described in detail elsewhere [*1*]. A summary of the approach is as follows:

1. An analysis of the previously completed RSDP ventilation data was performed to gain an understanding of the factors that influence ventilation in these residences. Prior analysis indicated that ventilation rates in these homes were strongly influenced by heating system type, architecture type, and climate zone.
2. A random telephone survey in the region was conducted to determine the age, geographical distribution, heating system type, and house architecture of 1980 and newer current practice homes (Category 1) in the region. This survey was conducted in four stages: (*1*) a simple random sample from the 136 counties; (*2*) a random sample stratified by county with allocation proportional to the estimated household growth in 43 counties; (*3*) a random sample stratified as stratified above for Missoula, Gallatin, and Ravalli counties in Montana; and (*4*) a random sample drawn to meet weights in Kalispell and Lewis and Clark counties in Montana.
3. This survey involved contacting over 60 000 homes, with a target of approximately 290 qualified homes with occupants indicating a willingness to participate in the study. The results of the telephone survey were used to characterize the target population and serve as the sampling frame used in the recruiting of participants. It also provided the basis for developing separate strata such as heating system type for use in data analysis once the study was completed.
4. The recruiting of homes generated a list of project participants who signed a cooperative agreement to participate in the study. A target of 160 homes of the approximately 290 candidate homes for field testing was set based on a 95% confidence level for the estimate of the true target population mean value of ±8% of the sample mean value.

Recruitment of Residences

Battelle was responsible for obtaining from the residents a signed cooperative agreement that allowed project personnel access to the residence to conduct the tests.

Considerable effort was spent in the development of the sample frame to ensure that it was a representative and clearly interpretable sample of the region. The recruitment activity was designed to make sure that the final sample drawn is defensible and as unbiased as possible. All cooperative agreements were mailed simultaneously in late November, 1987, to the 292 potential participants from the list. This was to ensure that, if it became necessary to set a cutoff date for the return of the agreements, all potential participants had an equal opportunity to respond.

Of the 292 households mailed agreements, 149 residents returned signed agreements prior to the recruiting cutoff of 29 Jan. 1988. Because the target number of field testing was 160, there was no final selection to make, and all 149 households were chosen as candidates for testing. An analysis of possible sample biases were performed as part of the sample design report [*1*].

The detailed recruitment plan, including procedures for tracking the recruitment data, is described in a separate document [*2*].

Field Data Collection Procedures

The field data collection phase of the project involved performing a blower door test on each home, collecting structural and occupant characteristics data, and recording significant occupant activities during a two- to four-week measurement of air exchange rate using PFT. The residents were requested to mail exposed PFT samplers to Battelle at the end of the measurement period for analysis.

Battelle prepared a comprehensive field manual for completing the measurements in the homes [*3*]. Detail of the field protocol and example of the forms used are given in this manual. Two procedures described in that manual are important for discussion in this paper. These are the procedures for performing the PFT measurement and for the blower door test. Both procedures were developed with extensive input and review from the POC.

Procedures for Placement and Recovery of Perfluorocarbon Tracer (PFT) Source Capsules and Sample Tubes

The procedures that were followed in the handling, placement, and recovery of PFT source capsules and passive sample tubes in homes closely followed those recommended by BNL [*4*].

Principles for PFT Deployment

Information about the heating system(s) and architecture of the homes to be monitored in this study was obtained from the telephone survey. This information was important for estimating the number of airflow zones in the home and, therefore, the type of number of PFT sources and samplers to be deployed in each home. This was done prior to assigning a home to the field technician in order to help the technician make the final decision about source and sample tube placement.

Zoning

Every home in the study was monitored for air exchange rate using a PFT in a minimum two-zone configuration. This required two different PFT types (compounds) in each home, one PFT type per zone. A maximum of three different PFT types was deployed in this study, correspondingly limiting the number of zones to be studied in any home to three. The principles for zoning are described in detail elsewhere [*3*].

Source Deployment

One source type was deployed in each zone. Because it was important to ensure that the PFT was well mixed in the home in each zone, the following deployment strategy was followed:

1. A minimum of one source (capsule) was placed in every zone in every room greater than 7.4 m^2 (80 ft^2) that had a door, even if the room was closed off.
2. One source was placed every 47 m^2 (500 ft^2) in large rooms (areas) of zoned-heated homes.
3. One source was placed every 70 m^2 (750 ft^2) in large rooms (areas) of centrally heated homes.

Each source type exhibited a different mass emission rate from the capsules, and therefore they were deployed according to their emission rate. It was necessary to place the source type with the highest emission rate in the highest zone of the home in order to ensure that sufficient tracer migrated to, and was detected in, the lowest zone of the home. The principles for choosing the source type for each zone are described in detail elsewhere [*3*].

Source Locations

The sources were placed near an exterior wall in the extremities of the zone. This was to ensure that the source was carried into the room or zone by the air that normally infiltrates the home from exterior wall areas. The sources were placed no less than approximately 0.6 m (2 ft) from the floor.

Good locations for sources were on objects that are not easily moved or normally relocated, including: shelves, picture frames, door frames, cabinet tops, plants, counter tops, and large furniture (legs, under the table, and ledges). The sources were hidden, if possible, and secured with poster putty to keep them from rolling or falling on the floor.

The sources were placed no closer than 0.9 to 1.5 m (3 to 5 ft) from items that emit heat or ventilation air. These included: any vent/grill (including window air conditioners), window (whether it opens or not), exterior/garage/basement door, wood stove/fireplace, refrigerator/freezer/microwave, and not above a baseboard/wall heater or lamp. The sources also were not to be placed in the direct or indirect sun.

Sample Tube Deployment

The sample tubes were 7.6-cm (3-in.)-long, 0.6-cm (0.25-in.)-diameter glass tubes packed with charcoal-based absorbent. They were capped at both ends and, during measurement, were uncapped at one end to absorb PFT. An average of five samplers was deployed in each home in this study. Generally, the larger the home, the greater the number of samplers used. In a few selected homes, we deployed samplers in replicate pairs and sent one sampler to BNL for analysis as a quality check. The actual deployment strategy for the replicates was coordinated with the field specialists.

Sample tubes were secured in a foam holder and hung from the ceiling using a tack punched through the string that was glued to the holder. Each foam holder was capable of holding two samplers. The sampler deployment strategy for the homes in the study is detailed elsewhere [*3*].

Temperature Recorder Deployment

Each blower door field specialist was issued several credit card-size, battery-operated temperature recorders to be used in homes to record time series temperature data during the time of the PFT test. The emission rate of the PFT sources is temperature-dependent, and therefore it was important to know (record) the average temperature in zones of homes that experienced wide diurnal fluctuations in temperature during the time of the PFT test.

A limited number of recorders were available for the study, and therefore recorders were not placed in all homes. The recorders were reused and returned to the specialist for reuse once that data from a home were extracted from the recorder.

Sources, Samplers, and Temperature Recorder Recovery Tactics

The uncapped sample tubes were left in the homes for two to four weeks. At the end of this period, Battelle contacted the resident by telephone and requested that the sample tubes be taken down, capped, and mailed to Battelle in a mailer left by the field specialist.

The resident was also asked to record the date and time of recovery and capping of the tubes on a form and insert the form in the mailer. If the resident was contacted at home, we requested the resident, if possible, to cap the tubes and place them in the mailer while we remained on the phone in order to aid them in any way. At this time, we likewise recorded the date and time of capping on a PFT data sheet that was returned in the booklet by the field specialist.

Each mailer contained a small charcoal filter to absorb any fugitive PFT vapor that might come in contact with the mailer. The resident was also requested to mail the temperature recorder in the mailer used for the sample tubes. The resident was not requested to turn the recorder off prior to mailing.

Once the sample tubes were received at Battelle, they were logged into the PFT air exchange rate analysis program and submitted for chemical analysis. The resident was immediately sent a letter requesting recovery and return of the sources. We provided mailers (with charcoal filters) for the sources. In order to avoid possible contamination with the sample tubes that were also in the mail system, the sources were mailed to the Battelle Portland Office, collected, and then transmitted express mail to a Battelle staff member's home.

Blower Door Test Protocol

The procedures for the blower door test were based on ASTM Standard Method for Determining Air Leakage Rate by Fan Pressurization Test (E 779-87). Certain deviations from this standard were recommended by the POC due to the number of homes to be tested and the inclusion of PFT measurements in this study. Generally, requirements were as stringent as those in the standard. Significant exceptions or extensions to ASTM E 779-87 for this study were the following:

1. Only blower doors manufactured by a recognized, reputable manufacturer were allowed. All blower doors used were of the orifice flow measurement type.

2. Blower door tests occasionally were performed under other than the preferred wind and temperature conditions. The field specialist was advised to avoid driving to the home on windy days, but once at the site they performed the blower door test and deployed PFT materials regardless of weather conditions. On-site wind speed and temperature were recorded on the blower door test form, and arrangements for a second test were made if test conditions were unfavorable.

3. All flow data were corrected to standard conditions (298 K, 101.325 kPa pressure) using on-site temperature and uncorrected station pressure data. Battelle determined the actual station pressure for the day of the testing from other sources of information.

4. Test accuracy was based on the correlation coefficient. A correlation coefficient of 0.998 or higher was sought as determined from on-site blower door test program analysis results. If not attained, the test was to be repeated; however, no more than two tests were conducted.

5. Target test pressures ranged logarithmically from 12.5 Pa to 60 Pa (0.06 to 0.24 in.) rather than 12.5 to 75 Pa as recommended by ASTM. The target pressures in the range are only guidelines; the specialist recorded the actual pressures attained at the time of the test(s). A minimum of eight flow data points were taken unless the house was too leaky to sustain higher pressures.

6. Because of the time and cost limitations, it was impossible to use a smoke stick to determine the leakage distribution in the structure between the floor, wall, and ceiling. Instead, the specialist recorded the four to five greatest leakage locations in the home based on their best professional judgement.

Data Management

Management of the data for the study was a critical element to the success of the study. Therefore, careful attention was paid to data collection, entry procedures, and checking. All permanent primary projects were kept on a spreadsheet database. The primary database includes information from seven sources [*3*]:

1. Telephone survey (identifying candidate participants).
2. On-site homeowner survey and walkthrough survey.
3. On-site structural measurements and sketches.
4. Meteorological data and exterior building parameters.
5. Blower door test.
6. PFT data sheet.
7. PFT air exchange rate analysis.

All of the data were in a numerical format suitable for such statistical functions as mean, standard deviation, linear and nonlinear regression, graphing, and frequency.

Blower door air change rates were calculated using the LBL algorithm and representative National Weather Service (NWS) meteorological data for that site during the time period of the PFT test as well as for a heating season using TMY data. The meteorology used to calculate these numbers was retained as raw data in the LBL air exchange programs whether it was average, monthly, or hourly data.

Perfluorocarbon tracer data in the primary database included zone description, zone temperature, floor area, volume, and source type for each zone. The overall whole-house air exchange rate and standard deviation were also included in the primary database.

Perfluorocarbon tracer data in the ancillary database included the four-digit identification number of each sample tube, date and time of recovery, date and time of deployment, number of sources of each type in each zone, and zone-to-zone air flow.

Results and Discussions

The results and data for the first year's recruiting effort and summarized field measurements are presented and discussed.

Sample Design and Selection

A final report discussing results and analysis of the sample design, selection, and recruiting is under final revision [*1*]. Therefore, the potential biases in the sample are not discussed in the final detail.

It is evident from the recruiting effort, however, that a definite bias exists in the distribution of the homes within the region as shown by the large number of homes in Washington compared to the regional population distribution. The sample tested also appears to have a higher proportion of homes with wood as a main heat source. Also evident in the homes tested (compared to the regional population) is a smaller proportion with forced-air furnaces, a larger proportion of two-story houses without basements, and a smaller proportion of one-story houses without basements. Of these differences, the most statistically significant are those for one-story homes and for wood as a main source of heat.

Field Measurements

A total of 149 residents returned signed agreements and were qualified for testing. The blower door measurements began in western Washington on 19 Jan. 1988, and the last blower door test was completed in western Montana on 22 Apr. 1988. The last set of PFT samplers were capped and mailed on 8 May 1988. The summary results of the field work are given in Table 1.

As noted in Table 1, only 140 of the 149 qualified homes were ultimately tested. The majority of the homes that were not tested were dropped because the homes were constructed prior to 1980 as determined by the field specialists upon inspection of the structure prior to performing the measurements.

Field Data

Of the over 600 PFT sample tubes deployed in the homes, only one sample tube broke during shipment from the homes to Battelle. Greater than 98% of the PFT sample tubes were successfully analyzed and used in the data analysis. PFT data are available in the data set that includes the air exchange rate for each zone in the home as well as zone-to-zone air flows. All PFT chemical and data analysis were performed by Battelle. We employed a modified BNL-developed matrix solution program to produce the air exchange rates, zone-to-zone airflows, and error analysis.

Blower door data that met the acceptance criteria were available for all 140 homes tested; usable PFT data were available for 134 of these homes. In two of the three homes with unusable PFT data, the residents returned PFT sources with samplers, contaminating the samplers. In the third home, the sample tubes were inadvertently deployed with the wrong (leaky) caps at the one end of the tube that required leak-tight caps. This allowed the PFT

TABLE 1—*First year's heating season field work summary by state.*

	Number of Homes				
Criteria	ID	OR	MT	WA	Total
Qualified and in Study	10	14	14	110	149
Field Work Completed	9	14	13	104	140
With Central Heating Ductwork	4	9	0	60	73
Ductwork Leakage Measured (Blower Door)	1	4	0	43	48
Recorded Temperature Data (Indoor)	5	7	9	49	70
Occupant Activities Records Completed	9	14	13	104	140

to enter at both ends of the tube at an unknown diffusion rate. An additional three homes had large discrepancies in the PFT and blower door results and were not used in the analyses. The results are therefore based on data from 134 homes.

A summary of the results for the PFT tests blower door tests, and calculated air changes per hour (ACH) for the blower door tests are given in Table 2. A detailed analysis of this data is currently being conducted by Ecotope, Inc., and will be available early summer, 1989.

The first block in the table are the average inside temperature during the PFT tests and outside temperature and wind speed data for the region. The next block are data from the blower door tests. The blower door test results reported in Table 2 are the depressurization tests only. The LBL Effective Leakage Area (ELA) and air change rate at 50 Pa (ACH50) were calculated by Battelle from raw flow and pressure data recorded by the field specialist.

The next block in the table gives several air exchange rate and airflow estimates based on the NWS data for the time period of the PFT tests. The first value is the effective air changes per hour for the PFT tests (EPFT NWS) and is the PFT value measured in the study adjusted for site density. The next value is the effective air changes per hour (ELBL NWS) estimated from the LBL model using hourly weather data from the NWS during the time period of the PFT testing. The next two values are the actual air changes determined from weather data for the time period of the testing for both the PFT and LBL model. The actual air changes (ALBL NWS) value was predicted from the LBL model; the actual air changes (APFT NWS) was determined by multiplying the PFT effective ACH by the LBL model predicted ratio of effective air changes to actual air changes. It should be noted here that the effective air change rate is the pertinent quantity for evaluating ventilation and indoor air quality.

The last block in the table gives heating season air exchange rates based on TMY weather data for both the PFT (PFT TMY) and LBL model (LBL TMY). The LBL values are by direct calculation; the PFT values were estimated by multiplying the NWS PFT air changes by the ratio of the LBL-model NWS to the LBL-model TMY. These are the best estimates of the long-term heating season infiltration rates in the regional population.

The difference of 0.04 ACH (or 10%) between the last two values given in Table 2 as determined from two measurement techniques (blower door and PFT) is too large to have occurred due to random error. This indicates the presence of a systematic difference between the two methods used to predict air exchange rates. It is a reasonable assumption to believe

TABLE 2—*NORIS preliminary summary of numerical data.*

	Mean	Standard Deviation	Min	Max
Inside temp., °F	67.2	3.85	54.0	76.0
NWS outside temp., °F	43.2	4.29	25.9	52.1
TMY outside temp., °F	40.6	4.17	29.5	44.1
NWS wind speed, m/s	4.0	0.79	2.4	5.6
TMY wind speed, m/s	4.1	0.67	1.9	5.2
ELA LBL, cm^2	806.4	458.1	129.0	2464.5
ACH50, 1/h	9.3	3.5	1.9	17.5
EPFT NWS, 1/h	0.37	0.18	0.11	0.95
ELBL NWS, 1/h	0.41	0.18	0.085	0.94
APFT NWS, 1/h	0.38	0.18	0.12	1.03
ALBL NWS, 1/h	0.43	0.19	0.09	0.97
PFT TMY, 1/h	0.40	0.19	0.13	1.11
LBL TMY, 1/h	0.45	0.20	0.09	1.18

that each of the techniques, as used in this study, may have a systematic error of 5 to 10% or more. Given this likely systematic error, our knowledge about the ventilation characteristics in the population studied is less exact than indicated by the confidence intervals.

Significant in the PFT data is the observation that the standard deviations approach 50% of the mean. This is typical of prior PFT measurements of this type in the region in single family electrically-heated detached homes [5].

A preliminary examination of the PFT data by home (not shown) indicates that there is not a significant difference in PFT air exchange rate between homes that burn wood as a primary heating source and those that do not. However, there appears to be a significant difference in the air exchange rate between homes that heat with baseboard or wall (radiant) heat and those that have a forced air furnace. The forced air furnace homes have a 35 to 45% higher air exchange rate compared to homes with baseboard or wall heaters. There appears to be no significant differences in the PFT results for homes of different architecture types.

Conclusions

A great deal of preplanning and peer review were intentionally built into this project prior to conducting the sample selection and recruitment, field data collection, data archiving, and quality control. The project was structured so that special emphasis was placed on the scientific statistical defensibility of the data within the time and budget constraints. In particular, the sample of homes was to be statistically representative for the purpose of estimating the regional population mean values of the measured parameters.

A large data set on the structure, occupant, and ventilation characteristics of homes built since 1980 in the Pacific Northwest is available for detailed analysis. Because the data set is new, no conclusions can be drawn concerning the data itself, until analyses are completed. However, some important observations and conclusions can be made regarding the sample design, recruiting and data collection process. These are:

1. A random telephone survey to identify the sample that meets the study criteria is the most scientifically sound approach and should be considered for any study of this type. This study did not use a truly random survey since we concentrated on the top 43 growth counties in the region representing 90% of the regional population. However, once the sample of qualified homes was identified, weights were assigned to each county to correct sampling bias.

2. Requiring signed participatory agreement can be a critical stumbling block to participation in a field monitoring study. A significant number of residents that initially indicated a willingness to participate chose not to participate in the study once sent an agreement to sign.

3. Many residents became confused by the explanatory material (brochure) prepared and sent by Battelle with the cooperative agreement [3]. From conversations with the residents, we concluded that too much and too detailed information was provided at this time, particularly about the nature of the air exchange rate measurement tests.

4. A small payment to the resident prior to conducting the field measurements was important in maintaining good resident relationships. The field specialists noted how cooperative the residents were and attributed much of this to the prepayment.

5. Prefield training in protocol and procedures was necessary to assure consistency among the field specialists in the data collected. This was especially critical for deployment of the PFT materials. Training manuals are not a substitute for field training since few manuals can be written with sufficient detail and field specialists will generally not read nor comprehend a detailed manual.

6. With the help of the POC, a state-of-the-technology protocol has been developed for

the deployment of PFT materials (sources and samplers) in a multizone configuration in all types of homes in combination with a blower door test. This protocol was based on extensive field experience and measurements over the past several years.

7. Procedures have been developed for successful recovery and mailing of PFT materials by residents. The key to the success of the recovery procedures was the phone contact by Battelle staff at the time for recovery of the materials. Only two residents failed to follow the instructions.

8. The final estimates for the average heating-season infiltration air exchange rates are 0.40 ACH using the PFT technique and 0.45 ACH using a blower door and the LBL model. There is large variation in the measured air exchange rates. The sample of homes range from extremely tight to very leaky. Most of the variation in air exchange rates is likely due to differing levels of tightness per unit size.

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Comparison of Methods for the Measurement of Air Change Rates and Interzonal Airflows in Two Test Residences

REFERENCE: Fortmann, R. C., Nagda, N. L., and Rector, H. E., **"Comparison of Methods for the Measurement of Air Change Rates and Interzonal Airflows in Two Test Residences,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 104–118.

ABSTRACT: Four different but complementary methods—the tracer gas dilution method, single-tracer constant concentration, passive perfluorocarbon tracers (constant release), and constant release of multiple halocarbon tracers with semicontinuous analysis—were used to obtain detailed information on air exchange and interzonal airflow rates in the two GEOMET bilevel research houses. The four methods yielded comparable measurements of single-zone (whole-house) air exchange rates. Constant concentration tracer gas, perfluorocarbon tracer, and multiple halocarbon tracer measurements yielded comparable measurements of upstairs and downstairs air infiltration rates; downstairs infiltration rates were as much as seven times higher than upstairs. The constant-concentration method also provided detailed information on room-specific infiltration rates. Perfluorocarbon tracer (PFT) measurements of airflow rates between conditioned zones, the attic, and garage demonstrated the effectiveness of house-tightening retrofit procedures to reduce airflows to the unconditioned airspaces. Perfluorocarbon and halocarbon measurements of week-long, time-averaged interzonal airflow rates were comparable, but the halocarbon system showed that hourly interzonal airflow rates could be as much as an order of magnitude higher than the week-long average.

KEY WORDS: air infiltration, interzonal airflows, air exchange rate, tracer gas methods, tracer gas dilution, constant concentration, constant release

Infiltration of outdoor air into a structure and the patterns of air movement between conditioned and unconditioned airspaces can have a significant impact on energy use and air quality in the structure. Outdoor air infiltrating into a structure may serve to dilute concentrations of pollutants generated indoors, but this same outdoor air may contain elevated levels of other outdoor pollutants. Air movement indoors may impact energy use and air quality in different areas of a residence. Occupant exposure to contaminants generated indoors will be affected by the direction and magnitude of air movement in a residence. For example, an occupant's exposure in a zone adjacent to emissions, as would occur with some consumer products, is a function of not only the contaminant source strength, but also the direction and rate of movement of the contaminant to areas adjacent to the area of use.

A number of different tracer gas methods have been used for the measurement of air change rates in residential dwellings. Some of these, such as the dilution method with a single tracer, are relatively easy to implement. Other methods that employ more elaborate release and sampling methods or that use multiple tracer gases are generally more expensive

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and difficult to implement, but also provide a higher level of information on zonal infiltration rates and interzonal air movements.

Under the sponsorship of the Electric Power Research Institute, GEOMET has conducted detailed measurements of air exchange and interzonal airflow rates in GEOMET's two research houses. Four different but complementary tracer gas methods were used in this study to measure whole-house air exchange rates, infiltration rates for individual zones, and interzonal airflow rates between zones. This paper describes the results of selected measurements in the research houses for comparison of the performance of the various measurement methods. The advantages and limitations of each method are also discussed.

Tracer Gas Methods Tested

The four methods used in this study represented the following three basic tracer gas techniques:

1. Tracer gas dilution.
2. Constant concentration.
3. Constant release.

Characteristics of the four measurement methods are summarized in Table 1.

The tracer gas dilution method used in this study was based on a modification of the ASTM Standard Test Method for Determining Air Leakage Rate by Tracer Dilution (E 741-80). Modified for automated release and semicontinuous sampling, the method has been used on a nearly continual basis during the past six years to measure whole-house air infiltration rates for the two test residences. The GEOMET system consists of an automated release system that injects sulfur hexafluoride (SF_6) into each house once every 6 to 12 h; the furnace blower and central air distribution system were used to distribute the gas uniformly throughout the house. An automated sampling system cycles on 3-min intervals through each of five zones, so that SF_6 is measured in each zone once every 15 min. SF_6 was sampled in the upstairs living room and downstairs of each house (Fig. 1). The fifth sampling zone was outdoors, to provide a continual check on background and system performance. The concentrations measured on each level of the house were weighted by their respective fractions of the total house volume (0.65 upstairs and 0.35 downstairs) in calculating the air infiltration rate for the entire house. The logarithmic decay in SF_6 concentration with respect to time was used to determine the average hourly air infiltration rate in air changes per hour (ACH).

The constant-concentration tracer gas (CCTG) system used in this study was developed by Harrje et al. [*1*]. The system consists of a gas chromatograph with an electron capture detector, a series of sampling and injection lines, an auxiliary pump, and a microcomputer-based measurement and control system. A single tracer gas, SF_6, is maintained at a constant concentration in all measurement zones. To accomplish this, the SF_6 concentration is measured, the SF_6 injection rate needed to maintain a constant concentration is automatically calculated, and then tracer gas is injected by the system on a 60-s cycle in each zone. Six zones, five upstairs and one downstairs, were defined for the GEOMET research house. Each zone included an injection point and a sampling point plus a small fan used to mix the tracer gas within the zone. Because only one analytical system was available, constant-concentration measurements were performed only in one of the research houses. The system was used to calculate infiltration rates into each zone from the tracer injection rate into the zone divided by the target concentration. Whole-house infiltration rates were calculated from the volume-weighted averages for the individual zones.

Two different systems for constant release of multiple tracers were used in this study to measure air infiltration rates and interzonal airflows. The passive perfluorocarbon tracer

TABLE 1—*Characteristics of the measurement methods.*

Method/Technique	Number of Tracers	Sampling Method	Averaging Period	Measurement Parameter(s)
Tracer dilution, sulfur hexafluoride (SF_6)	1	semicontinuous	hour	single-zone infiltration
Constant concentration (SF_6)	1	semicontinuous	hour	multizone infiltration
Perfluorocarbon tracers (PFT)/ constant release	4	integrated	7-day	multizone infiltration and interzonal airflows
Halocarbon tracers/constant release	2	semicontinuous	hour	multizone infiltration and interzonal airflows

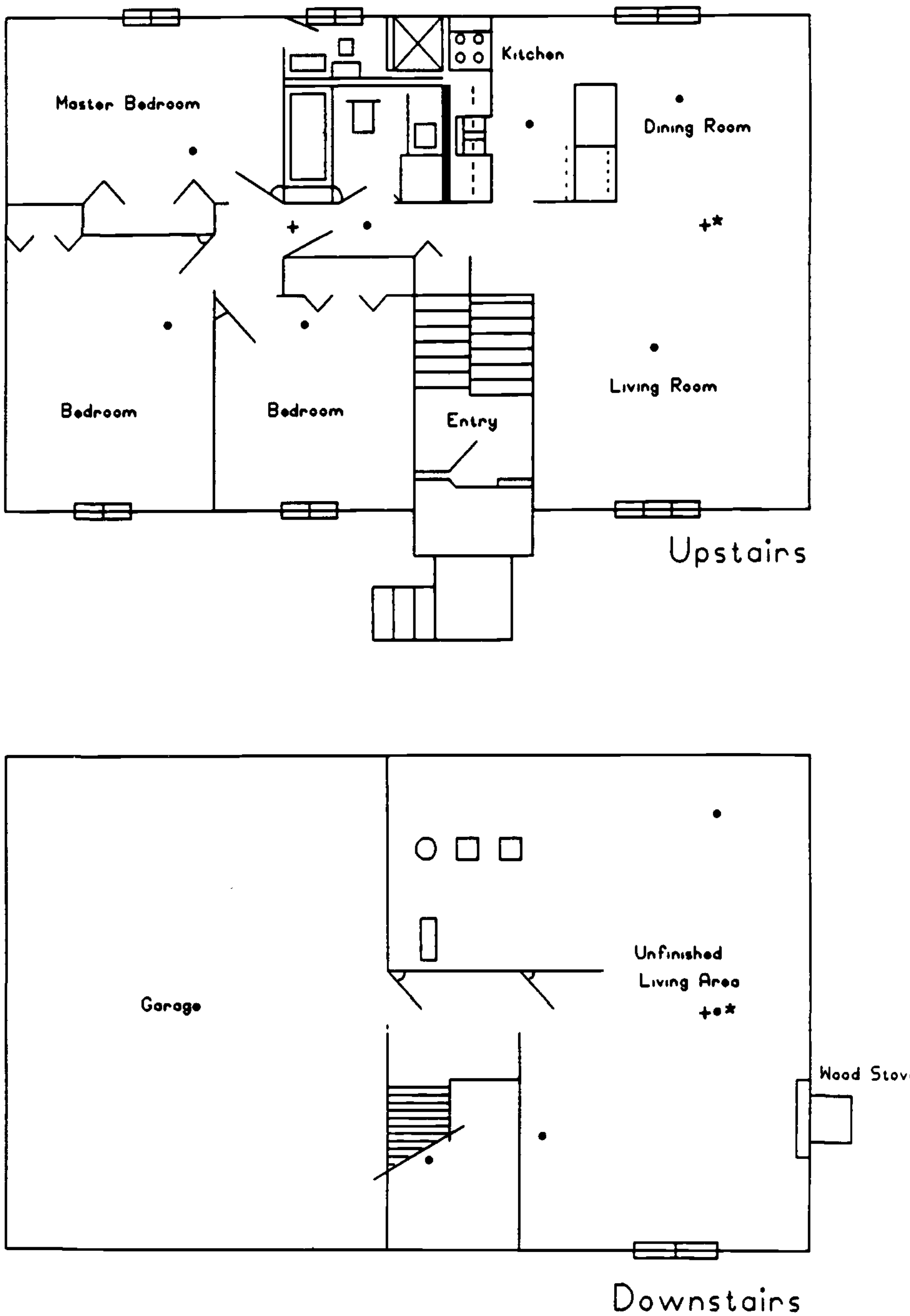

FIG. 1—*Floor plan of the GEOMET research houses. Sampling locations indicated for the* SF_6 *dilution method (*), PFTs and Halocarbons (+), and* SF_6 *constant concentration (•).*

(PFT) method developed at Brookhaven National Laboratory (BNL) [2] was used to measure air change and interzonal airflow rates among both conditioned and unconditioned airspaces in both houses. The BNL technology consists of miniature PFT sources that release the tracer at a temperature-dependent rate and capillary adsorption tubes for passive sampling. PFT sources were deployed in each room according to standardized BNL protocols. The passive samplers were deployed for a period of seven days to ensure collection of sufficient quantities of tracer from all zones. The measurement zones included the attic, garage, and upstairs and downstairs conditioned interior zones. A single sampler was placed at a height of 1.1 m above the floor near the center of each zone, except in the upstairs of the house, for which one sampler was placed at the living room probe site, and a second sampler was placed at the end of the hallway centered on the entrances to the three bedrooms (Fig. 1). PFT sources and samplers were supplied by BNL, and sampler analysis was performed by BNL.

The second constant-release system used in the study was a constant multiple halocarbon tracer gas (MHT) release system with a continuous sampling system and analysis by an on-site gas chromatograph. The system was used to calculate hourly air infiltration rates and interzonal airflows in the conditioned airspaces of the research house. The halocarbon tracers selected for the two-zone measurements were halocarbon 114 ($C_2Cl_2F_4$—dichlorotetrafluoroethane) and halocarbon 13B1 ($CBrF_3$—bromotrifluoromethane). Both halocarbons are nontoxic at the parts-per-million (ppm) concentrations used in this study (threshold limit value of 1000 ppm). They are gases at room temperature and can be easily separated and detected with the gas chromatograph-electron capture detector (GC-ECD) used for analysis.

Halocarbon 114, at a tank (source) concentration of 2.2% in air, was released in the upstairs of the house, and 13B1 (source concentration of 0.4% in air) was released downstairs. The release system consisted of the compressed gas cylinder, a two-stage pressure regulator, a sintered stainless steel filter element, and variable lengths of 0.25-mm inside diameter capillary tubing downstream of the regulator. Tracer gas was released at a single point near the center of each room. Release rates were controlled by adjusting the length of the capillary tubing and pressure to provide release rates proportional to the volume of each room.

Air samples were collected sequentially from the upstairs and downstairs once every 7.5 min with an automated sampling system. The halocarbons were separated on a 4.6- by 3-mm stainless steel column containing Porapak Q (80/100 mesh) and analyzed by GC-ECD.

Infiltration, exfiltration, and interzonal airflow rates were calculated from the concentration data using algorithms drawn from the multiple chamber description of the mass balance [3,4]. Results from measurement methods that were not tested concurrently were compared on the basis of relative differences in average indoor-outdoor temperature differences (ΔT) and windspeed using a model of air infiltration in the form of the regression relationship

$$AI = a + b \cdot |\Delta T| + c \cdot V \tag{1}$$

where

AI = air infiltration rate (ACH),
ΔT = indoor-outdoor temperature difference, °C,
V = windspeed, m/s, and
a, b, c = constants that were estimated by least-squares techniques in previous tests at the research houses [5].

Tests were performed in the control house with the SF_6 tracer dilution method, PFTs, and the constant-concentration system. In the experimental house, the methods included tracer dilution, PFTs, and halocarbons. Because of resource constraints, the halocarbon method (experimental house) and constant-concentration method (control house) were configured in only one house and were not tested concurrently. The tracer gas dilution method and the constant-concentration system could not be operated concurrently because both systems used SF_6 as the tracer gas. However, measurements were compared by referencing the results to windspeed and indoor-outdoor temperature differences during each season.

Description of the Test Site

The GEOMET research houses were constructed in 1982 in a new subdivision approximately 35 km northwest of Washington, DC. The bilevel wood-frame houses are of identical design and are located on adjacent lots. Details of the house construction and initial characterization have been described previously [*5,6*]. The floor plan of the houses, depicted in Fig. 1, consists of a main living area and three bedrooms upstairs, and a downstairs area divided into an unfinished living area and an integral garage. The upper and lower levels are connected by an open stairway.

Both houses are modestly furnished, including beds, tables, bookshelves, sofa, and chairs. Each contains a standard set of appliances including a gas range, water heater, washing machine, clothes dryer, dishwasher, refrigerator, and range-hood and bathroom exhaust fans. The houses are heated and cooled with a central forced-air system. The research houses are unoccupied; when necessary, occupant activities are simulated through standardized simulation protocols. One of the research houses, designated as the experimental house, has been retrofitted to reduce air leakage. The other house, designated as the control house, remains in as-built condition and has an average air infiltration rate approximately 25% higher than the experimental house [*6*].

A separate laboratory space equipped with a large array of analytical instrumentation, support and calibration equipment, and data acquisition systems is located between the two research houses. Sample lines extend from the houses to the laboratory to transfer gaseous substances to real-time monitors and to provide vacuum sources for samplers placed in the houses. Signal cables connect various sensors in the houses to the data acquisition system in the laboratory.

Parameters monitored at the research houses, described previously [*5,6*], fall into the following categories:

1. Air exchange and interzonal airflow parameters.
2. Meteorological parameters.
3. Indoor environment parameters.
4. Air quality parameters.
5. Energy consumption parameters.

For the experiments reported here, measurements were performed during winter, spring, and summer to assess differences in air change and interzonal airflow rates for the two houses and to compare performance of the measurement methods under a range of conditions. Results of these tests are described in the following sections.

Whole-House Air Change Rates

Average whole-house air change rates measured by the four methods over week-long measurement periods ranged from 0.11 ACH during summer to 0.75 ACH in winter. The SF_6 dilution method has been used on a continual basis in the houses and served as the reference method for whole-house air change rate measurements.

For the tests described in this paper, the passive PFT method was configured for four zone measurements that included the unconditioned attic and garage. Week-long measurement periods were necessary to ensure that sufficient mass of each tracer was collected in all four zones. The constant concentration tracer gas (CCTG) system was also used for week-long periods; hourly measurements were integrated over the entire measurement period for comparative purposes. The multiple halocarbon tracer (MHT) system was used for periods of one to seven days. For comparison to the PFTs, hourly averages were integrated over the exposure periods.

Measurements of the air infiltration rate of each research house, treated as a single zone, with the four methods are compared in Table 2. Concurrent PFT and SF_6 dilution method measurements yielded nearly identical infiltration rates during spring and summer. During winter, the air change rate estimated from PFT measurements exceeded those estimated from SF_6 measurements by 0.05 and 0.09 ACH in the experimental and control houses, respectively, but the difference was not significant over the week-long measurement periods. The PFT measurements, although exhibiting a positive bias with respect to SF_6 measurements in winter, differed by only 10 to 14%. Differences of this magnitude are within the predicted measurement error with the passive PFTs, for which the release rate from the sources varies by ± 7 to 10% and sampling rates vary by an average of ± 2 to 3% [*2*].

Measurements with the CCTG method could not be performed concurrently with the SF_6 dilution method because SF_6 was also used as the tracer for the CCTG method. The relative performance of the two methods, however, can be compared if referenced to the indoor-outdoor temperature difference (ΔT) and windspeed, the major driving forces for air infiltration. As shown in Table 2, summertime CCTG measurements were 0.03 ACH higher than the SF_6 dilution method measurement, despite a smaller ΔT and lower windspeed, but the differences were not significant. During spring and winter, the CCTG-measured rates were lower than the SF_6 dilution method measurements, consistent with the lower ΔTs.

Multiple halocarbon measurements were performed concurrently with both the SF_6 dilution method and PFT measurements during the summer. For the week-long summer period, the MHT measurements were similar to the concurrent PFT and SF_6 measurements. During spring and winter measurement periods, the MHT method did not compare as favorably to the concurrent SF_6 dilution method measurements. Springtime MHT results were 42% higher; wintertime results were 35% lower than concurrent SF_6 dilution results. Differences between the SF_6 and MHT methods did not exhibit consistently positive or negative bias. Comparisons of hourly average measurements with the two systems suggested that differences between the short-term (hourly) measurements may have been related to poor mixing of the halocarbon tracers because the MHT system did not include auxiliary fans to promote mixing, and the release of the halocarbon tracers was limited to a single point in each room. Further testing with multiple release points in each room will be required to address the differences observed in these tests.

Zonal Air Infiltration Rates

Previous measurements of air change rates in the GEOMET houses by the SF_6 dilution method indicated substantially higher infiltration rates in the downstairs than upstairs, based on differences in SF_6 dilution rates in the two zones. The CCTG, PFT, and MHT methods can all provide measurements of infiltration rates in individual zones within a structure.

Infiltration rates of the upstairs and downstairs of the two houses measured with PFT, CCTG, and MHT methods are summarized in Table 3. The PFT and CCTG methods were not used concurrently during these tests, but qualitative comparisons can be made if referenced to the average ΔTs and windspeeds for the measurement periods. In the control house, week-long average upstairs infiltration rates ranged from 0.06 to 0.24 ACH, using PFTs. Downstairs rates were substantially higher, ranging from 0.35 to 1.69 ACH as measured with the PFTs. CCTG and PFT measurements were similar during the summer, differing by only 0.04 ACH. During spring and winter measurement periods, the differences were larger, but were consistent with the differences in ΔTs and windspeeds between the

TABLE 2—*Comparison of methods for the measurement of whole-house air infiltration rates.*

Season	Method[b]	ΔT, °C[c]	Windspeed, m/s[c]	Air Infiltration Rate (ACH)[a] Control House	Air Infiltration Rate (ACH)[a] Experimental House
Spring	SF_6[d]	14.2	1.2	0.49 ± 0.18	0.33 ± 0.11
	PFT[e]	14.2	1.2	0.50 ± 0.47	0.33 ± 0.31
	CCTG[f]	7.7	2.8	0.37 ± 0.14	. . .
	MHT[g]	9.6	1.7	. . .	0.47 ± 0.06
Summer	SF_6[d]	4.1	2.3	0.17 ± 0.07	0.13 ± 0.05
	PFT[e]	4.1	2.3	0.16 ± 0.15	0.11 ± 0.11
	CCTG[f]	2.7	1.4	0.20 ± 0.08	. . .
	MHT[g]	4.1	2.3	. . .	0.14 ± 0.04
Winter	SF_6[d]	24.9	1.3	0.66 ± 0.14	0.49 ± 0.13
	PFT[e]	24.9	1.3	0.75 ± 0.71	0.54 ± 0.51
	CCTG[f]	12.9	1.2	0.57 ± 0.13	. . .
	MHT[g]	21.1	4.6	. . .	0.32 ± 0.04

[a] SF_6 and PFT measurements performed concurrently; summer PFT and halocarbon measurements concurrent; other measurements not concurrent.

[b] CCTG: Constant concentration tracer gas; MHT: multiple halocarbon tracers.

[c] Average over measurement period.

[d] Integrated average ± standard deviation of hourly measurements for 7-day period.

[e] Seven-day sample [standard deviation based on predicated source (10%) and sampling (5%) errors].

[f] Integrated average ± standard deviation of hourly measurements for 5- to 7-day periods.

[g] Integrated average ± standard deviation of hourly measurements for 12-h (spring), 24-h (winter), and 7-day (summer) periods.

TABLE 3—*Infiltration rates of the upstairs and downstairs of the GEOMET research houses measured with constant concentration and constant release methods.*

Season	Measurement Method	WS, m/s[a]	ΔT, °C	Air Infiltration Rate, ACH				
				Control House		Experimental House		
				Upstairs	Downstairs	ΔT, °C	Upstairs	Downstairs
Spring	CCTG	2.8	7.7	0.15	0.72	. . .	. . .	. . .
	PFT	1.2	14.2	0.23	1.0	14.2	0.18	0.62
	MHT	1.7	. . .	. . .	. . .	9.6	0.22	0.93
Summer	CCTG	1.4	2.7	0.10	0.39	. . .	. . .	. . .
	PFT	2.3	4.1	0.06	0.35	4.1	0.10	0.14
	MHT	2.3	. . .	. . .	. . .	4.1	0.07	0.27
Winter	CCTG	1.2	12.9	0.18	1.18	. . .	. . .	. . .
	PFT	1.3	24.9	0.24	1.69	24.9	0.32	0.96
	MHT	4.6	. . .	. . .	. . .	21.1	0.10	0.73

[a] Average over measurement period.

measurement periods. Additional concurrent measurements are required, however, to quantitatively relate the magnitude of the differences to ΔT and windspeed.

The comparability of the CCTG and PFT data is supported by the relative difference between downstairs and upstairs infiltration rates measured by the two methods. During the winter, for example, the downstairs infiltration rate measured with the CCTG method was 6.6 times higher than the upstairs rate. With the PFT system, the downstairs/upstairs ratio was 7.0. Similarly, downstairs/upstairs ratios of 4.8 and 4.3 were observed during spring with the CCTG and PFT methods, respectively. This indicates good agreement in measuring the relative differences between downstairs and upstairs rates. Concurrent testing, however, is required to quantitate any systematic differences.

A valid comparison of the MHT and PFT methods for measurement of upstairs and downstairs infiltration rates could be achieved only for the summer period when the two methods were used concurrently; during spring and winter, the MHT method was used for limited periods only. During the summer, the MHT and PFT methods yielded measurements that differed by 0.03 ACH upstairs, but the downstairs rate for the week measured with the PFT method was nearly half that of the MHT measurement. PFT measurements during the spring were lower than MHT measurements both upstairs and downstairs, which was contrary to model predictions based on ΔT and windspeed. The differences during winter were larger than predicted by ΔT and windspeed. Reasons for the differences between the two methods, which ranged from 20 to 90%, and the inconsistent results in these tests, will be the subject of further testing at the houses.

All three systems tested in this study can be used for measurements in more than two zones. The CCTG system was configured in these tests to measure six zones in the GEOMET research house, but can be configured for up to ten zones. The variability of room-specific air infiltration rates was measured during all three seasons under a range of indoor and outdoor conditions. Examples of results with these measurements include:

1. Infiltration rates in the five upstairs rooms rarely exceeded 0.2 ACH during summer.
2. During winter, air infiltration rates of upstairs rooms ranged from 0.05 to 0.9 ACH.
3. Even during winter, infiltration rates in the upstairs kitchen, living room, and dining area did not exceed 0.4 ACH, and, generally, were less than 0.2 ACH.
4. Average week-long infiltration rates of the individual upstairs rooms varied substantially during the winter, but were similar during summer.

The BNL PFT system currently features four different tracer gases. For this study, all four tracers were used to include both conditioned and unconditioned airspaces. One advantage of the passive PFT system lies in the extended monitoring periods which allow measurement of the wide range of air change rates and interzonal airflow rates that can occur in unconditioned airspaces. In this study infiltration rates of the attic, garage, upstairs, and downstairs were measured. Week-long average infiltration rates of the attics of the GEOMET research houses ranged from 6.6 to 15 ACH in these tests; the rates were not substantially different during the three seasons [7]. The air infiltration rates of the integral garages were quite low. During summer, infiltration rates were less than 0.3 ACH. Even in January, when the average outdoor temperature was −8°C, the infiltration rates were only 1.18 and 0.84 for the garages of the control and experimental houses, respectively.

In this study, the MHT method was used only for measurements in the upstairs and downstairs. However, like the CCTG and PFT methods, the MHT method can be extended to measure three or more zones, the number of zones being limited only by the number of tracers that can be practically separated and quantified by the analytical system.

Interzonal Airflow Measurements

Interzonal airflows in the GEOMET research houses were measured with the PFT and MHT methods. The primary objective of the PFT measurements was to measure average airflow rates between conditioned and unconditioned airspaces. The objective of the MHT measurements was to obtain more detailed information on short-term variations in airflows between the upstairs and downstairs.

Measurements conducted with the MHT method during winter and spring were made while the MHT system was being developed. Therefore, PFT measurements were not made concurrently. During the summer, both MHT and the PFT methods were used concurrently over a one-week measurement period. Hourly MHT measurements were integrated over the one-week period for comparison to the PFT measurement. A comparison of the measurement results for the one-week period is depicted in Fig. 2.

Measurements with the PFTs over the week-long summer period yielded average net airflows of 7.2 m^3/h into the downstairs and 7.2 m^3/h out of the upstairs (Fig. 2). Hourly MHT measurements integrated over the same period yielded net airflows of 6.4 m^3/h into the downstairs and 6.3 m^3/h from the upstairs to outdoors. The net airflow from the downstairs to the upstairs was 7.1 m^3/h with the PFTs versus 6.3 m^3/h with the MHT method. The difference between the two measurement methods for measurements of net airflow rates was less than 15%, well within the predicted measurement error for either method.

Although average week-long interzonal airflows measured by the two methods were quite similar, short-term interzonal airflow rates, as measured by the MHT method, varied substantially during the period. Figure 3 depicts hourly airflow rates between the upstairs and downstairs during the measurement period. As shown in the figure, hourly airflow rates ranged from near zero to over 400 m^3/h. At certain times during the measurement period, hourly average airflow rates were more than an order of magnitude higher than the average week-long rates measured with the PFT method. Periods of high airflow rates were clearly related to the percent of time that the central air conditioner was operating each hour, illustrating the utility of the MHT method for measurements of temporal variations in airflow rates between the two conditioned zones.

PFTs were used to measure airflow rates between the attic, garage, upstairs, and downstairs. Examples of PFT results include:

1. Airflows from the conditioned airspaces into the garage were low (less than 6 m^3/h in all tests).
2. Airflows from the garage into the downstairs were significant, being as high as 67 m^3/h for the control house during winter.
3. Airflow rates from the garage into the downstairs of the experimental house, retrofitted for tightness, were nearly 60% lower than in the control house.
4. Average week-long airflow rates from the upstairs to the attic ranged from 15 to 70 m^3/h in the experimental house and from 19 to 168 m^3/h in the control house during the three measurement periods.
5. Average airflows from the attic to the upstairs ranged from 12 to 53 m^3/h in the control house and ranged from 1 to 57 m^3/h in the experimental house.
6. PFT measurements of interzonal airflow rates clearly demonstrated the effectiveness of house-tightening retrofit procedures to reduce airflows to the unconditioned airspaces.

Advantages and Limitations of the Methods

The selection of a method for measuring air change and interzonal airflow rates depends on many factors. Each method has specific applications, advantages, limitations, and costs that must be considered. Some of these factors are summarized in Table 4 for the four measurement systems used in this study.

The primary consideration in selection of the measurement method is the objective of the study. A clear distinction can be made between methods for measurements of air infiltration rates or interzonal airflow rates. Although all three basic methods—tracer di-

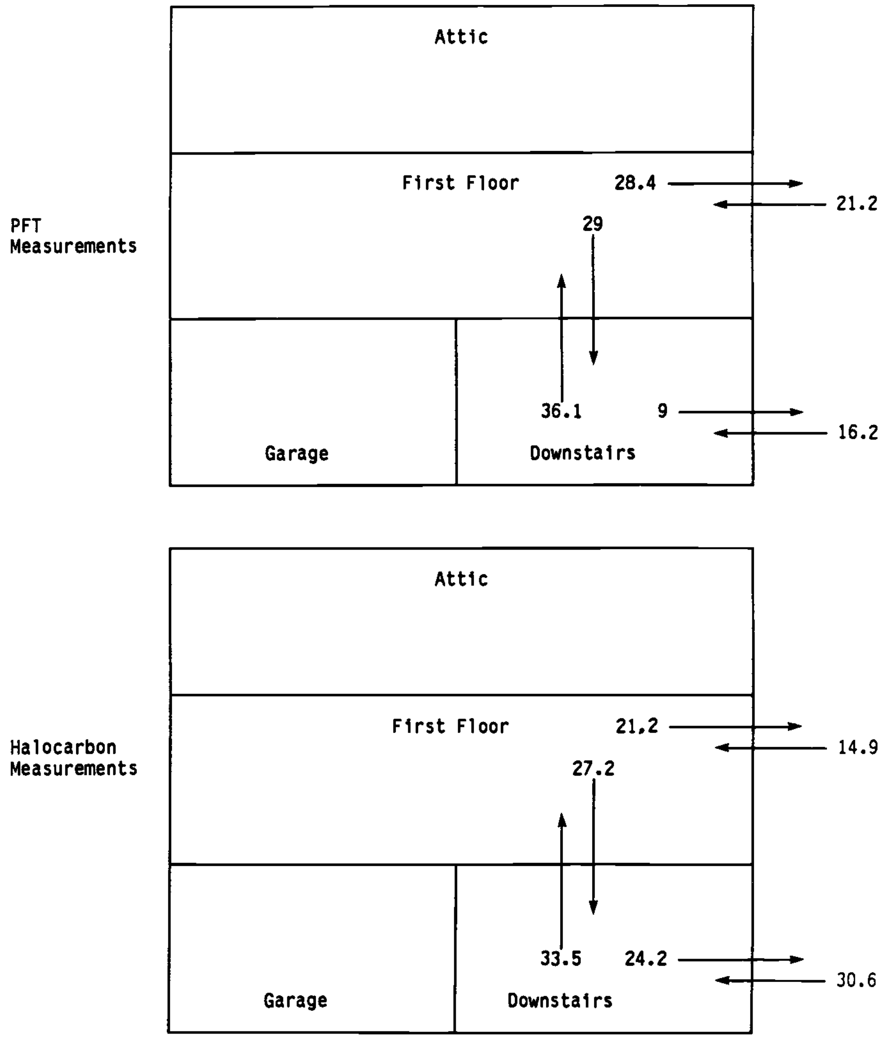

FIG. 2—*Comparison of PFT and halocarbon measurement results for a week-long period in June (rates in* m^3/h*).*

lution, constant concentration, and constant release—can be used for measurement of either parameter, simultaneous measurements of interzonal airflow rates require the use of multiple tracer gases.

For measurements of air change rates in a single zone, the SF_6 dilution method and the passive PFT method with a single tracer are the most attractive methods. Both the release and sampling methods are relatively easy to use in field monitoring programs. Samples can be collected in the field and returned to the laboratory, precluding the requirement for expensive and complex analytical systems at the measurement site. User costs, therefore, are relatively low. The two methods provide complementary information; PFTs provide long-term average measurements, while SF_6 measurements yield short-term data that can be related to specific outdoor conditions or activities in the home that may impact air change

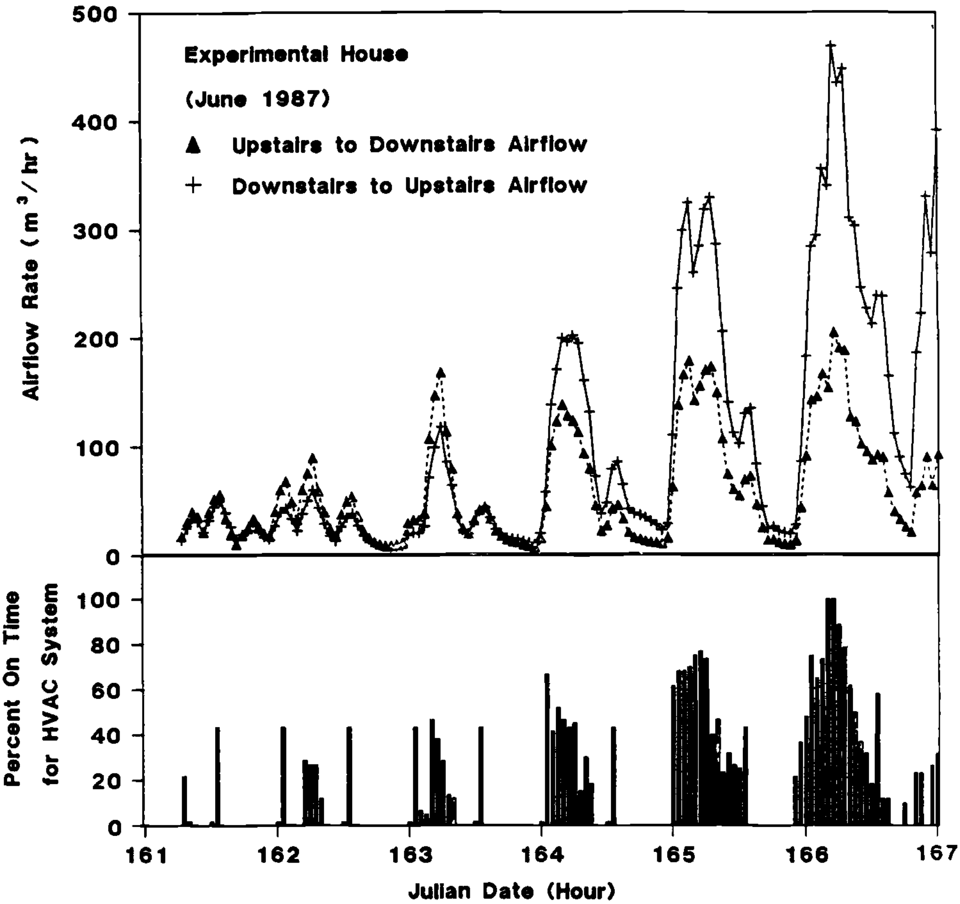

FIG. 3—*Interzonal airflow rates in the experimental house during air conditioner operation, June 1987.*

rates. Results of the tests in this study showed good agreement between the SF_6 dilution and PFT measurements for long-term (week) measurements.

Constant-concentration methods with a single tracer can provide highly detailed data on room- or zone-specific air infiltration rates. Because measurements can be performed in up to ten zones, the method can provide a higher level of spatial detail than can be obtained with the four perfluorocarbon tracers. The CCTG system, however, requires a large investment of labor and resources to configure the release and sampling system in a structure. The system is generally only practical for longer-term sampling. Capital costs for the system are substantially higher than for the SF_6 dilution system and somewhat higher than the halocarbon system.

Results of tests at the GEOMET research houses demonstrated the applicability of the PFTs for measurements in both unconditioned and conditioned airspaces. The PFT method is easy to use and relatively inexpensive for conducting long-term integrated measurements. The multiple tracer halocarbon method, with a GC-ECD analytical system, provides a higher level of temporal resolution, but is not as applicable to simultaneous measurements in both conditioned and unconditioned zones because the ECD detector does not have a sufficiently wide analytical range to accommodate the large differences in tracer gas concentrations.

TABLE 4—*Comparison of factors related to the selection of methods for air infiltration and interzonal airflow measurements.*

	Method			
Factor	SF_6 Dilution	Constant Concentration (SF_6)	Perfluorocarbon Tracers	Halocarbon Tracers
Release method	Periodic release	Automated periodic release	Constant (passive)	Constant (active)
Sampling method	Active (pump)	Active (pump)	Passive	Active (pump)
Number of zones	1	Up to 10	Up to 4	2 to 4[a]
Type of measurement	Infiltration	Infiltration	Infiltration/interzonal	Infiltration/interzonal
Type of output	Short-term	Short-term	Long-term	Short-term
Application for large field studies	Applicable	Limited	Applicable	Limited
Capital equipment costs[b]	<$10 K[b]	$10–20 K	$10–20 K	$10–15 K
User equipment required	Release/sampling system	Fully automated system	Passive sources and samplers	Release/sampling/analytical system
Relative user cost	Low	Moderate	Moderate	Moderate
Ease of use	Easy	Complex	Easy	Complex

[a]Number of zones depends on the configuration of the analytical system for separation of multiple tracers on a single column (two to four zones easily implemented).

[b]K: dollars in thousands; estimated costs for release, sampling, and analytical systems.

The dynamic range of analysis, however, could be extended by use of the less-specific flame ionization detector. For measurements within the conditioned zones, the MHT method was applicable.

Conclusions

Tests at the GEOMET research houses demonstrated that all four measurement methods provided comparable results for single-zone (whole-house) air change rates. The CCTG, PFT, and MHT methods, however, also provided more detailed information on zone-specific air infiltration rates. All three methods showed that downstairs infiltration rates were substantially higher than upstairs. The CCTG system also provided detailed spatial information for individual upstairs rooms.

PFT measurements in both unconditioned and conditioned airspaces demonstrated the effectiveness of house-tightening procedures to reduce airflows between the conditioned airspaces and unconditioned airspaces (the attic and integral garage). Concurrent PFT and MHT measurements in the conditioned airspaces provided comparable results for week-long rates of airflow between the upstairs and downstairs, but hourly rates during some periods, as measured with the halocarbon system, were as much as an order of magnitude higher than the weekly averages.

Acknowledgement

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Residential Airtightness

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Results of a Pre-Field Measurement Program Fan Pressurization Comparative Test

REFERENCE: Hadley, D. L., "**Results of a Pre-Field Measurement Program Fan Pressurization Comparative Test,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 121–131.

ABSTRACT: The Northwest Residential Infiltration Survey (NORIS) was a field study conducted in the Pacific Northwest to determine air leakage rates and infiltration characteristics of electrically heated, single-family, detached residences. Air leakage rates were measured using fan pressurization (blower door) techniques. The results of the blower door tests were used to estimate the natural building air infiltration rates.

A detailed set of measurement protocols based on the ASTM Standard Method for Determining Air Leakage Rate by Fan Pressurization Test (E 779–87) was developed prior to implementing the field testing. The measurement protocols were tested on two residences during a training workshop by five independent blower door testing technicians. The objectives of this workshop were: (*1*) to instruct the technicians on the specifics of the NORIS protocols in order to develop consistency in measurement among the technicians; (*2*) to evaluate the ability of the technicians and their respective blower doors to measure the leakage area of an orifice plate; and (*3*) to compare the results of depressurization and pressurization tests.

This paper will review briefly the field protocols used during the full field measurement program and present a detailed comparison of the results of the blower door tests conducted during the workshop.

KEY WORDS: NORIS field study, ventilation, blower door testing, training workshop

A detailed residential infiltration study, referred to as the Northwest Residential Infiltration Survey (NORIS), was conducted by Battelle, Pacific Northwest Laboratories (Battelle) to measure ventilation characteristics in electrically heated, single-family, detached residences in the Pacific Northwest region. Approximately 140 homes constructed since 1980 were studied during the 1987/1988 heating season, and another 50 homes constructed to new energy-efficient standards were tested during the 1988/1989 heating season. The sponsors for this program were the State of Idaho Department of Water Resources and the Bonneville Power Administration (BPA).

Two techniques were used for estimating infiltration and air leakage rates in each home: (*1*) a two- to three-week-long integrated perfluorocarbon tracer (PFT) release and capture measurement; and (*2*) a one-time fan pressurization (blower door) test. The Northwest region relies extensively on this type of information for establishing policy and program directions. A critical environmental issue confronting new energy-efficient homes is the effect that reduced levels of ventilation may have on indoor air quality and the subsequent health effects on the occupants. In addition, the measurement and evaluation of fresh air

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ventilation in homes is necessary for deciding the level of heat loss associated with the incidental infiltration of cool outside air into a dwelling (during the heating season) and for determining the necessary fuel requirements to bring that air to an appropriate temperature.

A previous study of over 200 new residences in the Northwest [*1*] indicated that the PFT-derived air changes per hour (ACH) differed significantly from the ACH estimated from the blower door test results. These results raised concerns about the state of knowledge on fresh air ventilation rates in homes and the techniques for estimating those rates. As a result, a second, more rigorously controlled field measurement program (NORIS) was designed to reduce the uncertainties in the data and to avoid the problems that plagued the initial study. All aspects of the new program were governed by a set of strict project protocols and data quality control procedures. A Project Oversight Committee (POC) was set up to provide focus and guidance to the research effort as well as to review interim results. Members of the POC consisted of nationally recognized experts in building infiltration measurement.

The PFT placement/recovery protocols were developed by Battelle. The blower door test procedures were based on the ASTM Standard Method for Determining Air Leakage Rate by Fan Pressurization Test (E 779-87). However, certain deviations from this standard were incorporated in the final NORIS protocols at the recommendation of the POC, principally because of the number of homes to be tested and the inclusion of PFT measurements in this study. Generally, the requirements were as stringent as those in ASTM E 779-87.

The actual field work was directed by Battelle, but performed by five subcontractors, representing some of the most experienced blower door technicians in the region. In the fall of 1987, prior to the planned beginning of the field measurement program, the blower door technicians participated in a two-day training/testing workshop in Richland, Washington. The purpose of this workshop was twofold. First and foremost, the workshop's purpose was to familiarize the technicians with the NORIS field protocols; secondly, its purpose was to test the workability of the field protocols for both the PFT measurement component and the blower door testing before beginning the full-scale study.

The results of this workshop shed considerable light on the standard testing procedures routinely employed by blower door technicians and the resultant calculations of infiltration/ventilation. Some aspects of the protocols were modified, based on these results and on feedback from the technicians. It is the purpose of this paper to describe the results of that workshop, to present the results of the various blower door tests, and to share some of the insights gained from the experience. Although the workshop covered both the PFT and blower door test protocols, only the results of the latter are presented.

Field Protocols

The measurement protocols used in conducting the NORIS blower door test were based on ASTM E 779-87. Features of the standard that were of particular importance to NORIS were:

1. Acceptable test apparatus and the required accuracy of instrumentation (ASTM E 779-87, Section 6).
2. Preferred meteorological conditions (ASTM E 779-87, paragraph 8.12).
3. Procedures for preparation of the building envelope; and heating, ventilation, and air conditioning (HVAC) systems (ASTM E 779-87, paragraphs 8.1 and 8.2). Interconnecting doors were open and closet doors were closed. HVAC dampers and registers were not adjusted. Fireplace dampers were closed, but not sealed. Likewise, exhaust fans were not sealed unless they had a functioning damper.
4. Definition of the building volume for calculation of air change rates (ASTM E 779-87, paragraph 3.4). Interior volume was defined as conditioned space, generally excluding attics,

basements, and garages, unless the spaces are connected to the heating and air conditioning system.

5. Equations for the calculation of leakage area (ASTM E 779-87, Section 9). The assumed reference pressure for effective leakage area (ELA) calculation was 4 Pa.

Modifications and additions to ASTM E 779-87 that were incorporated into the NORIS protocols were:

1. Only blower door equipment manufactured by a recognized, reputable manufacturer was allowed. All blower doors used were of the orifice-flow measurement type.
2. Blower door tests were performed at times exceeding the preferred wind and temperature conditions.
3. Wind direction and indoor relative humidity were not measured, as they were not required in any calculation.
4. All flow data were corrected to standard conditions of 101.325 kPa and 293 K.
5. Blower door test acceptability was based on a correlation coefficient greater than 0.998 as determined by on-site data analysis. A correlation coefficient less than 0.998 on a specific blower door test required a second repeat test. No more than two tests were conducted.
6. Target test pressures ranged logarithmically from 12.5 to 60 Pa (0.06 to 0.234 in. water), rather than ranging linearly from 12.5 to 75 Pa, as recommended by the standard. The target pressures were only guidelines; the technician recorded the actual pressures attained at the time of the test. A minimum of eight flow data points were taken.
7. Both depressurization and pressurization tests were performed. A depressurization test was not done if there was a risk of entraining wood ashes into the home.
8. Duct work leakage was measured in homes with ducted heating systems (central forced air furnace or heat pump). All heat system registers and cold air returns were sealed, and a second depressurization test was performed. The leakage area attributable to the duct system was assumed to be the difference in leakage area measured with the ducts sealed and in their as-found condition.
9. A smoke stick was not used to determine leakage distribution in structure between the floor, wall, and ceiling. Instead, the four or five greatest leakage locations in the home were reported.
10. The zero-flow pressure differential across the building envelope induced by natural conditions was measured and recorded before beginning the blower door test. The pressure gages were not adjusted to compensate for this offset in the pressure readings. The blower door test was conducted regardless of the magnitude of the natural pressure differential.

Training Workshop

Each of the five blower door technicians selected for this program was an independent operator from different regions of the Pacific Northwest. It was expected that the routine procedures for conducting the blower door test would vary widely, potentially introducing a regional bias in the results. Therefore, a training workshop was held in Richland, Washington the last week in October 1987 before the start of the full-scale field measurement program in January 1988. The objectives of this workshop were: (*1*) to instruct the blower door technicians on the specifics of the NORIS protocols in order to standardize procedures and achieve comparability of measurement results; (*2*) to evaluate the ability of the technicians to measure the leakage area of an orifice plate; and (*3*) to compare the results of depressurization and pressurization tests. The workshop was not a tightly controlled experiment, and no attempt was made to make comparisons between or evaluate the performance of the specific blower door equipment represented.

The field measurement protocols were tested by each technician on the same two residences. The first test home was a 165-m^2 (1800-ft^2), split-entry, 1978 vintage home. The second home was a newly constructed energy-efficient, 280-m^2 (3000-ft^2) home with a partial basement, loft, and sunroom.

The workshop covered two days for each technician. The morning of the first day was devoted to a review of the NORIS project objectives and protocols and a discussion of the purpose, theory, and mechanics of conducting the field measurements. During the afternoon session the technician, under Battelle's close supervision, conducted a complete field test according to the NORIS protocols.

Each technician independently (but in frequent consultation with Battelle) derived four building parameters and determined on-site meteorological conditions. The building parameters that were required were building volume, leakage distribution, and the terrain and shielding classes. The building volume, leakage distribution, and the terrain and shielding classes are inputs to the infiltration model used to estimate the seasonal natural air change rate.

The measured airflow rates required correction for differences in the air density between the conditions at which the doors were calibrated (same as standard conditions for the door fans used in the project) and site conditions at the time of the test. If the results are reported at standard conditions, the corrected volumetric airflow is a function of the measured airflow rate and only the indoor and outdoor temperatures. However, if the results are to be reported at site conditions, the corrected flow rate is also a function of station barometric pressure. At the time of the workshop, it had not been determined if the airflow rates for the tests would be reported at site conditions or at reference conditions, so the station atmospheric pressure was obtained for each test day.

An orifice plate with a 0.20-m (8-in.) and a 0.30-m (12-in.)-diameter hole sealed in an open ground floor window was used to evaluate the response of the blower door equipment to a known incremental change in leakage area. Both a depressurization and a pressurization test was conducted for each orifice plate configuration.

During the second day, the technicians conducted the complete field test on the second test home without supervision.

Results

Building Parameters and Site Meteorological Conditions

For each test home, the technicians determined four building parameters (volume, terrain class, shielding class, and leakage distribution) and site meteorological conditions. The values for these parameters as determined by each technician are shown in Table 1 and Table 2. Not unexpectedly, the five technicians arrived at markedly different values for the building parameters for the test homes. In some instances (see description below) the technicians used default values established in their respective computer software provided with the blower door equipment.

Accurate volume measurement turned out to be the most difficult and time-consuming parameter to derive, particularly for the larger, more complex second home. The first two technicians averaged more than 3 h to complete this task. It was then decided that, in order to expedite the process and minimize the actual time in the home, the building volume was provided to the last three technicians. The measured building volume for the first home ranged from 380 to 435 m^3, a range of 55 m^3. During a post-workshop debriefing, the technicians agreed that the error in determining the building volume would be 5 to 10%.

The second, most difficult, parameter to obtain and probably the least understood, was the site barometric pressure. It is required only if airflows are to be corrected to any condition other than that at which the gages were calibrated (normally mean sea level pressure). This

TABLE 1—*Building parameters and site meteorological conditions obtained for test home No. 1.*

Parameter	Technician ID Number 1	2	3	4	5	Units
Volume	423	434	. . .[a]	380	435	m^3
Terrain class	. . .[a]	2	. . .[a]	. . .[a]	3	. . .[a]
Shielding class	. . .[a]	3	. . .[a]	. . .[a]	3	. . .[a]
Leakage distribution						
Ceiling	. . .[a]	0.25	. . .[a]	. . .[a]	0.30	. . .[a]
Floor	. . .[a]	0.50	. . .[a]	. . .[a]	0.30	. . .[a]
Walls	. . .[a]	0.25	. . .[a]	. . .[a]	0.30	. . .[a]
Site barometric pressure	101.60	93.13	. . .[a]	102.10	101.33	kPa
Indoor temperature	21	21	. . .[a]	21	22	°C
Outdoor temperature	14	16	. . .[a]	21	18	°C
Wind speed	0	0	. . .[a]	0	2	mps

[a]Parameter not obtained.

parameter is the atmospheric pressure at the elevation of the residence, but is frequently confused with the routinely reported sea level pressure. As a matter of practice, this information is obtained by contacting the nearest National Weather Service Station (NWS) or Federal Aviation Administration (FAA) facility on the day of testing (assuming there is no significant difference in elevation between the NWS office and the residence). However, because of inappropriately used terminology, three of the five technicians used sea level pressure [varying between 101.325 kPa (29.92 in.) and 102.104 kPa (30.15 in.), depending on the day of the testing] while one technician used a default value of 93.130 kPa (27.50 in.), normal pressure for an elevation of approximately 600 m (2000 ft). Only one technician obtained the correct site pressure (98.95 kPa).

Determination of the indoor and outdoor temperature at the time of testing was straightforward and did not present any problem to the technicians. The outdoor temperature was measured once during the time the blower door was being set up. Indoor temperature was an average of several one-time spot measurements taken in various rooms in the house.

A direct measurement of on-site wind speed during the time of the blower door testing was not made and is not feasible during routine blower door testing. The wind speed was estimated by visual observation of the drift of smoke from nearby chimneys, motion of tree branches, etc. and relied principally on the experience of the technician. Since the wind speed parameter was to be used only for subjective interpretation of the results and not in any subsequent calculations, accurate measurement was not critical.

None of the technicians were accustomed to determining site-specific estimates of the terrain and shielding classes and the leakage distribution. Either no value was reported or it was a default value established in the computer software provided with the blower door equipment.

Leakage Area Determination

The results for each blower door test are summarized in Tables 3 through 7. All airflows have been corrected to a standard condition of 293 K and 101.325 kPa. The same building volume was used in the calculation of the air change rate at a pressure differential of 50 Pa (ACH-50) for each test conducted on a particular building. For the first test home, the response of each blower door to a known incremental change in leakage area was tested. An orifice plate with 0.20- and 0.30-m-diameter holes, with a cross-sectional area of 0.032 m^2 and 0.073 m^2, respectively, was installed in a lower level window. Both a depressurization

TABLE 2—*Building parameters and site meteorological conditions obtained for test home No. 2.*

Parameter	Technician ID No. 1	2	3	4	5	Units
Volume	823[a]	823	823[a]	823[a]	711	m³
Terrain class	. . .[b]	2	. . .[b]	. . .[b]	3	. . .[b]
Shielding class	. . .[b]	3	. . .[b]	. . .[b]	2	. . .[b]
Leakage distribution						
Ceiling	. . .[b]	0.25	. . .[b]	0.30	0.30	. . .[b]
Floor	. . .[b]	0.50	. . .[b]	0.30	0.30	. . .[b]
Walls	. . .[b]	0.25	. . .[b]	0.30	0.30	. . .[b]
Site barometric pressure	101.60	98.95	101.33	101.63	101.33	kPa
Indoor temperature	21	21	21	21	22	°C
Outdoor temperature	14	11	14	21	13	°C
Wind speed	0	0	0	0	2	mps

[a]Volume supplied to technician by Battelle.
[b]Parameter not obtained.

TABLE 3—*Blower door test results for test home No. 1 with the orifice plate openings sealed.*

ID[a]	Test[b]	n[c]	C[d]	r[e]	v[f]	ELA[g]	ACH-50[h]
1	*d*	0.658	0.057	0.999	1.029	0.053	6.0
2	*d*	0.580	0.107	0.999	1.036	0.090	8.3
3	*d*	. . .	. . .	. . .	. . .	. . .	. . .
4	*d*	0.604	0.105	1.000	1.024	0.092	8.9
5	*d*	0.574	0.115	0.999	1.021	0.096	8.7
1	*p*	0.676	0.057	1.000	1.012	0.055	6.5
2	*p*	0.575	0.118	0.998	1.045	0.099	9.0
3	*p*	. . .	. . .	. . .	. . .	. . .	. . .
4	*p*	0.562	0.137	0.995	1.073	0.113	9.9
5	*p*	0.592	0.113	1.000	1.011	0.097	9.2

[a]ID = technician identification number.
[b]Test indicates test type where d = depressurization, and p = pressurization.
[c]n = exponent of the least squares regression on flow and Δ pressure.
[d]C = coefficient of the least squares regression on flow and Δ pressure.
[e]r = correlation.
[f]v = estimate of the variance around the regression line at a pressure differential of 4 Pa.
[g]ELA = effective leakage area, m².
[h]ACH-50 = air change rate at a pressure differential of 50 Pa in air changes per hour.

and a pressurization test were completed for each of three orifice plate configurations: (*1*) no holes open, (*2*) 0.20-m hole open, and (*3*) 0.30-m hole open. The results are shown in Tables 2, 3, and 4. No useful data were obtained by technician No. 3 due to equipment malfunction not detected until after the testing was completed. The calculated effective leakage area (ELA) for technicians Nos. 2, 4, and 5 are reasonably consistent and within an acceptable range. For some inexplicable reason, the ELAs for technician No. 1 were significantly and consistently lower than the ELAs of the other three technicians. The cause of this was explored at length with the technician after the workshop was completed, but no satisfactory explanation for the problem could be identified. The problem did not occur on the second test home.

The results of the blower door tests on the second test home are summarized in Table 6. The mean ELA for the five depressurization tests was 0.110 m² with a standard deviation

TABLE 4—*Blower door test results for test home No. 1 with the 0.2-m-diameter hole open.*

ID[a]	Test[b]	n[c]	C[d]	r[e]	v[f]	ELA[g]	ACH-50[h]
1	*d*	0.564	0.101	0.998	1.036	0.083	7.3
2	*d*	0.571	0.129	1.000	1.009	0.108	9.7
3	*d*	...	...	...	...	...	...
4	*d*	0.523	0.166	0.997	1.049	0.129	10.3
5	*d*	0.584	0.131	0.999	1.023	0.111	10.3
1	*p*	0.635	0.081	0.998	1.043	0.074	7.8
2	*p*	0.572	0.139	1.000	1.004	0.116	10.4
3	*p*	...	...	...	...	...	...
4	*p*	0.498	0.201	0.998	1.042	0.151	11.3
5	*p*	0.582	0.137	1.000	1.016	0.116	10.7

[a]ID = technician identification number.
[b]Test indicates test type where d = depressurization, and p = pressurization.
[c]n = exponent of the least squares regression on flow and Δ pressure.
[d]C = coefficient of the least squares regression on flow and Δ pressure.
[e]r = correlation.
[f]v = estimate of the variance around the regression line at a pressure differential of 4 Pa.
[g]ELA = effective leak area, m^2.
[h]ACH-50 = air change rate at a pressure differential of 50 Pa in air changes per hour.

TABLE 5—*Blower door test results for test home No. 1 with the 0.3-m-diameter hole open.*

ID[a]	Test[b]	n[c]	C[d]	r[e]	v[f]	ELA[g]	ACH-50[h]
1	*d*	0.546	0.133	0.992	1.084	0.107	9.0
2	*d*	...	...	...	...	...	...
3	*d*	...	...	...	...	...	...
4	*d*	0.511	0.204	0.999	1.026	0.156	12.1
5	*d*	0.578	0.156	1.000	1.018	0.131	12.0
1	*p*	0.563	0.128	1.000	1.019	0.106	9.3
2	*p*	0.641	0.140	0.999	1.025	0.129	13.8
3	*p*	...	...	...	...	...	...
4	*p*	0.502	0.225	0.999	1.029	0.171	12.9
5	*p*	0.569	0.167	1.000	1.012	0.139	12.4

[a]ID = technician identification number.
[b]Test indicates test type where d = depressurization, and p = pressurization.
[c]n = exponent of the least squares regression on flow and Δ pressure.
[d]C = coefficient of the least squares regression on flow and Δ pressure.
[e]r = correlation.
[f]v = estimate of the variance around the regression line at a pressure differential of 4 Pa.
[g]ELA = effective leak area, m^2.
[h]ACH-50 = air change rate at a pressure differential of 50 Pa in air changes per hour.

of 0.010 m^2. The mean and standard deviation of the ELAs for the five pressurization tests was 0.121 and 0.023 m^2, respectively. Again, the results are consistent and within an acceptable range, except for the results from technician No. 4.

The ELAs determined from the pressurization tests for technician No. 4 for both test homes were significantly and consistently higher than for the other technicians. At the time of the workshop this was not recognized. Only after an examination of the results from the full NORIS field testing was it determined that this was a significant systematic error and not a random phenomena. Extensive testing of his blower door at the conclusion of the field program did not reveal a source of the problem, and only reinforced the fact that there was

TABLE 6—*Blower door test results for test home No. 2.*

ID[a]	Test[b]	n[c]	C[d]	r[e]	v[f]	ELA[g]	ACH-50[h]
1	*d*	0.682	0.100	0.999	1.027	0.098	6.3
2	*d*	0.699	0.105	1.000	1.023	0.105	7.1
3	*d*	0.645	0.118	0.999	1.029	0.109	6.4
4	*d*	0.589	0.147	0.999	1.030	0.126	6.5
5	*d*	0.635	0.121	0.999	1.031	0.111	6.4
1	*p*	0.644	0.120	0.998	1.041	0.111	6.5
2	*p*	0.746	0.099	0.999	1.037	0.105	8.0
3	*p*	0.768	0.094	0.998	1.058	0.103	8.3
4	*p*	0.531	0.202	1.000	1.006	0.159	7.0
5	*p*	0.628	0.139	0.999	1.021	0.126	7.1

[a]ID = technician identification number.
[b]Test indicates test type where d = depressurization, and p = pressurization.
[c]n = exponent of the least squares regression on flow and Δ pressure.
[d]C = coefficient of the least squares regression on flow and Δ pressure.
[e]r = correlation.
[f]v = estimate of the variance around the regression line at a pressure differential of 4 Pa.
[g]ELA = effective leak area, m^2.
[h]ACH-50 = air change rate at a pressure differential of 50 Pa in air changes per hour.

TABLE 7—*Change in ELA (m^2) in response to a fixed incremental change in the leakage area for test home No. 1. The value in parentheses is the ratio of ΔELA to the known area of the fixed opening.*

	Depressurization		Pressurization	
ID	ΔELA, 0.032 m^2 hole	ΔELA, 0.073 m^2 hole	ΔELA, 0.032 m^2 hole	ΔELA, 0.073 m^2 hole
1	0.030 (0.94)	0.054 (0.74)	0.019 (0.59)	0.051 (0.70)
2	0.018 (0.56)	...	0.017 (0.53)	0.030 (0.41)
3	...	...	...	...
4	0.037 (1.16)	0.064 (0.88)	0.038 (1.19)	0.058 (0.79)
5	0.015 (0.47)	0.035 (0.48)	0.019 (0.59)	0.042 (0.58)

something systematically wrong in the way the blower door was performing in the pressurization mode.

In Table 7, a comparison is made between the actual incremental increase in leakage area for each configuration and the change in ELA derived from the blower door tests. For each technician there is general consistency in the measurement of the leakage area, but there were significant differences among technicians. The ratio of the change in ELA to the actual incremental change in leakage area for the 0.20-m hole ranged from 0.46 to 1.14 for the depressurization test, and from 0.52 to 1.17 for the pressurization test. For the 0.30-m hole, the ratio ranged from 0.48 to 0.88 and 0.41 to 0.80 for the depressurization and pressurization tests, respectively.

Depressurization versus Pressurization Tests

The NORIS protocols specified the completion of both a depressurization and a pressurization test. This workshop presented an opportunity to make an initial direct comparison of results of the two types of tests. For each experiment conducted, the technicians completed both a depressurization and a pressurization measurement, resulting in 16 and 17 tests, respectively. The average ELA for the depressurization test was 0.107 m^2 with a standard deviation of 0.023. For the pressurization, the average ELA was 0.117 m^2, with a standard deviation of 0.029. Although in 14 of the 16 pairs of tests, the ELA for the pressurization test was greater than the depressurization, the difference is not statistically significant at the 95% confidence interval.

The average ratio of the pressurization ELA to the depressurization ELA for each of the technicians for each test conducted is shown in Table 8. This ratio averaged 1.064 over both houses tested and ranged up to 1.23 on the first test home (technician No. 4) and up to 1.14 on the second home (technician No. 5).

Conclusions

This training workshop, conducted well in advance of the start of the NORIS field measurement program, was invaluable and contributed significantly to the overall success of the program. Based on the results of the workshop, revisions were made to the field protocols and supporting documentation. These changes were intended to fine-tune the protocols and make the field data collection process more efficient. Specific modifications to the field data collection procedures included:

1. Numerous field document forms were clarified and revised.
2. The order in which some of the work was performed was altered at the suggestion of the blower door technicians.
3. The procedure for obtaining site barometric pressure was modified so that this information would be obtained by Battelle.
4. The requirement for determining the leakage distribution was dropped from the protocol in favor of identifying the top four or five leakage locations in the residence. This information was to be used later to estimate the actual leakage distribution for each residence.

Extensive modification to the protocols were made before the start of the second heating season field data collection based on the results of the first heating season data. These changes were designed to make the measurement results more reliable and repeatable.

In addition, the following observations are worth noting:

1. For several of the technicians, this workshop was their first introduction to the derivation of some of the site-specific parameters that are used as input into the infiltration model, such as the terrain and shielding classes and the leakage distribution.
2. There was a general misunderstanding of the meaning and application of the site barometric pressure. The site pressure is only required if the airflows are to be determined for site conditions, instead of at standard conditions. If the calculations are to be made for

TABLE 8—*Ratio of ELA for the pressurization to the depressurization tests.*

	Test Home No. 1			
	Test Hole Size			
ID	0 m	0.2 m	0.3 m	Test Home No. 2
1	1.04	0.89	1.03	1.13
2	1.10	1.07	...	1.00
3	...	...	...	0.94
4	1.23	1.17	1.07	1.12
5	1.01	1.05	1.03	1.14

site conditions, the incorrect use of sea level pressure will lead to significant (>15%) overestimates of the leakage rates for site elevations above 600 m.

3. Most of the technicians used on NORIS normally do not perform a pressurization test for their other blower door work. As a result, some of the subtle differences in calculation of the ELA and ACH were not understood, such as the need to switch the indoor and outdoor temperature parameters to account for the reversed direction of air flow through the cracks in the building envelope.

Less tangible results were also derived from the workshop. Principally, this was the first face-to-face meeting between those of us at Battelle who would be directing the field work and those who would be doing the work. Prior contacts had been limited to either written correspondence or phone conversation. This workshop established a good working rapport between us that survived some of the more logistically difficult times encountered during the first year of field measurements.

Reference

[1] Bonneville Power Administration (BPA), "Draft Environmental Impact Statement on New Energy-Efficient Homes Programs—Assessing Indoor Air Quality Options," DOE/EIS-0127, Bonneville Power Administration, Portland, OR, 1987.

DISCUSSION

P. Lagus[1] *(written discussion)*—I'm concerned that by taping all vents and exhaust registers prior to attempting to measure duct leakage, you may in fact have enhanced the duct leakage, since the static pressure in the duct would increase after taping. Did you make any measurements of duct pressure to investigate this?

D. L. Hadley (author's closure)—We did not attempt to measure the duct pressure at any time. Our procedure for determining duct leakage was to first determine the whole house ELA with the heating system ducts in the "as found" condition. The heating system duct openings and return air grills were then sealed and the pressurization test repeated. The duct leakage was assumed to be the difference in the ELAs for the "as found" condition and the ducts' sealed condition.

J. T. Reardon[2] *(written discussion)*—(1) Were not weather data available by telephone from a nearby airport or radio/TV station? This could have been a substitute or complementary check of evaluations made by your contractors; (2) What procedure was followed to try to eliminate errors (bias) due to different contractors?

D. L. Hadley (author's closure)—(1) For the training session in Richland, Washington, the nearest reporting weather station was at Hanford, approximately 15 km northwest of the test homes. Data from this station were used as a verification of the conditions reported by the contractors as well as to establish the "correct" values in the final calculation of ELA. During the full study, we had available to us a report containing the 1 p.m. hourly observation of temperature, wind speed, and sea level barometric pressure for all of the reporting National Weather Service stations in the northwest region. This information was used to verify the reasonableness of the data collected onsite by the contractors. However, this data had to be used with caution as the weather station was frequently at a considerable distance

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[2]Institute for Research in Construction, National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6.

from the home being tested. It was not uncommon to have an elevation difference between the residence and the nearest NWS station exceeding 600 m (2000 ft). In these instances we had to rely on the data collected by the field contractors without verification.

(2) We attempted to eliminate the possibility of a procedural bias in the resultant data by developing a detailed set of field measurement protocols each of the contractors was to follow strictly in conducting field testing. These protocols specified the procedures to be followed in all aspects of their work. We were hopeful that by specifying exactly what needed to be done and how to do it, and then making sure that each of the contractors followed the procedures, the possibility of contractor bias would be eliminated. In the final analysis, the procedures were still not specific enough and there appears to be some contractor bias in the data. Fortunately, we conducted a debriefing of the contractors after the program concluded and were at least able to understand where and how the contractors deviated from the protocols.

Mark P. Modera[1] *and David J. Wilson*[2]

The Effects of Wind on Residential Building Leakage Measurements

REFERENCE: Modera, M. P. and Wilson, D. J., "**The Effects of Wind on Residential Building Leakage Measurements,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067*, M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 132–145.

ABSTRACT: Over the past ten years, the measurement of the airtightness of single-family building envelopes has made the transition from laboratory research tool to practitioner's (home energy auditor's) tool. Along with this transition have come ASTM and CGSB standards for fan pressurization measurements, and an ASHRAE standard for single-family building airtightness levels. Two major sources of uncertainty identified for fan pressurization measurements of effective leakage area (the air leakage parameter specified in the ASTM and ASHRAE standards) were the statistical uncertainty associated with extrapolating fan pressurization measurements down to 4 Pa and the individual flow and pressure uncertainties induced by the wind and by instrumentation inaccuracies. This report analyzes the effects of wind on fan pressurization measurements and describes a series of experiments performed to examine a methodology that combines two techniques for reducing these effects. The methodology for reducing the effects of wind on fan pressurization measurements, which employs four-surface pressure averaging and time averaging of pressure and flow data, is examined using multiple fan pressurization measurements at a single site. The results of these experiments are compared with a similar experimental examination of the standard ASTM procedure under calm conditions. It is shown that the combined surface-averaging/time-averaging technique has significantly lower scatter at calm conditions (3 versus 6.5%), and that the scatter remains below 11% up to a windspeed of 5 m/s. Another significant result is that surface pressure averaging always causes a negative bias in the leakage area measured at high windspeeds. Despite this bias, it is concluded that surface-pressure averaging generally should provide better leakage area measurements compared to using single-pressure-tap measurements.

KEY WORDS: air leakage, field measurement, measurement uncertainty, pressure measurement, residential buildings, wind

Over the past ten years the measurement of the airtightness of single-family building envelopes has made the transition from laboratory research tool to practitioner's (home energy auditor's) tool. Along with this transition have come an ASTM standard for fan pressurization measurements (Standard Test Method for Determining Air Leakage Rate by Fan Pressurization, ASTM E 779-87), a Canadian General Standards Board (CGSB) standard for fan pressurization measurements (Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method, Canadian General Standards Board, CAN/CGSB-149.10-M86), and an American Society of Heating, Refrigerating, and Airconditioning Engineers (ASHRAE) standard for single-family building airtightness levels [Air Tightness Requirements for Single-Family Detached Residential Buildings, ASHRAE Standard 119 (1989)]. During the development of these standards, numerous questions were raised concerning the accuracy of the fan pressurization technique. Some of the discussion

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points included: the best parameter to characterize leakage, the effects of wind and indoor-outdoor temperature differentials on measurements, the seasonal variation of leakage (that is, temperature and moisture-induced variations), the differences between pressurization and depressurization (due to asymmetric leaks and valve-like leaks), the appropriateness of the power-law model at low pressures, what (if any) vents to seal during a measurement (for example, chimneys, flues, bathroom vents, etc.), how to measure the fan flow rate, and how to make measurements repeatable. A number of these issues are addressed in the literature [*1,2*].

Excluding seasonal variations, the scatter in fan pressurization measurements of effective leakage area (ELA) (the air leakage parameter specified in the ASTM and ASHRAE standards) stems principally from flow and pressure uncertainties induced by the wind and by instrumentation inaccuracies, and from statistical uncertainty associated with extrapolating measurements down to 4 Pa. This report analyzes the effects of wind on fan pressurization measurements and describes a series of experiments performed to examine two techniques for reducing these effects.

Influence of Wind on Fan Pressurization Measurements

The wind-induced uncertainties in leakage determined by fan pressurization can be attributed to several physical mechanisms. Basically, the wind changes the measured flows and pressures associated with a fan pressurization measurement. These changes appear as both bias and scatter in the pressure-flow data used to characterize building leakage. A perfectly steady wind would create biases between the measured pressure differential and the actual pressure differential across the leaks in the envelope and the pressurization fan. A typical turbulent wind, in addition to creating these biases, also induces time variations in the pressures and flows measured over the course of a test. These time variations translate into scatter in the pressure-flow pairs and therefore into uncertainty in the ELA determined following the ASTM or CGSB standards.

The wind-induced differences between the measured pressure differential and the actual pressure differential across the envelope leaks stem from the perturbation of the free wind by the building structure. On upwind faces the static pressures are higher due to the stagnation of the wind velocity. The downwind and side faces of the building are subjected to lower static pressures by virtue of the fact that they are in separated or accelerated flow regions. For example, a pressure probe on the windward side would accurately measure the pressure drop across the windward side leaks, but would not be representative of the pressure drop across the other building leaks. This effect increases rapidly with windspeed, because surface-pressure variations scale with the square of the windspeed.

To reduce the errors due to this effect, the Canadian General Standards Board recommends that the pressures on four faces of the building be spatially and temporally averaged using a mixing box connected to each face through a capillary-tube resistance and flexible hosing (CAN/CGSB-149.10-M86). Although this technique should improve the accuracy, several inherent assumptions should be noted. First, the averaging of the four surface pressures essentially assumes that each is representative of one quarter of the leakage sites. Thus, a nonuniform distribution of leakage on the four faces, or more likely, significant leakage on the ceiling or floor of the building, might not be properly represented by the pressure average. Second, even if the box could provide an accurate leakage-weighted average pressure, the nonlinearity of envelope flow implies that the appropriate averaging of spatial pressure variations would have to take into account the nonlinear flow rate and the pressure difference across the leaks.

The effects of wind on fan flow measurements depends on both the type of pressure sensor and the type of blower door utilized. For any blower door that uses outdoor pressure for determining the flow, a pressure-averaging probe is inappropriate, as it measures the pressure difference across the envelope and not across the fan. Also, most blower doors operate at small pressure differentials, making them sensitive to pressure fluctuations resulting from wind turbulence, which in turn makes flow measurements sensitive to the operator's response to time-varying signals (which is exacerbated by any nonlinearity in the fan curve).

The effects of wind turbulence (windspeed and wind direction variations) on leakage measurements stem from both fluctuations in the measured flows and fluctuations in the measured pressure differentials. Because of these fluctuations, fan pressurization tests are performed at large indoor-outdoor pressure differentials, and the results extrapolated down to the low pressures typically driving air infiltration in buildings. From a statistical point of view, this extrapolation leads to large uncertainties in the low-pressure leakage [*2*]. In principle, these difficulties potentially can be reduced by using signal enhancement techniques to allow measurements at small pressure differentials.

The most common type of signal enhancement used to treat fluctuating signals is time averaging (or filtering). Time filtering of pressure and flow signals is one potential means to reduce pressure and flow scatter, although the type of filtering, the compatibility of pressure and flow filtering, and the limitations of filtering must be checked carefully. Time filtering is inherent in every piece of measurement equipment, although the type of filtering is often unknown to the user. For example, tubes leading to a pressure sensor physically filter out pressure fluctuations above a certain frequency. The capillary tubes on the CGSB averaging pressure sensor are specifically designed to give that device a 5s-time constant. This time constant corresponds to a single-pole low-pass filter that reduces the amplitude at 0.3 Hz by 90%. In general, electronic filtering of the pressure and flow signals, although potentially more expensive, is more versatile and well defined. It should be noted that due to the nonlinearity of the leaks and nonlinearities in fan curves, time filtering should be employed with caution. As for spatial pressure averaging, temporal averaging will cause a bias in the measured value which increases with the relative magnitude of the temporal fluctuations and the degree of nonlinearity.

Field Test of Time-Averaging and Pressure-Averaging Techniques

To examine the potential for reducing the effect of wind on fan pressurization measurements of air leakage, multiple fan-pressurization tests were performed in a single building under variable wind conditions. The test building used was one of six unoccupied test houses built in Edmonton, Canada to examine airflow and heat transfer processes in buildings [*3,4*]. These test houses, which have been monitored continuously since 1981, are located on an agricultural research farm about 10 km south of the city of Edmonton and are situated in a closely spaced east-west line with approximately 2.8 m separating their side walls. The flat, exposed site was surrounded by rural farmland, planted with forage and cereal crops in the summer, when the fan pressurization tests were performed. Wind speed and direction were measured with low-friction cup anemometers and vanes on 10-m weather towers located on the north and south sides of the row of houses. There is little difference between the upwind and downwind values; the two-tower system simply provided additional reliability.

The tests reported here were conducted in Test House 5, located with one house on its east side and four houses on the west. Like the other houses, it has exterior dimensions of 7.3 by 6.7 m. Test House 5 is a wood-frame bungalow with a 2.6-m-deep poured concrete basement and has a floor area of 46 m^2 (about one third to one half the size of a typical North American house). It has three windows and one door, nominal 2 by 4 in. (5 by 10 cm) insulated stud walls, interior painted drywall over a continuous 0.1-mm polyethelene vapor barrier, and exterior plywood sheathing. There are eight electrical-box penetrations in the walls and three light-fixture penetrations in the ceiling. There are no interior partition walls, and the basement and main floor are connected by a large open stairwell. Test House 5, typical of residential construction in Canada, is relatively airtight (specific leakage area = 2 cm^2/m^2 floor area) and is electrically heated, but has an unheated dummy flue (0.15 m inside diameter with 0.075-m-diameter restriction orifice and rain cap).

Edmonton Fan Pressurization System

An automated leakage measurement technique was used to make continuous fan pressurization leakage measurements in Test House 5. Controlled by a microprocessor, one complete leakage measurement was made every hour. Each hour the microprocessor cycled the system through a complete series of pressure and flow measurements at indoor-outdoor pressure differentials between 1 and 100 Pa. At each specified pressure differential, the computer directed the measurement system through a 100 to 110-s cycle. It first measured the indoor-outdoor pressure differential (pressure offset) for 15 s (140 points) with the blower-door fan off and sealed, then opened the motorized damper used to seal the blower-door outlet, turned on the fan (15 to 20 s delay), and measured the indoor-outdoor pressure difference and fan flow for 35 s (140 points each). There was then a 35 to 40 s delay (to turn off and seal the fan), after which the cycle was repeated at a new indoor-outdoor pressure differential. To mimic the ASTM standard test, the leakage data presented here use seven indoor-outdoor pressure differentials: 10, 20, 30, 40, 50, and 60 Pa, along with the average of the pressure offsets measured at the beginning and end of this series of points as the pressure offset for the entire test.

The fan used for pressurizing and depressurizing was a 0.46-m-diameter axial fan driven by a variable-speed d-c motor. The flow through the fan was determined by measuring the pressure differential across a laminar flow element through which all of the fan flow was drawn. The flow-metering element was calibrated using a standard ASHRAE pitot-tube traverse in a 0.46-m-diameter duct. At the lower end of the flow range, this pitot-tube traverse calibration was checked using a standard ASME orifice in a 0.15-m-diameter pipe. The results of the two calibrations were in good agreement, and combined errors from all measurement effects were usually about 1% and never more than 2%. During calibration, a downstream suction fan and outlet flow blockage were used to verify that fan loading had a negligible effect on flow rate measurement.

The procedure tested incorporated two techniques to reduce the effects of wind on the measurements, spatial averaging of pressure and time averaging of both flow and pressure, neither of which is included in the present ASTM standard. The first of these techniques simply involved the use of a modified version of the pressure-averaging outdoor pressure probe specified in the CGSB standard. The principal difference between the modified probe and the standard CGSB probe is that the modified probe should provide spatial averaging with very little time filtering, unlike the 5-s time constant of the capillary-tube restrictors used for the standard technique. The apparatus consisted of four pressure-tap hoses mounted midway along each wall of the building approximately 0.5 m above the ground. The four equal-length hoses were connected to a manifold to provide a spatial average. The indoor/outdoor pressure differential was measured with a high-resolution metal-diaphragm pressure transducer (Validyne DP103) with an accuracy of 0.1 Pa (calibrated with a micrometer-micropoint manometer) and a resolution of 0.01 Pa. The second half of the uncertainty-reduction technique utilized was to time-average all pressure and flow measurements, with 15-s averages for the pressure offsets and 35-s averages for the indoor-outdoor pressure differentials and fan flow. Time averaging the pressure and flow signals, as described above, filters out turbulence-induced fluctuations at all frequencies higher than one over the averaging time. Thus, excluding the nonlinearity of the leakage, only wind turbulence at frequencies lower than 0.03 Hz should affect the measurements. In contrast, the standard CGSB averaging probe nominally filters out frequencies above 0.3 Hz.

Field-Test Results

The results of experiments performed with the spatial/temporal averaging methodology in the Edmonton test house are presented in Figs. 1 to 6 for two different leakage configurations. Figure 1 shows a sample of the raw fan flow and pressure differential data and gives a feel for the scatter in the data at different windspeeds and pressure differentials. Figures 2 and 3 show the leakage area of the test house with its flue sealed, determined respectively from depressurization and pressurization data, as a function of the average windspeed during each measurement series. The scatter plots shown in Figs. 2 and 3 suggest that, below approximately 8 m/s, the measured leakage area remains unbiased with respect to windspeed. Above 8 m/s, the leakage area seems to decrease with increasing windspeed for the pressurization data (Fig. 3); however, the general scatter in the data is too large to conclude that there is a clear trend.

Figures 4 and 5 present scatter plots of measured leakage area versus average windspeed for the test house with its flue open. Comparing this data with that obtained with the flue closed (Figs. 2 and 3), two differences are apparent: the flue-open data has much higher

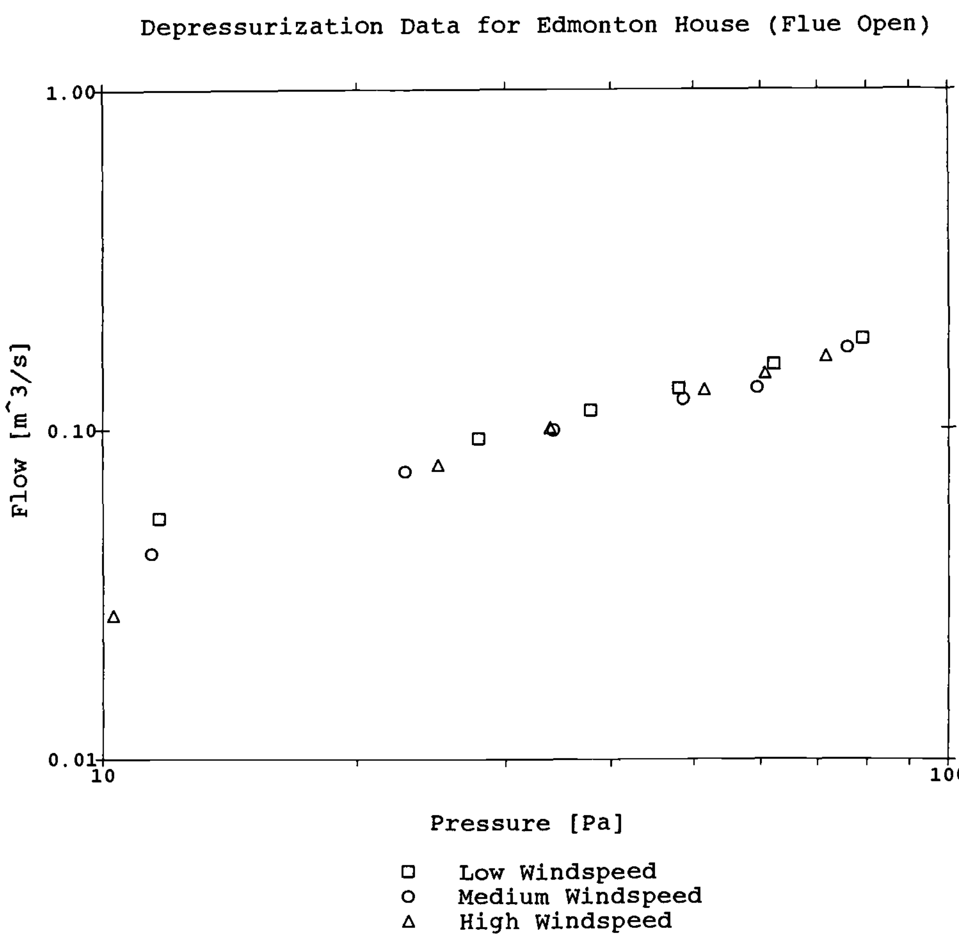

FIG. 1—*Typical sets of raw pressure and flow pairs obtained in the Edmonton house with the flue open for three windspeed levels (using spatial/time averaging method).*

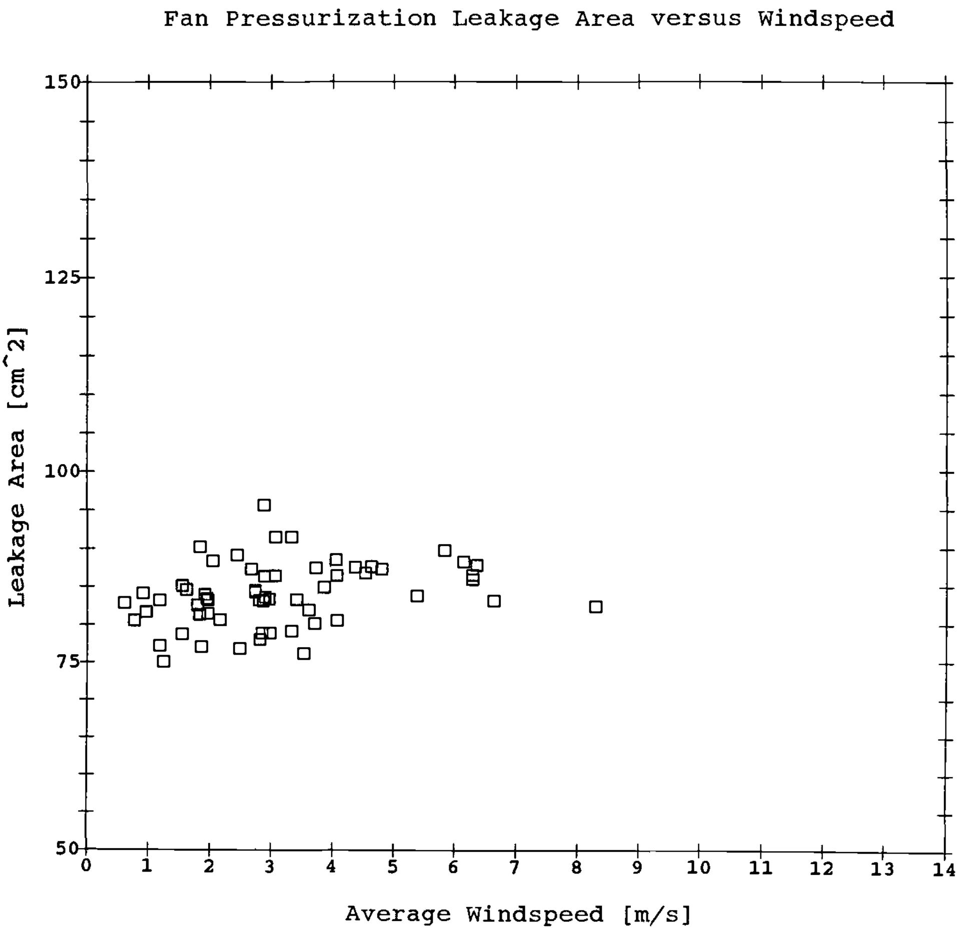

FIG. 2—*Measured effective leakage area versus windspeed for depressurization of Edmonton test house with flue sealed (using spatial/time averaging method).*

scatter, particularly at higher windspeeds; and the open-flue data seem to have a larger negative bias with respect to windspeed, which seems to begin at windspeeds lower than 8 m/s.

Figure 6 presents a summary of the scatter ($\sigma_x/\bar{x}$) in the leakage area measurements presented in Figs. 2 to 5. To construct Fig. 6, measurements were put into 2 m/s bins, for which the mean and standard deviation were computed. The results in Fig. 6 indicate that the scatter in the measured leakage area tends to increase with increasing windspeed and confirm the observation that the scatter is significantly higher when the flue is open. The results in Fig. 6 also indicate that the scatter in the leakage area remains below 11% for windspeeds lower than 5 m/s.

Berkeley Fan Pressurization Tests

Table 1 presents a comparison between the scatter of test-house leakage areas measured at the low windspeeds and similar data obtained in a laboratory building in Berkeley,

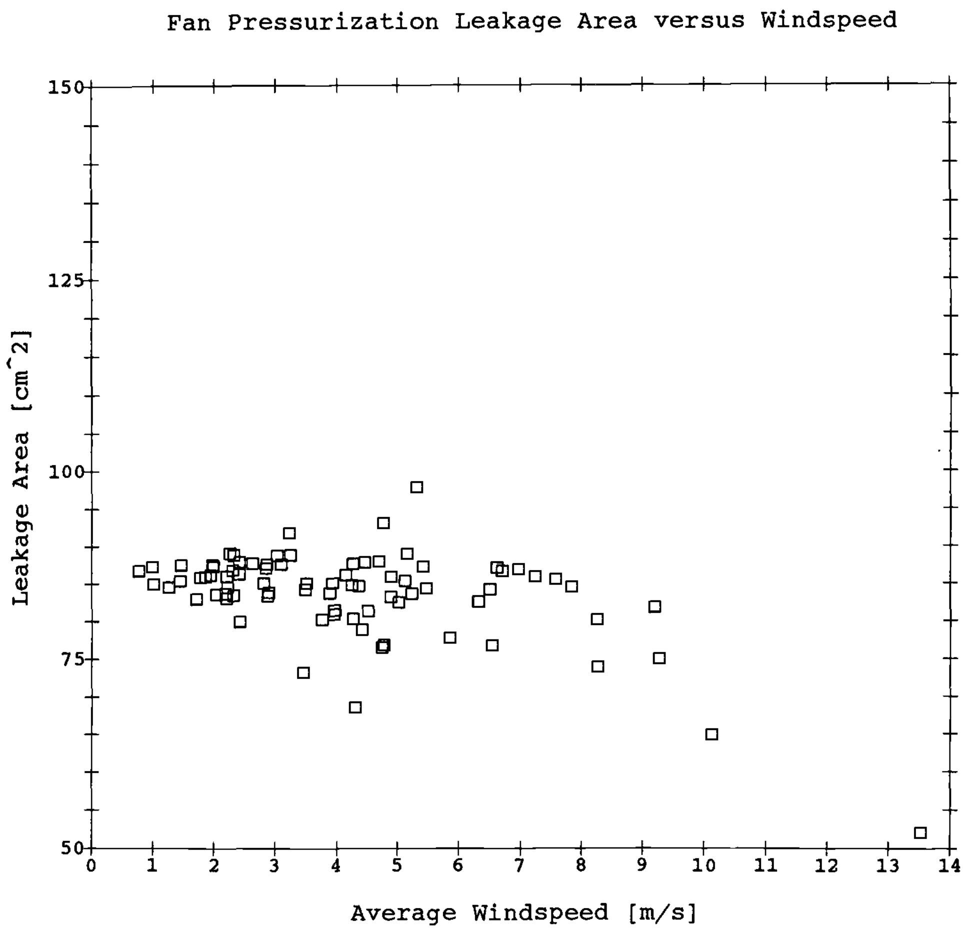

FIG. 3—*Measured effective leakage area versus windspeed for pressurization of Edmonton test house with flue sealed (using spatial/time averaging method).*

California. The latter data were obtained by a single team manually following the ASTM procedure with a single outdoor pressure sensor and simple visual averaging to pressure differentials and angular fan speed. The Berkeley tests were made with an "RPM" blower door (that is, flow determined from the pressure differential and the angular velocity of the fan), for which the flow uncertainty was determined from calibration tests to be approximately 25 m^3/h, or less than 1% of full scale. Envelope-pressure differentials for the Berkeley data were based upon a static pressure probe for the outdoor pressure and were measured with the same electronic pressure transducer used for the Edmonton measurements. The low average windspeeds for the Berkeley data stem from the fact that the building was located in a small canyon well shielded from the wind. The Berkeley measurements took place over a two-month period in the winter of 1986–87, whereas the Edmonton data was collected between May and September 1987.

As the Edmonton and Berkeley experiments were performed on different buildings and do not use the same flow measurement equipment, the comparison in Table 1 cannot be considered a definitive test of spatial-pressure-averaging and time-averaging techniques. However, the Berkeley data do serve as a suitable reference point for the standard ASTM

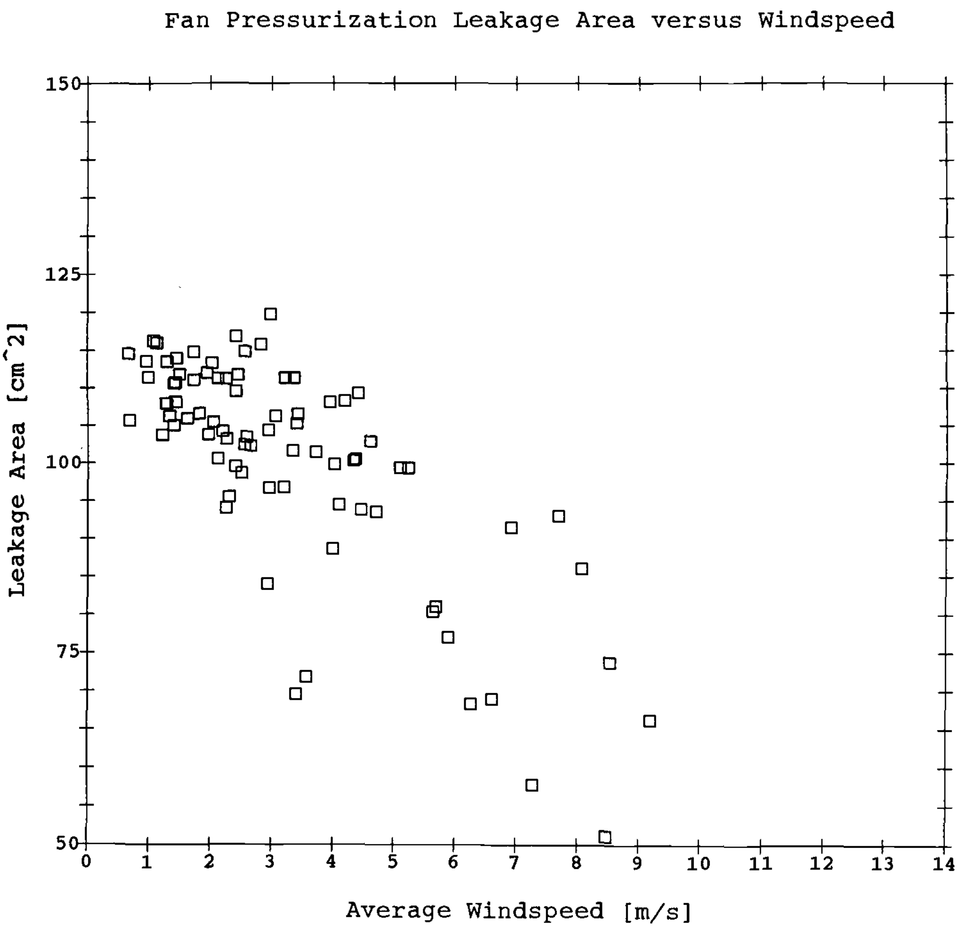

FIG. 4—*Measured effective leakage area versus windspeed for depressurization of Edmonton test house with flue open (using spatial/time averaging method).*

measurement procedure. Keeping these issues in mind, examination of Table 1 indicates that the scatter of the Edmonton data is approximately half that for the Berkeley data, demonstrating a potential for improvement of the ASTM standard procedure.

Discussion of Results

One result of the Edmonton field tests that merits further discussion is the observed negative bias in the measured leakage area with respect to windspeed. Intuitively, one might imagine that the biases in measured leakage area due to the wind should have opposite signs for pressurization and depressurization, yet the measured results indicate a consistent negative bias. However, this consistent bias can be explained by examining the effect of linearly averaging the external surface pressures.

The CGSB pressure-averaging manifold, as well as the modified version used for the Edmonton field tests, linearly average the pressures at the four pressure-tap locations. However, the flow through a given surface of the house does not vary linearly with the pressure differential across the leak, but rather is proportional to the pressure differential

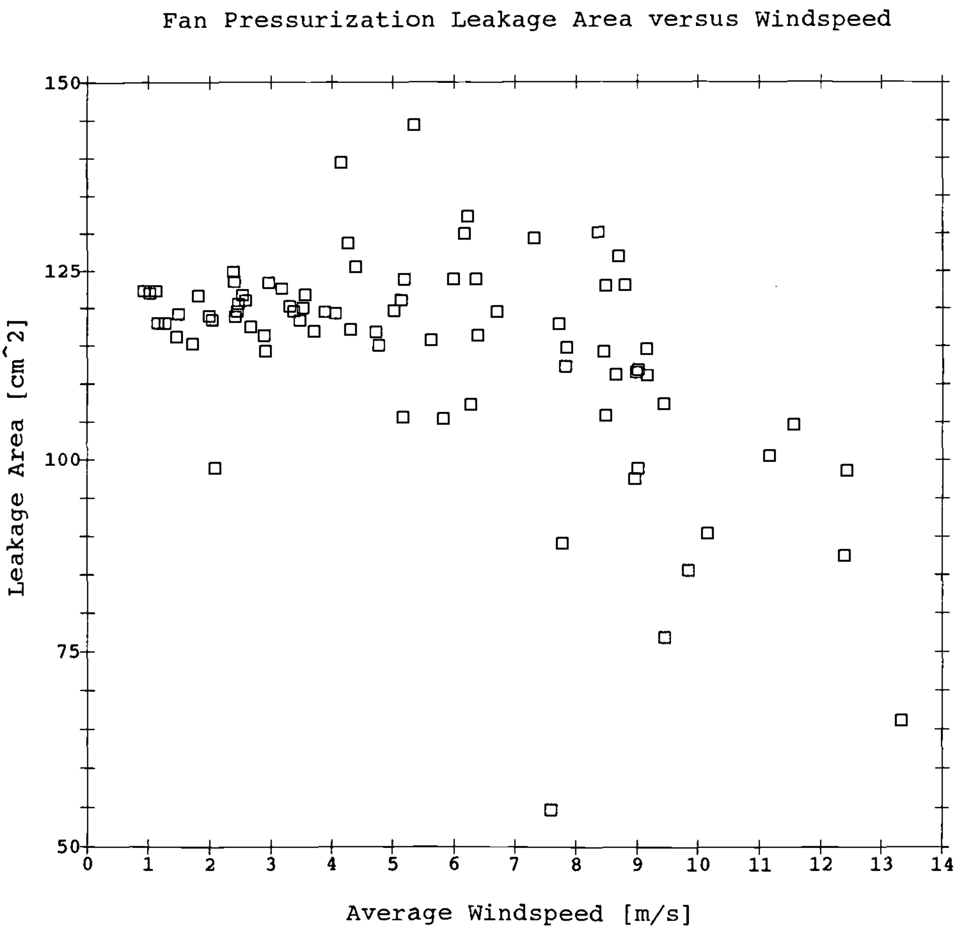

FIG. 5—*Measured effective leakage area versus windspeed for pressurization of Edmonton test house with flue open (using spatial/time averaging method).*

raised to a power, typically 0.65 [*5,6*]. The surface pressures should therefore not be averaged linearly, but rather the pressure differentials across each leakage site (surface) should be measured separately, raised to the appropriate power-law exponent, weighted according to its contribution to the total flow, and then averaged. Thus, whenever there are spatial variations in the indoor-outdoor pressure differentials (such as when the wind blows), the linear average pressure differential will not be the appropriate pressure differential to which the flow should be referenced.

If we assume a uniform distribution of leakage with a single power-law exponent, because the power-law exponent is always less than 1.0, the linear-average pressure will always be larger (in absolute value) than the appropriate pressure differential. This result stems from the general mathematical inequality expressed in Eq 1:

$$(\overline{X})^n \geq \overline{X^n} \tag{1}$$

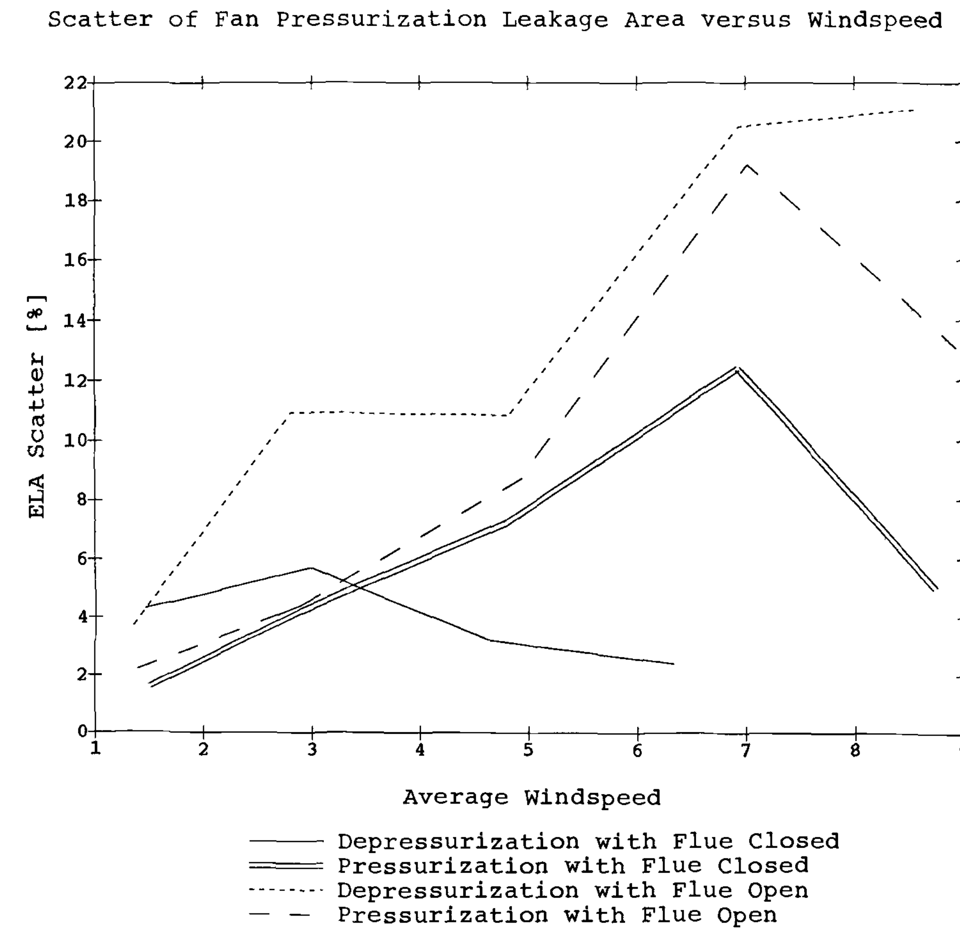

FIG. 6—*Scatter of effective leakage area measurements in Edmonton test house as a function of average windspeed for four test conditions (using spatial/time averaging method).*

TABLE 1—*Means and standard deviations of leakage areas measured by fan pressurization.*

Structure	Flow	Number of Points	Windspeed Range, m/s	Leakage Area: Mean, cm^2	Leakage Area: Standard Deviation, cm^2	Leakage Area: Standard Deviation, %
Edmonton test house, flue closed	Depress	18	0–2	82	3	4
	Press	12	0–2	86	1	2
Edmonton test house, flue open	Depress	22	0–2	110	4	4
	Press	10	0–2	119	3	2
Berkeley, window closed	Average	16	0–2[a]	288	25	9
Berkeley, window open	Average	16	0–2[a]	594	35	6

[a]Estimated by operators.

where

X = any variable that only takes on positive values, and

^{n} = a number between zero and one.

The nature of nonlinear averaging implies that, for a given windspeed and wind direction (that is, surface-pressure variation), the percentage difference between the linear average and the appropriate nonlinear average will be larger at smaller average pressure differentials. Thus, at high pressure differentials (for example, 50 Pa), the wind will not cause a large bias in the measured flow/pressure pair, whereas at small pressure differentials (for example, 10 Pa) the flow at the measured pressure differential will be underestimated significantly. This bias has the effect of causing a consistent overestimation of the power-law exponent and underestimation of the leakage area. The magnitude of the bias will depend upon wind speed and direction, but generally will be in the same direction regardless of whether the house is being pressurized or depressurized (see Fig. 7).

The issue being discussed can perhaps be best illustrated by an example simulation of the effects of wind on a fan pressurization test. Such a simulation was made based upon a two-point fan pressurization test. For the purposes of this example, a square house with a uniform distribution of leakage on the four walls and the roof was assumed to be subjected to a steady wind of 7 m/s impinging perpendicular to one of its faces. The leaks were all assumed to be orifice-like, that is, to have a flow exponent of 0.5. Under unshielded conditions the pressure coefficients were assumed to be: +0.65 on the windward face, −0.65 on the side faces, −0.40 on the leeward face, and −0.20 on the roof. The house was then subjected to nominal pressure differentials (that is, no wind) of 50 and 25 Pa. At each of these pressure differentials, the surface pressures based upon the assumed windspeed and pressure coefficients were used to determine the actual flow that would be measured by a pressurization fan, and the indoor-outdoor pressure differentials that would be measured by a CGSB pressure probe and by single-surface pressure taps. For each nominal pressure differential, Table 2 contains the pressure differentials for each surface, the pressure differential that would be measured with CGSB probe, and the appropriate average pressure differential. Table 3 contains the bias in the power-law exponent and leakage area determined for each indoor-outdoor pressure reference.

Our discussion thus far, and the results in Tables 2 and 3, illustrate an important defect of the CSGB pressure-averaging probe, but also point out that this defect will be amplified when using a single outdoor pressure tap as specified in the ASTM standard. When using a single pressure tap, the bias in both leakage area and exponent is generally much larger and much less consistent. It generally (but not always) changes sign when switching from pressurization to depressurization and is very sensitive to wind direction.

Conclusions

Based upon the examinations presented in this report, several conclusions about the effects of wind on fan pressurization measurements can be drawn. First, it has been shown that, up to windspeeds of 5 m/s, unbiased leakage area measurements with a scatter smaller than 11% can be obtained by fan pressurization measurements incorporating time averaging of pressure and flow signals and four-wall surface-pressure averaging. Furthermore, the measured increase in measurement scatter with increasing windspeed provides an experimental verification of the expected trend and provides a useful reference point for judging the appropriateness of measurement standards or the potential of measurement technique improvements.

Both the experimental results and the analytical examination of thee results point out the importance of choosing an appropriate reference for the indoor-outdoor pressure differ-

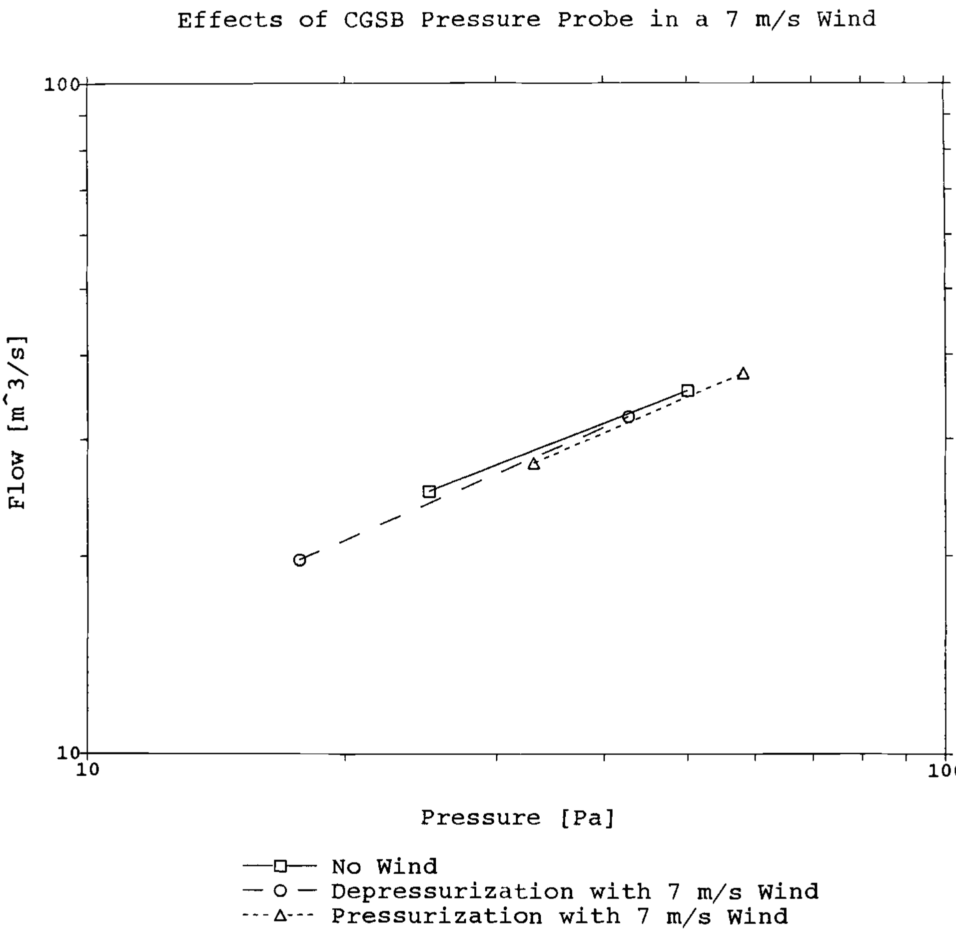

FIG. 7—*Example of the effects of wind on pressurization and depressurization measurements performed using the CGSB averaging probe to measure the outdoor pressure. The solid line and squares represent the flows that would be measured at zero windspeed. The triangles represent the flow/pressure pairs that would be measured under pressurization, and the circles represent the flow/pressure pairs that would be measured under depressurization.*

TABLE 2—*Indoor-outdoor pressure differentials for an example fan pressurization test in a 7 m/s wind.*

ΔP No Wind, Pa	ΔP Windward, Pa	ΔP Side, Pa	ΔP Leeward, Pa	ΔP Roof, Pa	ΔP CGSB, Pa	$(\overline{\sqrt{\Delta P}})^2$ True Mean, Pa
50	30.5	69.5	62.0	56.0	57.9	56.4
25	5.5	44.5	37.0	31.0	32.9	29.9
−50	−69.5	−30.5	−38.0	−44.0	−42.1	−41.4
−25	−44.5	−5.5	−13.0	−19.0	−17.1	−14.9

TABLE 3—*Bias in fan pressurization test results for an example house in a 7 m/s wind.*

Outdoor Pressure Reference	Pressurization: Bias in Power-Law Exponent, %	Pressurization: Bias in Leakage Area, %	Depressurization: Bias in Power-Law Exponent, %	Depressurization: Bias in Leakage Area, %
4-wall average	+10	−14	+12	−14
Windward wall	−60	+150	+122	−86
Side wall	+40	−49	−38	+72
Leeward wall	+21	−28	−8	+15
Roof	+6	−7	+18	−21

ential. Namely, it was shown that the CGSB pressure-averaging probe generally will cause a consistent negative bias in the measured leakage area at high wind speeds, irrespective of whether the house is being pressurized or depressurized. This result, along with the demonstrably larger bias and scatter associated with the use of single outdoor pressure taps, suggests that the ASTM fan pressurization standard should address the issue of how to measure the indoor-outdoor pressure differential.

Finally, based upon the above discussions, it seems that the application of noise-reduction filtering and averaging techniques to fan pressurization tests merits further consideration. Based upon the preliminary results presented in this paper, the time averaging of pressure and flow measurements may represent an important first step in that direction.

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DISCUSSION

J. T. Reardon[1] *(written discussion)*—With regard to the CGSB pressure averaging (on four faces) approach, the modest bias should be expected since stagnation pressure buildup is greater than leeward pressure drop and the "pressure averaging" device probably produces, as an average, the value of pressure midway between the lowest and the highest pressures, not a weighted average. Was this considered?

M. Modera (author's closure)—As the CGSB probe was designed to have equal linear resistances to pressure taps on all four walls, the pressure sensed by the probe should be the true linear average pressure of the four walls. This can be shown by applying the continuity equation to the volume which is connected to the four taps. However, there will

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be a pressure bias under virtually all measurement conditions. For a measurement to be completely unbiased, the building would have to have linear leakage ($n = 1$), four plane walls, each with one quarter of the total envelope leakage, and all leakage must be at locations with the same wind pressure coefficients as the pressure taps. The analysis in the paper focuses on the bias due to the typical nonlinearity of building leaks.

J. H. White[2]*(written discussion)* —(1) As opposed to the intent suggested at the presentation, the intent of the CGSB pressure averaging manifold and tubing set was three-fold: (a) to provide some damping; (b) to provide an average pressure under windy conditions which was at least better than any one of the single-wall or remote points; and (c) to have the zero offset (without the sun operating and its opening sealed) subtracted from all subsequent readings to obtain a second approximated improvement to results which ignored wind.

It was never our intent to remove all of the errors, since: (a) changes of wind speed and direction do occur; (b) different wind directions interact differently (and no single correction is "exact") with different leakage distribution; (c) wind affects the leaks differently with wind speed when the zero wind-speed neutral pressure plane is at different heights; and (d) we were only trying to move the allowable wind speed up a small amount (1 or 2 ms) to increase the number of testing hours per year.

(2) As the "author" of much of the work on the operation of chimneys (and other flues), I suggest that the author look slightly more closely at the effect of flues in the following areas: (a) the effect of an open flue on the vertical center of leakage (therefore, the effective leakage distribution); (b) the effect of the size of that flue (or its effective ELA); (c) the offset effect of the draft produced by that flue; (4) the effect of open flues and flue caps on the pressure coefficient of the chimney exit; and (5) the effect of the velocity increment at most chimney exits (velocity pressures may be ten times greater at chimney caps than at walls). The above could help explain many testing problems.

M. Modera (author's closure)—Relative to comment 1, the intent of the paper was not to suggest that the CGSB probe was not an improvement over single-point measurements, but was rather to explain the observed experimental results. However, if the windspeed were truly constant in speed and direction over the course of a test, subtracting the CGSB pressure measurement at zero-fan speed from subsequent readings, (as you suggested in comment 1*c*, would imply biases of different sign for pressurization and depressurization, but a larger overall negative bias of the average leakage area.

Relative to comment 2, the nonuniform distribution of leakage created by the flue does exacerbate the outdoor-pressure-reference problem; however, it is not the only source of bias, as the nonlinearity of the leaks causes a bias even for a perfectly uniform leakage distribution with all leaks in the four walls. As for whether the situation examined is sufficiently representative, having one quarter of a house's leakage in a chimney or flue is somewhat high, but not unreasonable. Concerning the draft of the flue, the pressure differentials created by fan pressurization are between one and two orders of magnitude larger than the extremes of the thermally induced pressure gradient in the houses examined—this is the case in almost all fan pressurization tests. Thus, the draft produced by the flue (which was at room temperature) is negligible, and the flow will not be bistable. Relative to the pressure coefficient comment, the flues in the test houses were not particularly exotic, and the pressure coefficients of those flues (and of almost all chimney caps) are negative, as was assumed in Table 2. Furthermore, a change in the assumed pressure coefficient for the flue in Table 2 does not substantially change the results or conclusions. In summary, the effects of the flues on the fan pressurization tests are documented experimentally in the text and can be reasonably well understood by their effect on the appropriateness of the outside-pressure reference.

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Fan Door Testing on Crawl Space Buildings

REFERENCE: Brennan, T., Pyle, B., Williamson, A., Balzer, F., and Osborner, M., "**Fan Door Testing on Crawl Space Buildings,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 146–150.

ABSTRACT: In order to learn something about the leakage characteristics of crawl spaces, a small-scale investigation was made using fan doors on nine buildings in Tennessee. This effort was part of a larger project to study the control of indoor radon levels in crawl space houses. The goal was to gain insight into the overall leakiness of crawl spaces and the leakage between the crawl spaces and the living spaces.

The investigation made first order estimates of the effective leakage areas (ELA) of the crawl spaces and the floor areas between them. It was discovered that, even with passive vents closed, crawl spaces are quite leaky compared to the building shell they support, and that the leakage area between the unconditioned crawl spaces and the conditioned upper part of the building were also large.

KEY WORDS: crawl space, fan door, effective leakage area (ELA), air leakage between two zones, duct work

Since the mid-1970s a number of researchers have used fan pressurization techniques to investigate the leakage characteristics of buildings [*1–3*]. These methods have been used to locate leakage sites and to estimate the tightness of the building shell. ASTM Committee E-6 on Performance of Building Constructions has developed the Standard Method for Determining Air Leakage Rate by Fan Pressurization Test (E 779-81) for making such measurements.

This paper presents the results of efforts to use this technique on the superstructure and substructure of crawl space houses located in Nashville, Tennessee. The tests were used to estimate the effective leakage areas (ELA) of the living space and crawl space and the floor that separates the two. ASTM E 779-81 was modified to make the estimate of the floor leakage area. Previous work on interzonal leakage has been reported by several other researchers [*4–7*].

The work reported here was part of a larger project on the control of radon in residential buildings. The project was funded by the USEPA Office of Research and Development, AEERL.

Procedure

Fifteen houses with elevated radon concentrations (>10 pCi/L) were selected from a pool of buildings supplied by a Tennessee survey. The buildings were included in the study because

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they met research needs for the EPA radon research program. Nine of the fifteen houses selected had crawl spaces.

As part of the investigation to evaluate the sources, transportation, entry, and dynamics of radon in these buildings, fan door measurements were made. Two commercially available fan doors were used to make the measurements. The crawl space vents and any hatch connecting the crawl space to the living area were closed during all the fan door tests.

First, an ordinary fan door test was completed on the living space in accordance with ASTM E 779-81. An effective leakage area (ELA) at 4 Pa pressure differential was calculated for the living space using methods developed at Lawrence Berkeley Laboratory [2].

Second, a similar test was done on the crawl space. This was not as simple because the fan door closure system could not be used in the small access openings found in the crawl spaces. These were typically between 10 by 28 in. (30 by 71 cm) and 24 by 28 in. (61 by 71 cm). Duct tape and polyethylene film were used to seal the fan door into the opening. Because the openings in some of these buildings were smaller than the diameter of the fan door nozzle, it is felt that turbulence as air flowed around the edges of these small openings and through the nozzle introduced additional experimental error into the crawl space measurements.

Third, fan doors were used to exhaust air from the crawl space and living space simultaneously, and their speeds were adjusted so that the difference in air pressure between the living space and the crawl space was maintained at zero. This was measured using an electronic micromanometer. This effort was aided by two operators and walkie-talkies. Figure 1 shows a schematic of this technique. By an analog subtraction of the ELA_{FL} of the

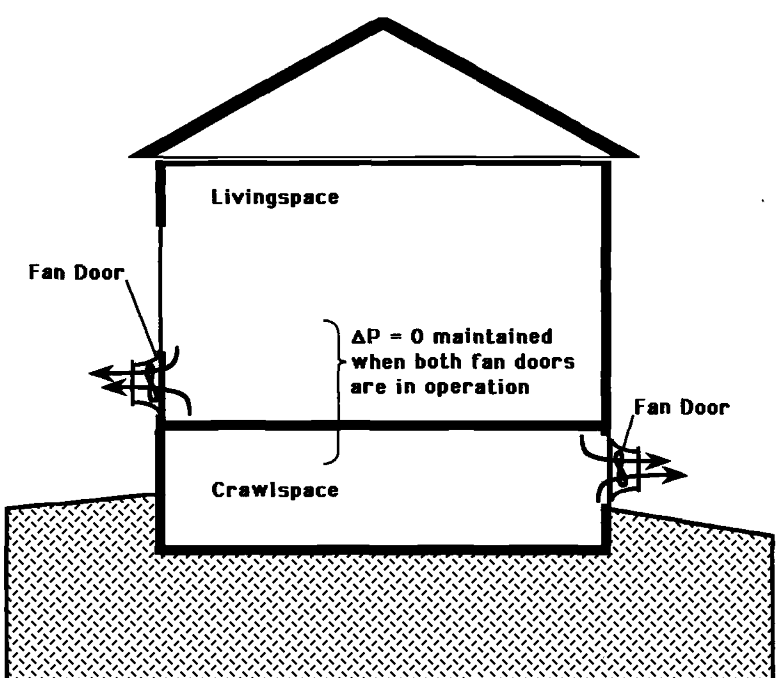

FIG. 1—*Schematic of fan door testing. Tests were made to determine the leakage characteristics of the living space and crawl space using the fan door as described by ASTM E 779-81. Both fans were used simultaneously to estimate the living space leakage area through the walls and ceiling only.*

floor from the living space, ELA_{LS}, the effective leakage area, $ELA_{LS\text{-}FL}$, through the living space walls and ceilings was estimated. By subtracting the resultant $ELA_{LS\text{-}FL}$ from the ELA_{LS} for the entire living space, the ELA_{FL} of the floor between them was estimated.

Equation 1 summarizes this:

$$ELA_{FL} = ELA_{LS} - ELA_{LS\text{-}FL} \tag{1}$$

where

ELA_{FL} = ELA of adjoining floor,
ELA_{LS} = ELA of living space, and
$ELA_{LS\text{-}FL}$ = ELA of living space less floor ELA.

Uncertainties in the resulting ELA_{FL} are expected to be large because the uncertainties in the calculation of an ELA for a single zone were large, and wind effects seemed greater on the double fan door test. In fact, the testing had to be done when there was essentially no wind at all. For future work along these lines, it would be better to consider one of three possible other techniques: (1) a method that solved fundamental flow equations simultaneously; (2) an experimental method under study at Lawrence Berkeley Laboratories that uses two fan doors, one of which holds a constant ΔP across the upstairs building shell [*4*], thus ensuring a constant airflow through living space walls and ceilings; and (3) a method outlined that does not depend on a double fan door test used by Lawrence Berkeley Laboratories in the study of basement houses in the Pacific Northwest [*5*]. This method measures estimates the ELA_W for the whole building, the ELA_P for the superstructure (including leakage area through the floor) and the ELA_B for the substructure (including leakage area through the floor) by using a single fan door to depressurize each of the three spaces. The results are used in Eq 2 to solve for the ELA_C of the substructure ceiling:

$$ELA_C = (ELA_P + ELA_B - ELA_W)/2 \tag{2}$$

Results

Physical inspection of the crawl spaces revealed the following:

1. All the buildings were brick veneer, wood-frame construction ranch-style houses.
2. The floor areas were:

DW60—1200 ft^2 (112 m^2)
DW90—1344 ft^2 (125 m^2)
DW27—2250 ft^2 (209 m^2)
DW82—1550 ft^2 (144 m^2)
DW29—3000 ft^2 (279 m^2)
DW84—2100 ft^2 (195 m^2)
DW31—1200 ft^2 (112 m^2)
DW66—1900 ft^2 (177 m^2)
DW03—1350 ft^2 (126 m^2)

3. All of the crawl spaces had from 8 to 14 screened vents of the same gross area as a concrete block 8 by 16 ft (23 by 46 cm). All the vents were screened with insect screen and were capable of being closed by a sliding grate or by snap-in metal covers.
4. Four of the nine, DW84, DW66, DW29, and DW27, had duct work located in the crawl spaces. These four also contained the HVAC equipment in the crawl space.

5. Three of the nine, DW03, DW90, and DW60, had fiberglass batt insulation placed between the joists of the floor separating the crawl space from the living space.

6. Two of the nine, DW03 and DW90, had a polyethylene film over the entire exposed earth area while an additional three, DW66, DW60, and DW29, had a polyground cover over one half the exposed earth.

The results for the fan door tests on the living spaces and crawl spaces are shown in Fig. 2. The mean ELA for the living space was 165 in.^{2} (1064 cm^2) and ranged from 54 in.^{2} to 295 in.^{2} (348 to 1903 cm^2). This places them in the 1 to 2 ft^2 range typically found in most of the United States. The mean ELA of 262 in.^{2} (1690 cm^2) for the crawl spaces was substantially larger than the mean ELA for the living spaces. The crawl spaces ranged from a low of 198 in.^{2} (1277 cm^2) to a high of 424 in.^{2} (2735 cm^2). The crawl spaces were measured with the vents closed. By opening the vents on DW27 and repeating the test, it was found that ten open vents produced an additional 200 in.^{2} (1290 cm^2) of ELA. This amounts to 20 in.^{2} (129 cm^2) for each 128 in.^{2} (825 cm^2) vent. It must be remembered that the vents were framed and screened and the net-free area was much smaller than the gross area.

Figure 3 shows the ELAs estimated for the floors added along with the data from Fig. 2 for comparison. The ELAs through the floors were fairly large, with a mean of 55 in.^{2} (355 cm^2) and ranged from 10 in.^{2} (65 cm^2) to 125 in.^{2} (806 cm^2). They were, however, all much smaller than the leakage area through the crawl spaces and living spaces. The houses with

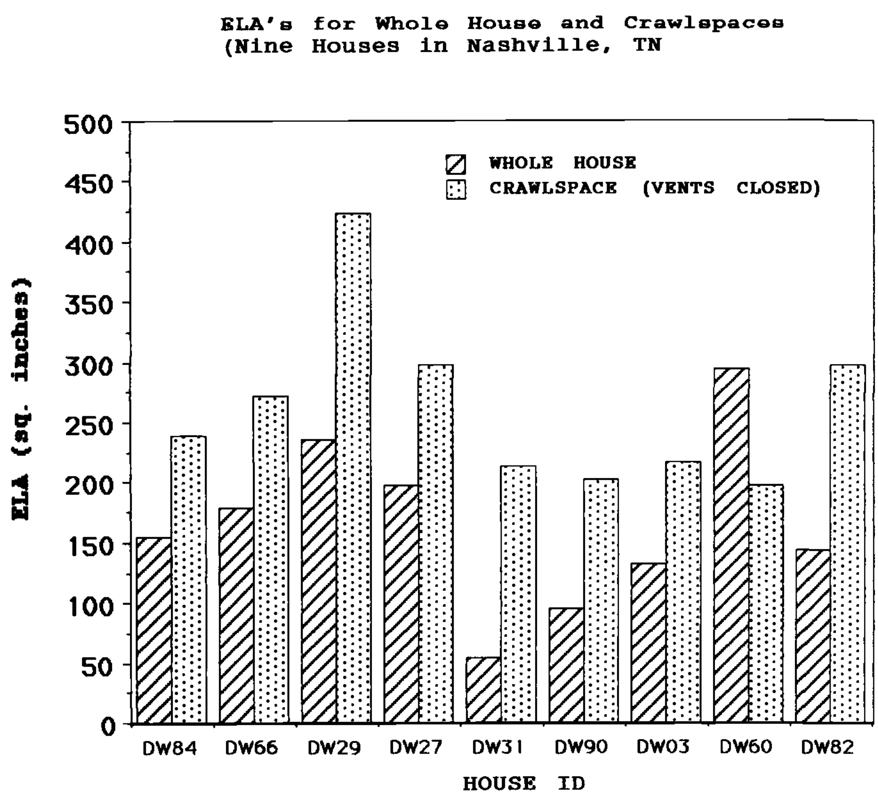

FIG. 2—*Mean ELA for whole house = 165 in.^{2}. Mean ELA for the crawl space = 262 in.^{2}. Even with vents closed, crawl spaces have a large leakage area compared to the ELA for the whole house.*

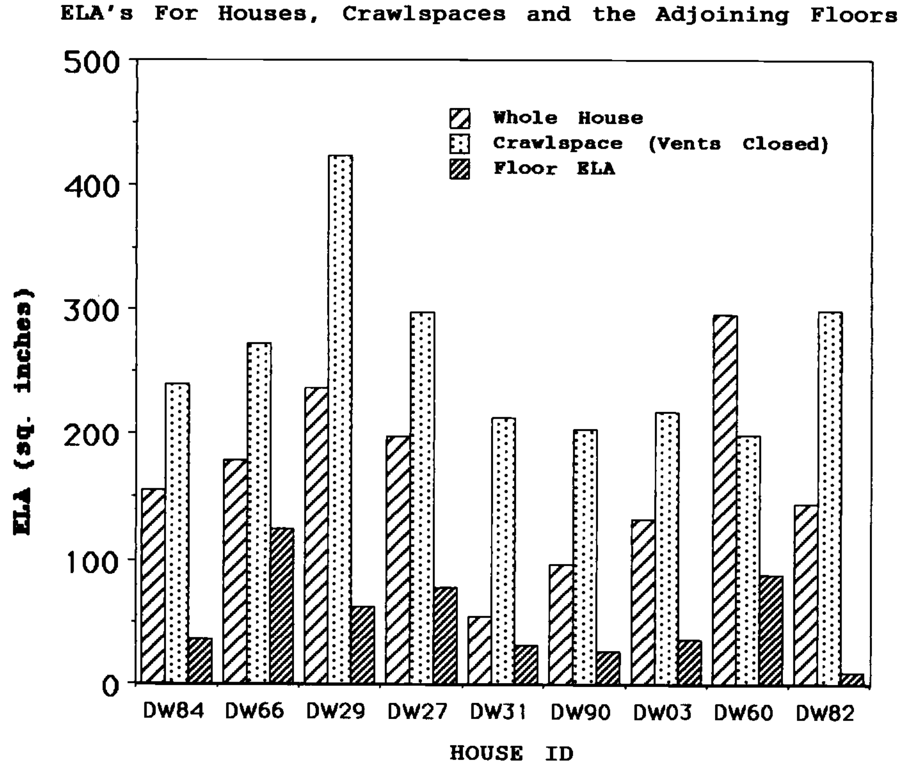

FIG. 3—*Estimated leakage areas of the crawl space and living space and the floor between them.*

duct work had substantially larger ELAs [the mean was 75 in.^{2} (484 cm^2)] than the houses without duct work [the mean was 38 in.^{2} (245 cm^2)], indicating that air-handling duct work introduces more leakage from one zone to another. The overall impact of this added leakage area is unknown when air is mechanically distributed through the systems. In addition to the larger floor ELAs, the houses with duct work also had somewhat larger living space ELAs [the mean was 192 in.^{2} (1238 cm^2)] than the houses without duct work [144 in.^{2} (929 cm^2)]. This might mean that the limiting leakage area for loss through the floor in this sample of houses is the floor ELA, not the crawl space ELA.

As part of the radon control method, in house DW82, the crawl space leaks to the living space and outside were sealed. Although, at this time, an additional fan door test has not been done to see how this affected the crawl space ELA, it is known that a blower exhausting approximately 70 ft^3/min of air from the crawl space is preventing crawl space air from entering the living space. This was determined by using smoke pencils and from the knowledge that the radon concentration in the living space fell by an order of magnitude ($\approx$20 to $\approx$2 pCi/L), while the crawl space radon concentration increased by a factor of two ($\approx$30 to 60 pCi/L). It is clear from this data that prevention of entry, not dilution, is the principle in operation here. In order for this to occur, the crawl space must be tighter than before.

Conclusions

This work is of interest mainly because it represents part of a small body of data that exists on crawl space buildings. It may help spark researchers in the fields of energy use, moisture migration, and radon control in crawl space buildings. It should be kept in mind that this is not a systematic investigation into the air leakage characteristics of crawl spaces. The purpose was to gain some first-order insight into the connections among the living space, crawl space, and outside air. A good deal of additional work must be done to gain a real understanding of the dynamics involved when air flows respond to temperature and mechanically induced pressure differentials.

Acknowledgments

The authors would like to thank the USEPA for sponsoring and participating in these investigations. We also thank Jackie Waynick and Suzie Shimek of the State of Tennessee.

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DISCUSSION

J. T. Reardon[1] *(written discussion)*— In the reported leakage areas, how was flue leakage dealt with? Did any of the houses have open flues? Were flues sealed for the tests? On a similar vein, do the leakage areas reported for the living space include or exclude the floor leakage?

T. Brennan (author's closure)—Fireplace dampers were closed. The houses had electric resistance or heat pumps for space heating and central air conditioners or window units for cooling. Figure 3 of my paper shows total house ELA, floor ELA, and total crawl space ELA.

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Air Leakage Tests of Manufactured Housing in the Northwest United States

REFERENCE: Ek, C. W., Onisko, S. A., and Gregg, G. O., "**Air Leakage Tests of Manufactured Housing in the Northwest United States,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 152–164.

ABSTRACT: Recently installed HUD-code manufactured housing in the Pacific Northwest region of the United States has been tested for air leakage characteristics. The tests were done to establish a database of air leakage under current manufacturing and installation practice. Test results will help establish the potential for future energy savings through air leakage control programs when applied to manufactured housing.

Average leakage rates for double-wide manufactured homes were found to be 8.40 air changes per hour (ACH) at 50 Pa pressure differential and are predicted by the LBL model to be 0.50 ACH under natural atmospheric conditions. These averages are based on 93 homes tested for air leakage with the blower-door or fan depressurization technique. The estimated coefficient of variation (COV) of the 50 Pa leakage rate was 0.23. Nineteen different manufacturer's homes were tested.

Twelve of the leakiest homes were "house doctored" for air leakage control. These homes averaged 11.75 ACH at 50 Pa before house doctoring, and 9.34 ACH after the retrofit work. The homes improved an average of 19.5%. The retrofit job took 3.5 h per home, with an average expenditure (including labor) of $200 (U.S.).

KEY WORDS: air leakage rates, manufactured housing, house doctoring

Manufactured housing represents nearly half of the electrically heated single-family housing stock currently being installed within the Pacific Northwest region of the United States. Consequently, the Bonneville Power Administration (BPA) Office of Energy Resources has been interested in the energy conservation potential of new manufactured housing. It has been anticipated that certain conservation practices could be initiated at the factory and during installation which would translate into reduced heating and cooling loads for the manufactured segment of new housing stock in the region.

To determine the need for improved house-tightening measures in new manufactured housing, BPA established a database of current practice air leakage performance in new manufactured homes sited within the Pacific Northwest *[1]*. The western side of the Cascade Range, where the testing was done, is known for its high winter precipitation, dry summers, and overall moderate temperatures.

The homes evaluated were recently installed, double-wide, U.S. Department of Housing and Urban Development (HUD)-code manufactured homes. Of the homes tested, 52% were produced by the five brands with major market penetration in the region, while the remaining 48% were shared among the 14 or so brands with minor representation in the region.

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[2]Manufactured housing program manager, Bonneville Power Administration, Portland, OR 97208.
[3]Owner, George O. Gregg Co., Bainbridge Island, WA 98110.

Test Method

An independent contractor tested each home for air leakage using the blower-door technique [ASTM Standard Practice for Measuring Air Leakage by the Fan-Pressurization Method (E 779-81)]. The reports provided to BPA included the following information:

Home Information

1. Manufacturer.
2. Age and condition.
3. Size, volume, and envelope area.
4. Site information (exposure, orientation, etc.).
5. Occupant characteristics.
6. Other pertinent information.

Test Information

1. Date.
2. Weather conditions.
3. Raw test data (flow and pressure).
4. Estimated performance curve, flow versus pressure.
5. Estimated effective leakage area (ELA).
6. Estimated air changes per hour (ACH) at 50 Pa pressure.
7. Estimated natural air exchange rate in ACH.

The homes tested were to be no more than two years old. No more than about 15 homes were to be of any one manufacture. Homes of varying size and price range were to be tested. Test sites were to be selected from a wide geographic area, essentially from Seattle, Washington, to Portland, Oregon.

Air Leakage Results

Tabulated Summary

In all, 93 valid tests were performed on 19 brands of double-wide homes. Testing was performed by a single contractor between August and November 1986. Each home was less than two years old and was equipped with central electric heat with air ducts in the floor. The results of the tests are given in Table 1.

The data in Table 1 suggest that, in general, double-wide manufactured homes in this region perform moderately better than site-built homes using current residential construction codes and practices, as reported in *ASTM STP 904* [*2*]. Evidence suggests that new site-built homes have 50 Pa leakage rates of about 10 ACH [*3*].

It would appear that the marriage line of double-wide units and the crossover ducting for the heating systems are major contributors to air leakage. Smoke sticks were used on twelve of the worst air leakage performers to establish where the air leaks were occurring for double-wide homes. These tests confirmed that the marriage line between the halves of the homes and the heating system ducts were the largest contributors to the measured air leakage. Leakage around windows and doors was generally low. Further discussion of these tests is provided below.

Figures 1 to 4 show statistical plots of the 93 homes shown in Table 1. Detailed test data are shown in Table A1 (Appendix). Figure 5 shows a poorly correlated relationship between the measured flow exponent, *n*, and the specific leakage area (effective leakage normalized

TABLE 1—*Manufactured housing air leakage performance (93 double-wide homes).*

	Specific Leakage Area[a] (SLA), cm^2/m^2	Air Changes per Hour (ACH) at 50 Pa	Natural Air Change[b] Rate, ACH
Average	2.70	8.38	0.50
Sample standard deviation	0.68	1.93	0.15
Coefficient of variation (COV)[c]	0.25	0.23	0.29

[a] Effective leakage area (ELA, cm^2) per square metre of building envelope area, as determined from the calculated flow rate at 10 Pa.
[b] As determined using the LBL model, based upon flow rate at 4 Pa.
[c] Ratio of sample standard deviation to average.

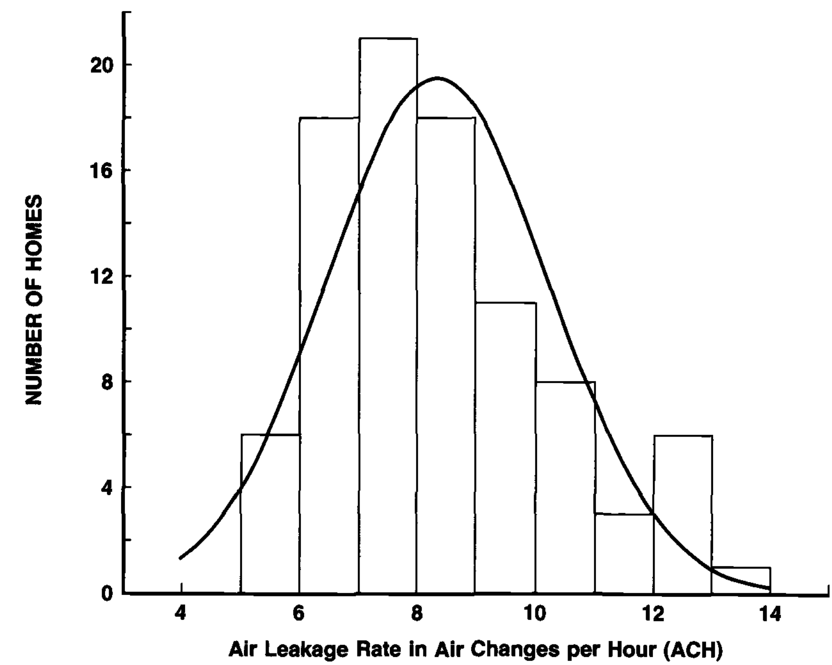

FIG. 1—*Frequency distribution of 50 Pa leakage rate of 93 manufactured homes.*

by envelope area). It becomes apparent that the leakiest homes tend to have flow exponents approaching 0.50, which may indicate that large leaks approach the theoretical value for orifice flow. This has been described by Sherman et al. [*4*]. Tight homes tend to have exponent values above 0.70, which might reflect the effect of crack-type laminar flow.

Tests at Bothell, Washington

Twenty-five new double-wide homes were selected from a large, modern development in Bothell, a suburb of Seattle, Washington. These homes produced leakage results shown in Table 2. These homes are also included in Table 1.

The Bothell results did not differ greatly from the results of homes tested throughout the region, as shown in Table 1. This may indicate that regional variations are not statistically

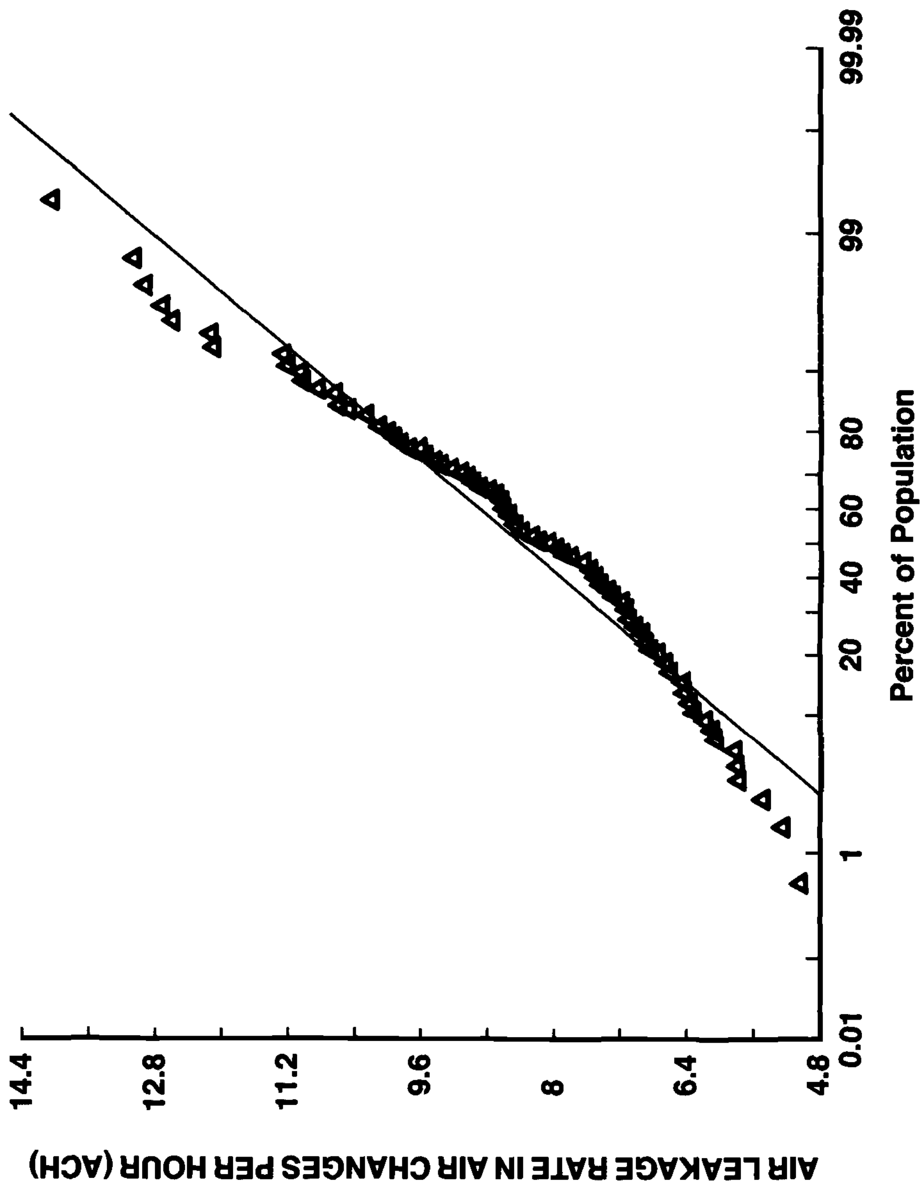

FIG. 2—*Normal distribution plot of 50 Pa leakage rate of 93 manufactured homes.*

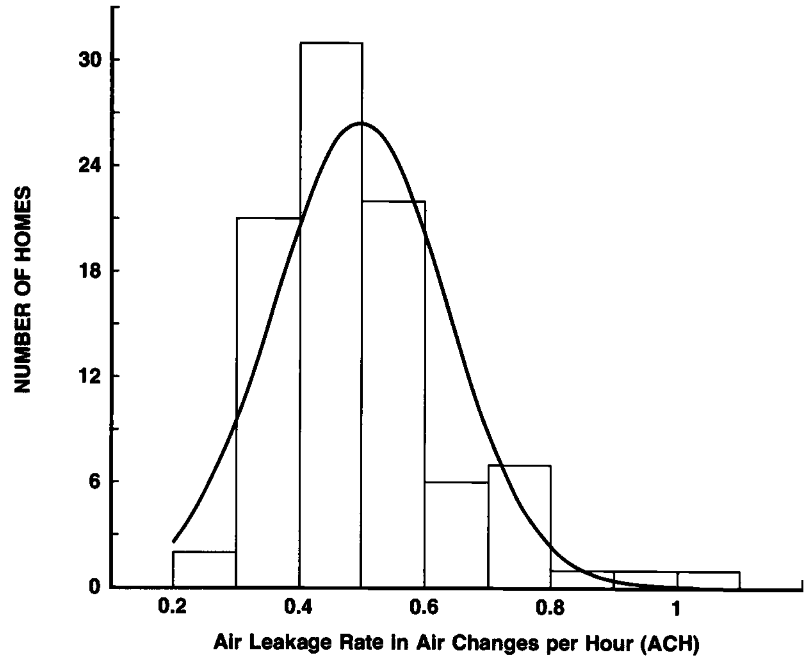

FIG. 3—*Frequency distribution of natural leakage rate of 93 manufactured homes.*

significant and that sample sizes as low as 25 homes may fairly represent the population of new manufactured housing. The Bothell test homes represented eleven different manufacturers.

Other Test Parameters

To determine whether homes with high glass area leaked more than others, 46 homes were measured for glass area. No statistical correlation was found between percent glass area and specific leakage area. However, smoke stick testing revealed that windows *were* contributors to leakage. The lack of correlation means window leakage was not statistically different than leakage elsewhere in the homes and that its effect was masked by other, more significant leakage. The plot shown in Fig. 6 shows the lack of correlation between percentage of glass area and the leakage rate at 50 Pa.

In addition to recording leakage data, 16 homes were tested for formaldehyde concentration at the owners' requests. Measured concentrations, using a commercially available passive monitoring device deployed by the homeowners, showed values ranging from 0.11 to 0.39 ppm. The recommended upper limit established by the U.S. Department of Housing and Urban Development (HUD) is 0.40 ppm.

House Doctoring

Twelve homes, each of which exhibited high leakage rates during initial blower door tests, were selected to receive "house doctoring" or retrofit leakage control measures. Each home was to receive up to four hours of caulking, sealing, and taping, to reduce its leakage rate. The house doctoring records, together with the post-retrofit performance data, would determine the cost effectiveness of the retrofit measures used.

The initial leakage of retrofitted homes is given in Table 3.

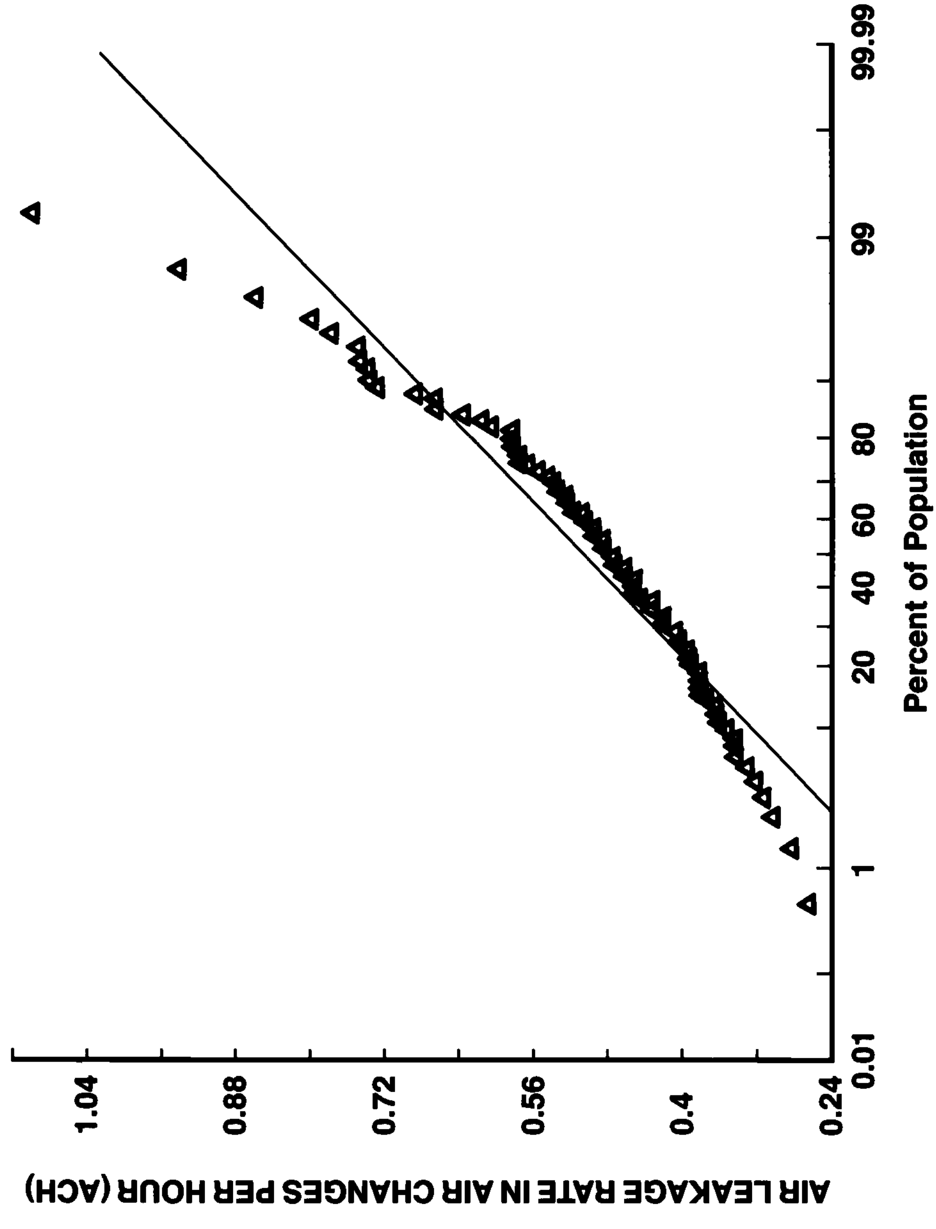

FIG. 4—*Normal distribution plot of natural leakage rate of 93 manufactured homes.*

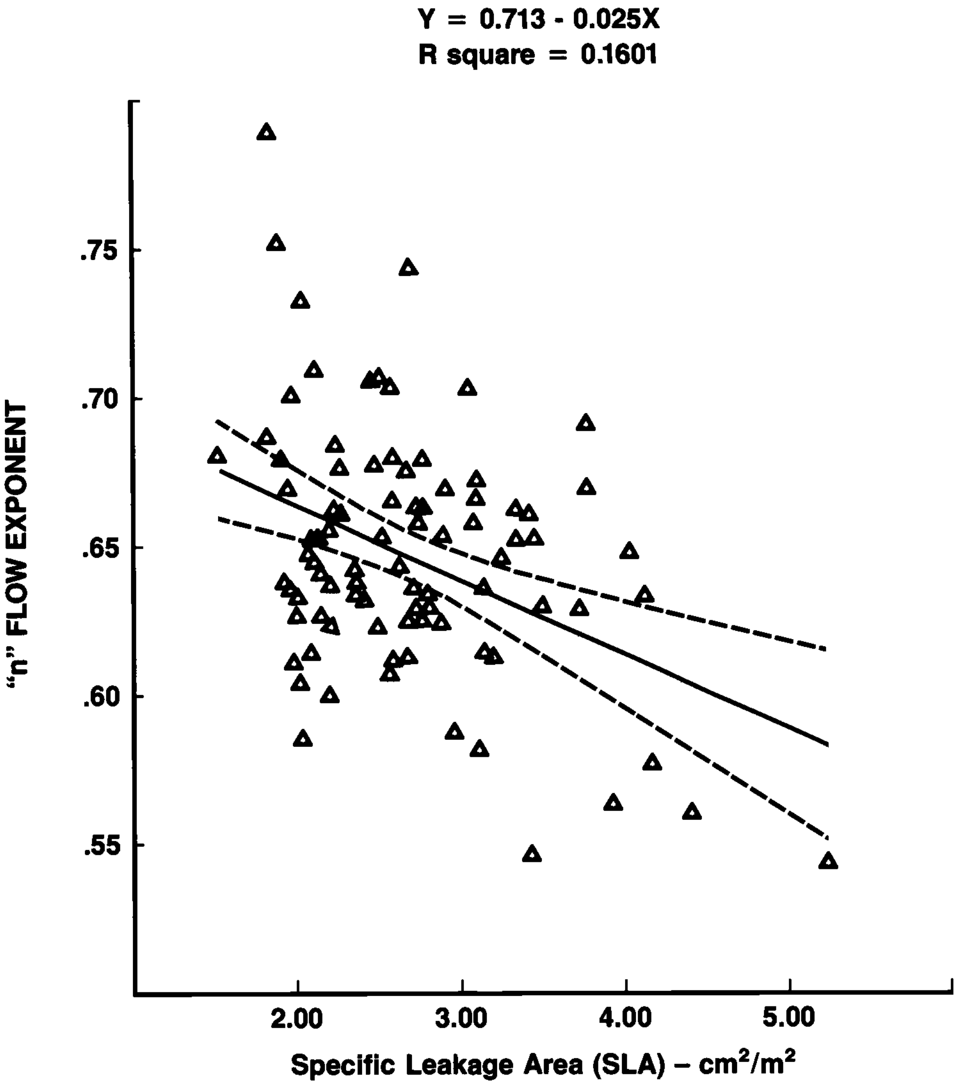

FIG. 5—*Correlation of flow exponent,* n, *with calculated specific leakage area.*

TABLE 2—*Bothell manufactured housing air leakage (25 homes).*

	Specific Leakage Area (SLA), cm^2/m^2	Air Changes per Hour (ACH) at 50 Pa	Natural Air Change Rate, ACH
Average	2.72	8.28	0.52
Sample standard deviation	0.74	1.94	0.16
Coefficient of variation (COV)	0.27	0.23	0.31

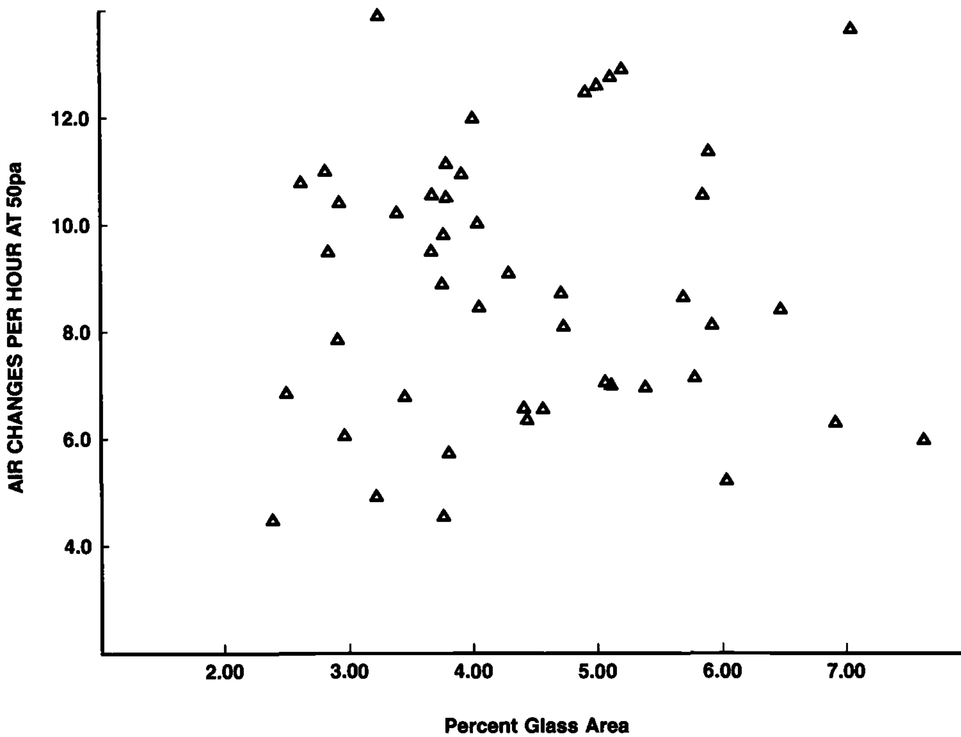

FIG. 6—*Lack of correlation of 50 Pa leakage rate with percent glass area.*

TABLE 3—*Initial leakage of retrofitted homes.*

Test Number	Specific Leakage Area, cm^2/m^2	ACH at 50 Pa	Natural ACH
035	4.22	11.01	0.71
036	3.91	10.54	0.63
037	3.43	11.15	0.66
045	5.21	13.97	1.09
046	3.72	9.81	0.74
054	3.84	10.95	0.73
074	3.70	11.14	0.58
077	3.75	12.81	0.73
092	3.75	12.52	0.66
094	4.99	13.68	0.96
099	4.09	10.80	0.85
103	4.40	12.64	0.93
Average	4.08	11.75	0.77
COV	0.13	0.11	0.20

House Doctoring Measures Performed

Table 4 shows the areas found to be high contributors to the leakage rates. Smoke stick testing located the sources. Those areas considered repairable within time and budget constraints were serviced with appropriate retrofit measures as described.

Final Leakage

Blower-door tests performed at the completion of house doctoring showed the results listed in Table 5.

TABLE 4—*Retrofit measures performed.*

Home	Leakage Sources	Repair Measures	Time Expended, h	Cost, U.S. dollars
035	Hole in duct	Taped		
	Marriage line	Caulk		
	Outlets	Added gaskets	3.75	210
036	Marriage line	Caulk		
	Plumbing holes	Caulk		
	Outlets	Added gaskets	3.00	170
037	Ducts	Not fixed		
	Marriage line	Caulk		
	Electrical panel	Caulk		
	Plumbing holes	Caulk	4.00	227
045	Ducts	Taped		
	Marriage line	Caulk and gasket		
	Outlets	Added gaskets	3.50	200
046	Marriage line	Caulk		
	Shower and bath	Caulk		
	Ductwork	Not fixed		
	Electrical panel	Not fixed		
	Outlets	Added gaskets	4.00	227
054	Marriage line	Caulk		
	Plumbing holes	Foam	3.50	205
074	Marriage line	Caulk		
	Shower and bath	Caulk	3.50	200
077	Marriage line	Caulk		
	Shower and bath	Caulk		
	Electrical panel	Caulk	4.00	227
092	Marriage line	Caulk		
	Shower and bath	Caulk		
	Ductwork	Not fixed		
	Outlets	Added gaskets	3.75	213
094	Ducts	Taped		
	Marriage line	Caulk and gasket		
	Outlets	Added gaskets	3.50	202
099	Marriage line	Caulk		
	Shower and bath	Caulk		
	Ductwork	Not fixed		
	Windows	Caulk		
	Plumbing holes	Caulk		
	Outlets	Added gaskets	3.75	213
103	Skylight	Caulk		
	Shower enclosed	Caulk		
	Ductwork	Attached (by owner)		
	Windows	Caulk		
	Plumbing holes	Caulk		
	Outlets	Added gaskets	2.00	114

TABLE 5—*Air leakage after retrofit.*

Test Number	Specific Leakage Area, cm^2/m^2	ACH at 50 Pa	Reduction, %	Natural ACH
035	3.49	10.51	4.54	0.56
036	2.29	7.87	25.33	0.43
037	3.72	11.67	−4.67	0.75
045	2.92	8.63	38.22	0.58
046	3.37	10.50	−7.03	0.62
054	2.77	8.28	24.38	0.51
074	2.68	8.83	20.74	0.40
077	3.03	11.38	11.16	0.56
092	2.67	8.74	30.19	0.46
094	3.57	10.42	23.83	0.66
099	3.13	8.81	18.42	0.62
103	2.03	6.50	48.57	0.40
Average	2.97	9.34	19.47	0.55
COV	0.17	0.16	0.84	0.20

Table 5 suggests that an average expenditure of $200 per home (labor and materials) has reduced the 50 Pa leakage rates by approximately 20%. The calculated effective leakage area (ELA) and the natural air infiltration estimates have each been reduced by about 28%. The airflow curve was calculated as follows:

$$Q = Cp^n$$

where

Q = airflow, l/s, and

p = pressure drop, Pa.

The airflow curve also changed: the pressure exponent, n, increased from 0.594 to 0.630 (reflecting a change from orifice to crack type leakage), while the average flow coefficient, C, decreased from 92.81 to 72.55 for the 12 homes.

Using the consumer's actual cost of electric power for space heating (average cost 4.55 ¢/kWh) the average annual cost of infiltration has been reduced from $135 to $104 for the twelve homes that were house doctored. The $31 annual savings per home, at an average retrofit cost of $200, indicates an average payback period of 6.5 years in constant dollars exclusive of interest costs.

Nagda et al. [*3*] indicate that a thorough retrofit of a fairly new site-built home can be expected to reduce the 50 Pa air exchange rate from 10.1 to 6.5, reflecting a 35% decrease in air leakage. The retrofit described by them includes extensive caulking, vapor barrier addition, taping, and sealing. According to the referenced report, two days were required for the retrofit work on one house. Actual retrofit costs were not reported.

Summary and Conclusions

In this study we have found that relatively new manufactured housing sited in the Pacific Northwest region of the United States has air leakage rates moderately lower than site-built homes. Ninety-three double-wide manufactured homes averaged 8.40 ACH at 50 Pa air pressure when tested with the blower-door depressurization method. Predicted natural air exchange rates averaged 0.50 ACH. A subset group of 25 homes within a large development produced statistically similar results.

A poorly correlated inverse relationship was noted of flow exponent, *n*, when plotted against specific leakage area. The highest leakers had average *n* values of 0.594, which increased to 0.630 after retrofitting. The overall average *n* value was 0.645 for the 93 homes in the as-found condition.

Major contributors to leakage have been found by smoke stick testing. The significant leakage areas were the marriage line between the halves of the home, the crossover ducting for the heating system, plumbing holes, windows, gaps around the shower or bath unit, and the area around the electrical panel. Glazing area was recorded for 46 homes; however, no meaningful correlation existed between glass area and leakage rates.

Twelve of the leakiest homes were house-doctored. With an average expenditure of about $200 (U.S.) per home, the leakage rates were reduced by about 20%. Of 16 homes checked for formaldehyde concentration, none exceeded the U.S. Department of Housing and Urban Development (HUD) recommended limit of 0.40 ppm.

Reference

[1] Ek, C. W., "Air Leakage Tests of New Manufactured Housing in the Bonneville Power Administration Service Area," Report ELMM 87-92, Bonneville Power Administration Division of Laboratories, Vancouver, WA, December 1987.

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[3] Nagda, N. L., Koontz, M. D., and Rector, H. E., "Energy Use, Infiltration, and Indoor Air Quality in Tight, Well-insulated Residences," EPRI Report EA/EM-4117, final report, Geomet Technologies, Inc., Germantown, MD, June 1985.

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APPENDIX

Detailed Test Data

TABLE A1—*Air leakage data of double-wide manufactured homes.*

Test Number	Envelope Area, m^2	Volume, m^3	Flow Equation: Exponent, *n*	Flow Equation: Coefficient, *C*	SLA, cm^2/m^2	ACH at 50 Pa	Natural ACH
056	315.50	256.94	0.679	24.824	1.51	5.01	0.26
105	434.23	409.74	0.685	40.529	1.81	5.25	0.28
106	371.14	338.44	0.678	36.344	1.88	5.50	0.34
053	315.50	256.94	0.585	41.521	2.03	5.80	0.39
113	392.70	322.75	0.610	47.628	1.98	5.83	0.38
080	383.50	323.38	0.635	43.173	1.95	5.84	0.35
024	330.17	280.08	0.668	34.185	1.93	6.06	0.36
064	333.43	275.15	0.613	42.040	2.08	6.12	0.39
B	446.95	381.82	0.646	51.895	2.06	6.21	0.39
098	451.32	370.04	0.599	61.951	2.19	6.35	0.43

TABLE A1—*Continued.*

Test Number	Envelope Area, m^2	Volume, m^3	Flow Equation Exponent, n	Flow Equation Coefficient, C	SLA, cm^2/m^2	ACH at 50 Pa	Natural ACH
119	449.74	378.25	0.644	53.237	2.09	6.36	0.40
068	387.03	328.39	0.652	45.097	2.10	6.42	0.38
093	384.62	288.74	0.637	42.246	1.91	6.44	0.38
118	304.35	234.04	0.626	35.737	1.99	6.45	0.37
121	362.50	297.07	0.626	45.655	2.14	6.49	0.42
008	366.59	304.21	0.699	35.756	1.96	6.61	0.30
049	354.33	306.30	0.655	42.809	2.19	6.62	0.38
081	357.67	289.93	0.640	43.635	2.14	6.71	0.41
025	353.68	250.86	0.604	43.828	2.00	6.76	0.46
050	351.08	277.93	0.622	45.785	2.19	6.85	0.42
109	450.85	371.91	0.751	37.320	1.88	6.90	0.34
097	332.31	241.34	0.631	38.241	2.00	6.91	0.42
SCH	447.14	405.07	0.611	70.560	2.58	6.92	0.45
120	328.69	254.96	0.651	38.010	2.08	6.93	0.40
086	430.14	364.15	0.641	57.297	2.34	7.05	0.42
C	327.39	256.77	0.636	41.323	2.19	7.05	0.45
042	371.42	311.06	0.658	46.026	2.26	7.07	0.40
100	395.48	333.12	0.708	40.515	2.10	7.09	0.36
026	377.18	316.30	0.731	35.223	2.02	7.10	0.34
070	256.13	194.31	0.651	29.840	2.10	7.16	0.33
073	393.16	318.22	0.660	47.521	2.22	7.19	0.36
084	414.62	351.15	0.607	65.593	2.57	7.30	0.47
082	357.67	289.93	0.637	48.210	2.35	7.34	0.43
034	295.34	243.75	0.683	34.040	2.23	7.36	0.32
041	384.06	305.76	0.788	28.535	1.83	7.43	0.31
085	323.95	256.10	0.633	43.899	2.34	7.44	0.46
038	346.90	278.49	0.632	48.232	2.39	7.48	0.45
067	295.80	239.67	0.675	35.181	2.26	7.49	0.43
108	422.43	343.28	0.622	62.327	2.49	7.55	0.72
F	403.47	358.37	0.627	64.639	2.72	7.64	0.49
071	371.42	320.03	0.624	58.502	2.67	7.66	0.48
039	429.30	364.69	0.652	59.961	2.51	7.68	0.45
055	390.93	338.27	0.636	60.726	2.70	7.88	0.47
057	449.83	401.53	0.634	72.680	2.79	7.88	0.49
110	451.13	379.90	0.642	67.290	2.63	7.96	0.48
087	365.85	312.95	0.628	59.904	2.79	8.13	0.51
090	548.49	448.11	0.676	71.194	2.47	8.17	0.44
079	319.77	251.59	0.612	51.770	2.66	8.23	0.53
107	397.25	342.35	0.660	59.773	2.76	8.41	0.53
069	454.01	400.54	0.678	65.172	2.75	8.42	0.46
044	338.44	276.71	0.587	64.462	2.95	8.42	0.55
043	307.41	260.63	0.674	43.063	2.66	8.43	0.38
088	402.82	343.11	0.662	59.473	2.73	8.44	0.51
052	417.69	332.95	0.664	57.869	2.57	8.52	0.47
078	339.37	278.97	0.633	54.773	2.78	8.52	0.52

TABLE A1—*Continued.*

Test Number	Envelope Area, m^2	Volume, m^3	Flow Equation Exponent, n	Flow Equation Coefficient, C	SLA, cm^2/m^2	ACH at 50 Pa	Natural ACH
083	323.95	256.10	0.625	52.423	2.74	8.59	0.54
A	360.83	295.46	0.705	44.308	2.50	8.61	0.48
111	442.77	364.69	0.662	65.046	2.71	8.66	0.51
101	258.45	213.62	0.581	52.245	3.10	8.67	0.58
075	365.38	300.67	0.702	46.349	2.56	8.75	0.38
048	321.63	260.99	0.657	48.020	2.72	8.75	0.50
095	394.28	308.37	0.678	53.176	2.58	8.90	0.50
G	356.84	306.10	0.668	55.099	2.89	8.95	0.45
013	453.73	396.77	0.635	81.790	3.13	9.01	0.57
089	425.31	347.93	0.653	67.494	2.87	9.11	0.56
066	450.85	392.58	0.742	54.509	2.68	9.24	0.54
001	410.63	363.95	0.612	79.755	3.19	9.35	0.47
D	360.09	290.56	0.614	68.181	3.13	9.43	0.51
104	447.05	399.77	0.702	66.808	3.03	9.51	0.48
114	346.53	285.29	0.623	58.993	2.88	9.54	0.49
112	411.56	363.33	0.651	76.041	3.32	9.73	0.57
046	367.80	313.75	0.564	92.731	3.72	9.81	0.74
011	406.54	359.11	0.661	73.332	3.33	9.90	0.74
E	322.00	278.75	0.634	63.778	3.42	9.95	0.79
063	382.85	317.03	0.704	55.666	2.95	10.04	0.53
058	332.78	268.44	0.665	55.132	3.08	10.09	0.57
051	321.26	252.24	0.657	54.034	3.07	10.22	0.61
040	284.47	225.82	0.645	51.821	3.23	10.43	0.52
102	378.58	344.19	0.577	103.590	4.15	10.51	0.74
036	296.27	246.67	0.563	78.890	3.91	10.54	0.63
076	359.62	296.05	0.629	73.126	3.48	10.55	0.68
099	334.45	276.45	0.545	97.094	4.09	10.80	0.85
054	333.05	274.47	0.591	81.733	3.84	10.95	0.73
062	248.51	185.79	0.671	40.650	3.08	11.01	0.60
074	359.07	297.55	0.628	77.815	3.70	11.14	0.58
037	401.52	320.35	0.652	76.474	3.43	11.15	0.66
072	332.78	247.40	0.660	61.573	3.40	12.01	0.58
122	410.63	351.21	0.647	92.230	4.01	12.04	0.58
092	382.48	315.81	0.690	72.897	3.75	12.52	0.66
103	362.04	281.98	0.560	109.195	4.40	12.64	0.93
077	325.72	253.77	0.668	65.280	3.75	12.81	0.73
065	375.14	298.40	0.633	88.955	4.10	12.95	0.77
045	315.12	255.81	0.543	117.292	5.22	13.97	1.09
Average	371.47	308.22	0.645	57.318	2.72	8.40	0.50
Standard deviation	53.03	52.97	0.042	18.272	0.69	1.93	0.15
COV	0.14	0.17	0.065	0.319	0.25	0.23	0.29

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Air Leakage Measurements in Dwellings in Turkey

REFERENCE: Tanribilir, A. H., Oskay, R., and Yener, C., "**Air Leakage Measurements in Dwellings in Turkey,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M.H. Sherman, Ed., American Society for Testing and Material, Philadelphia, 1990, pp. 165–179.

ABSTRACT: It has been necessary to check air leakage in dwellings due to complaints about thermal comfort and ever-increasing heating expenses. Airtightness of 18 rooms and air infiltration rate's of 34 rooms were measured using two blower doors and decaying tracer gas technique with nitrous oxide (N_2O). Due to their availability, Canadian and ASTM standards were used for measurement. One of the blower doors was designed and constructed in Turkey. The test rooms were selected from new, unoccupied multistory apartment buildings and two- or three-story dwellings. Airtightness of the rooms was about 2.64 to 20.54 air changes per hour (ACH) at 50 Pa indoor-outdoor air pressure difference, while air infiltration rates were in the range of 0.16 to 1.99 ACH. To compare this with test results obtained abroad and with Turkish standards, normalized air leakage areas and air permeabilities of windows were also calculated from the results of airtightness experiments. They were found to be in the range of 0.57 to 24.45 cm^2/m^2 and 1.7 to 4.5 $dm^3/(s.m)$, respectively, at 10 Pa indoor-outdoor air pressure difference.

KEY WORDS: air leakage, air infiltration rate

In Turkey, heating load calculations for buildings are made with a method very similar to that described in the German Standard DIN 4701 Regeln für die Berechnung des Warmebedarfs von Gebauden issued in 1959. The parameters used in the calculation are even the same as those of this standard. Since materials and workmanship used in constructing buildings influence the air infiltration rate in buildings, properties determined for Germany by DIN 4701 don't give reliable results when applied in Turkey, which has different meteorological conditions than Germany. On the other hand, an ever-increasing rise in fuel prices in Turkey has given rise to a decrease in fuel consumption for space heating. Thus, indoor air temperatures are usually maintained lower than the design values. As a result, precautions such as sealing window cracks have been taken against heat losses. Air renewal generally based on these openings has been restricted if not cut out. So, new problems such as condensation of water vapor on cold inside surfaces in addition to insufficient heating and natural ventilation have developed.

History of Air Leakage Measurement in Turkey

Laboratory experiments and field tests to overcome these difficulties have not begun on a large scale yet. An attempt has been made to determine air infiltration rate of prefabricated

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dwellings constructed for survivors of earthquakes in Turkey [*1*]. To check the air permeability of a few windows, laboratory experiments have been performed at the research laboratory of the Ministery of Construction and Settlement [*2*].

In the Building Research Institute of Turkey (TUBITAK-YAE), two research projects on air leakage of buildings have been conducted since 1983. In the first project, a pressurization test unit to measure airtightness of buildings has been designed and constructed [*3*]. In the second project, field tests referred to in the following pages have been performed utilizing the pressurization test unit, among other instruments [*4*].

Test Rooms

Experiments were performed in new, not yet occupied buildings in two sites within the suburbs of Ankara.

First Site

The buildings in the first site were constructed using tunnel formwork technology. Eighteen of the test rooms are in an 18-story apartment building which has four flats on a floor, and two test rooms are in two-story dwellings. Test rooms in the apartment were selected on three floors (the top, middle, and bottom floors) such that their locations are symmetric with respect to one of the diagonals of the floor which has a square cross section. Two of the test rooms are at diagonally opposite corners. There are two test rooms neighboring the corner room at two sides. The corner room has two windows, one on each of its external walls. The other rooms have one and three windows, respectively, on their unique external walls, which are coplanar with the external walls of the corner room. The windows are sealed, double glazed, and have single sashes (75 by 115 cm^2) hung on side. The test room with three windows also has a balcony door (80 by 190 cm^2) that has the same properties as the windows. The window and door sashes were made of wood. (See Fig. 1.)

The test rooms in the two story dwelling of terrace type are on the top floor. Each has one external wall on opposite facades of the dwelling. One of the rooms has two windows (60 by 90 cm^2, 95 by 90 cm^2), one hung on side and the other hung at bottom, and the other room has a balcony door (85 by 200 cm^2) and a window (45 by 85 cm^2) hung at bottom. The windows and the balcony door are unsealed, single glazed, and have wood, single sashes. (See Figs. 2*a* and 2*b*.)

Top floors of the multistory building may be taken as exposed to wind, and the other floors and the two-story dwellings are considered to be wind shielded as far as terrain is concerned. The internal doors (80 by 200 cm^2) have no threshold, but in some rooms the carpet on the floor may even make it difficult to operate the door.

In the multistory building, tracer gas experiments were made in each test room, but airtightness of only three of the test rooms in the same flat were measured on each floor.

Both the tracer gas experiment and airtightness tests were made in each of the rooms in the two-story dwellings.

Second Site

There were multistory apartment buildings constructed by different technologies and three-story dwellings erected by tunnel formwork technology in the second site.

In the four-story apartment buildings constructed by cell unit system, only one room on the top floor could be tested for air infiltration rate and airtightness. The room has one single sash window hung on side (75 by 135 cm^2) and a balcony door (70 by 200 cm^2) on its external wall. The buildings have been constructed such that three apartment buildings form a block by sharing their side walls. Each building has two flats on a floor. (See Fig. 3.)

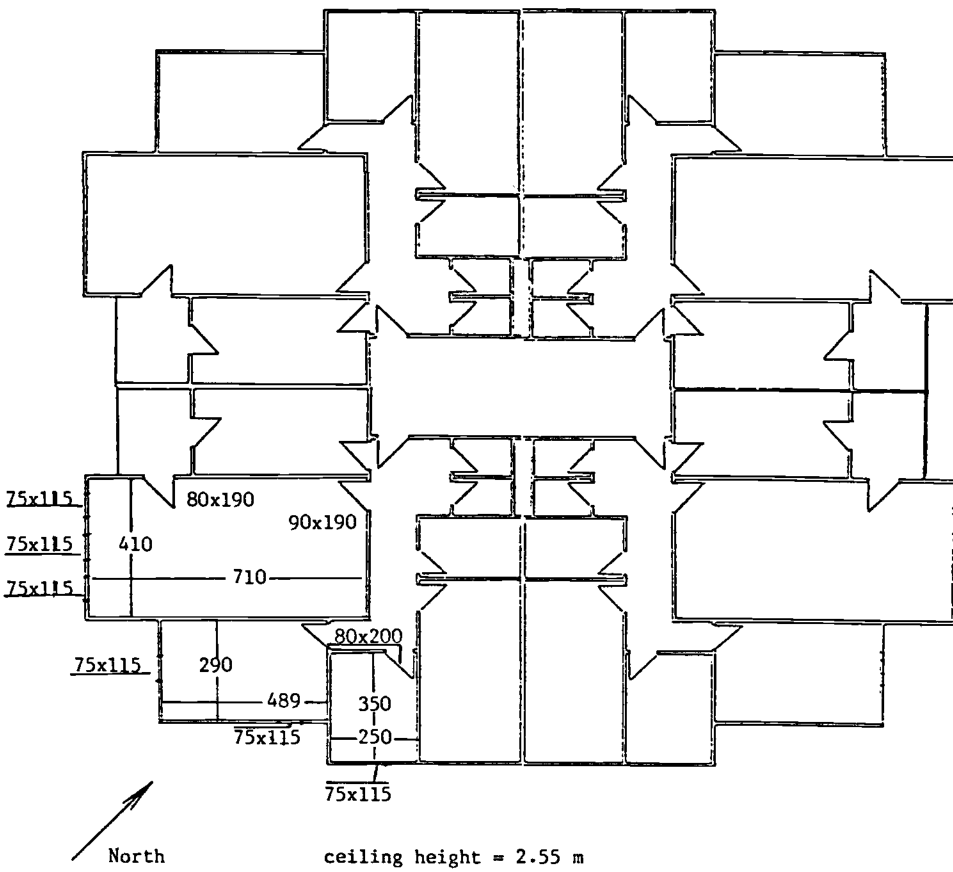


FIG. 1—*Floor plan of the multistory apartment building in the first site.*

In the second site, a group of five-story buildings, floor plan of which is given in Fig. 4, have been erected by the folded precast system. The test rooms, one at the top floor and the other at the bottom floor, have two single sash windows hung on side (65 by 125 cm^2) on their unique external walls. Blocks have been formed by constructing three apartment buildings side by side with common walls. A tracer gas experiment was made in each of the test rooms, but only the room at the bottom floor was checked for airtightness. There are two flats on a floor in each apartment building.

Ten-story apartment buildings, shown in Fig. 5, have been erected by tunnel formwork technology. They have four flats on a floor. Two rooms, one on the bottom floor and the other on the middle floor, have been tested for air infiltration rate. On the bottom floor test room, an airtightness experiment has been performed as well. The test rooms have two single sash windows (85 by 115 cm^2) hung on side on their external wall.

Traditional technology has been utilized to construct another group of five-story apartment buildings, the floor plans of which are given in Fig. 6. The test rooms, one on the top and the other on the bottom floor, have one single sash window (65 by 135 cm^2) hung on side. Again, both rooms were tested for air infiltration rate. The airtightness experiment was made only in the bottom floor test room.

The test rooms, on different floors in the multistory buildings in the second site, have been selected so that their external walls with windows face the same direction.

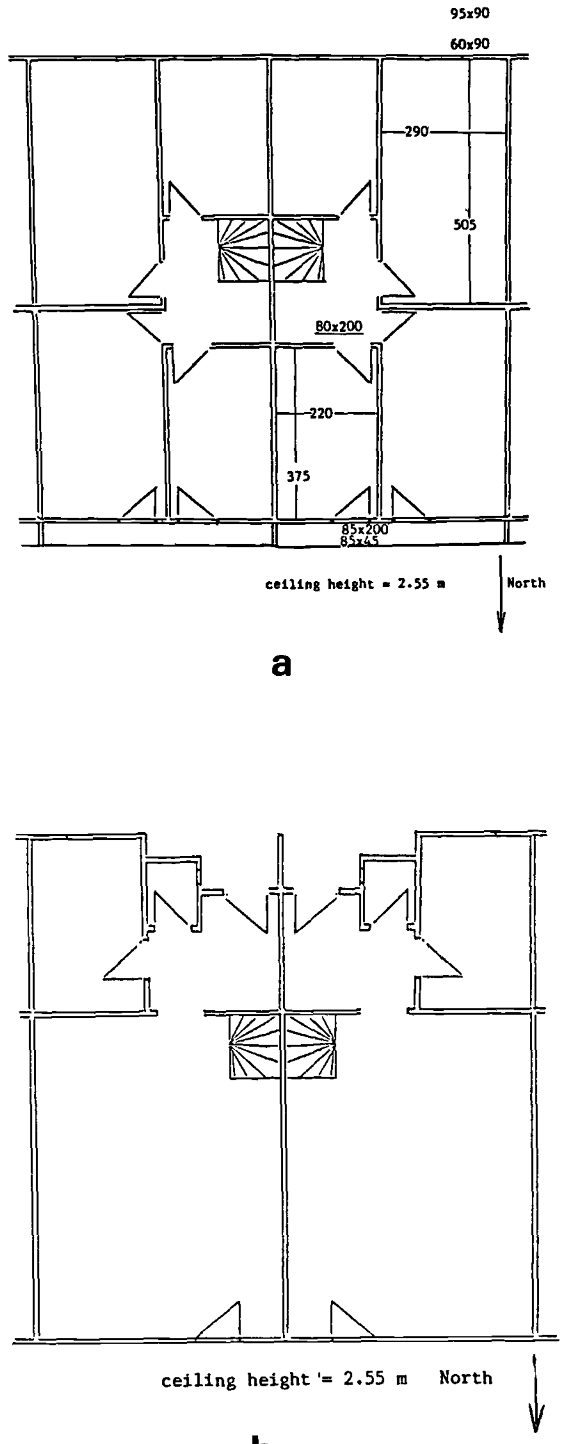


FIG. 2(a,b)—*Floor plans of the two-story dwelling in the first site.*

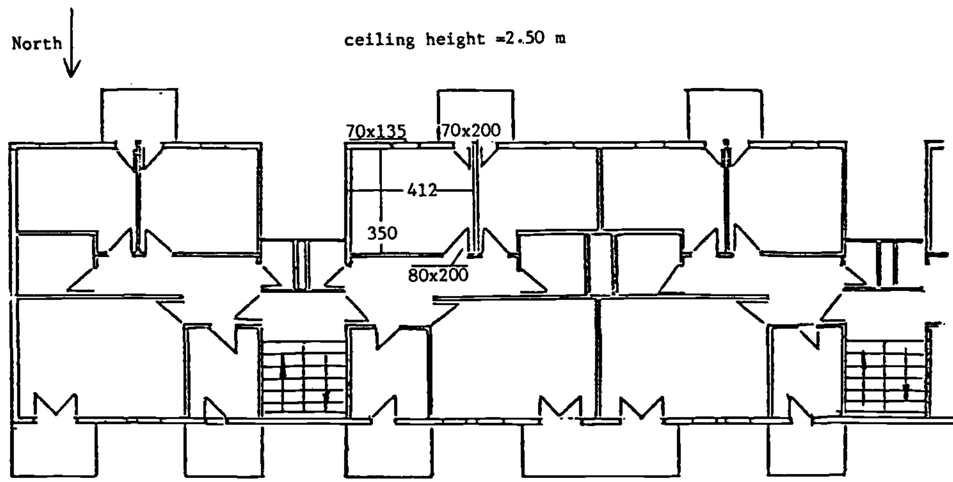


FIG. 3—*Floor plan of the four-story apartment building constructed by the cell unit system in the second site.*

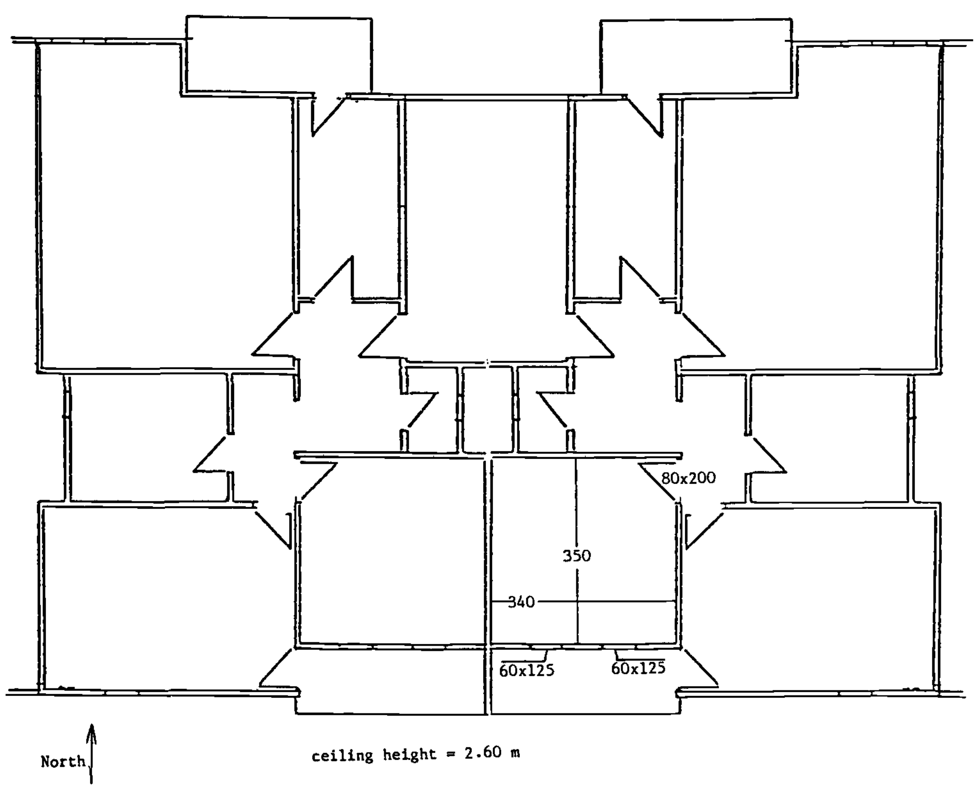


FIG. 4—*Floor plan of the five story apartment building constructed by folded precast system in the second site.*

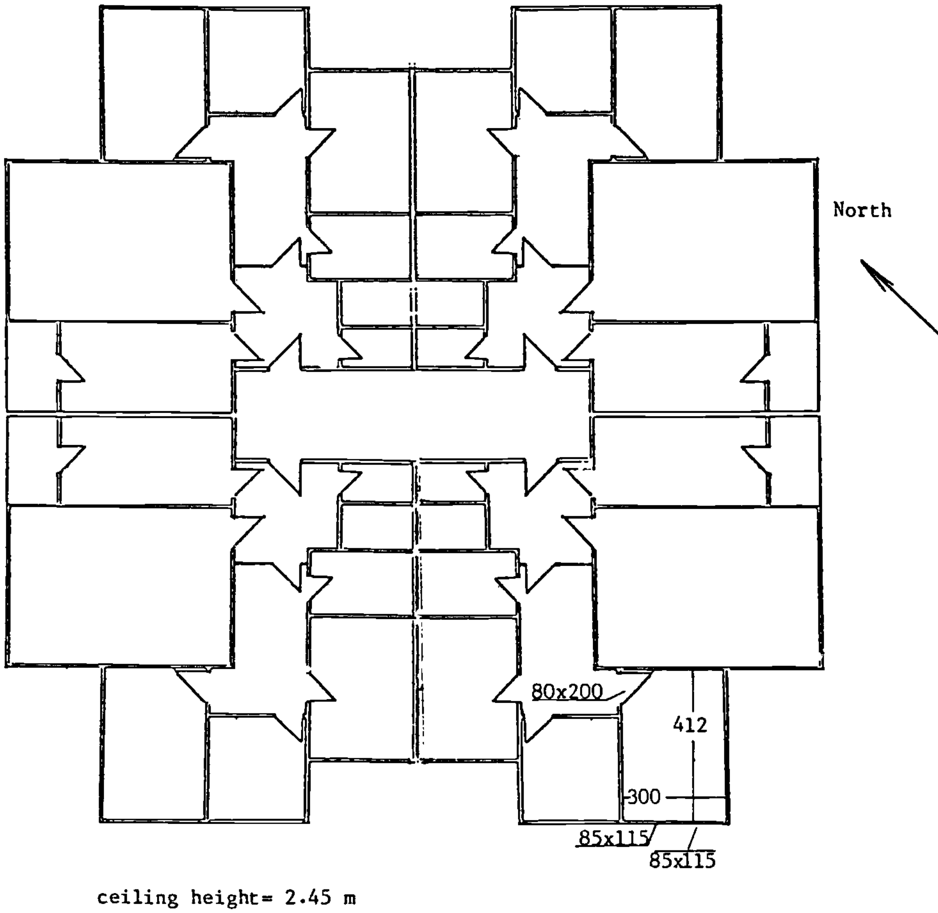


FIG. 5—*Floor plan of the ten-story apartment building constructed by tunnel formwork technology in the second site.*

A total of seven rooms, four in one dwelling and three in the other, selected from two dwellings with three-stories constructed by formwork technology, have been tested in the second site. Three of the rooms in one dwelling have a similar location with the three rooms in the other dwelling. One of these three rooms is on the bottom floor, and the other two rooms are on the top floor. The test rooms on the bottom floor have three windows: a small single sash window (40 by 45 cm^2) hung at the bottom on one wall and two single sash windows (70 by 145 cm^2) hung on the side on the other wall. The other similar test rooms on the top floor of the dwellings have single sash windows (70 by 145 cm^2) hung on side. Two of these rooms have balcony doors (65 by 235 cm^2) as well. The seventh test room, which is unique and on the top floor, has a single sash window (60 by 95 cm^2) hung on side. Four test rooms (i.e., all types of the test rooms) were tested for airtightness. Tracer gas experiments were performed in all of the test rooms in the tree-story dwellings.

Six of the dwellings, the floor plans of which are shown in Figs. 7*a*, 7*b*, and 7*c*, having common side walls, form a block. The windows are double glazed and sealed. Similar rooms in the two dwellings face the same direction.

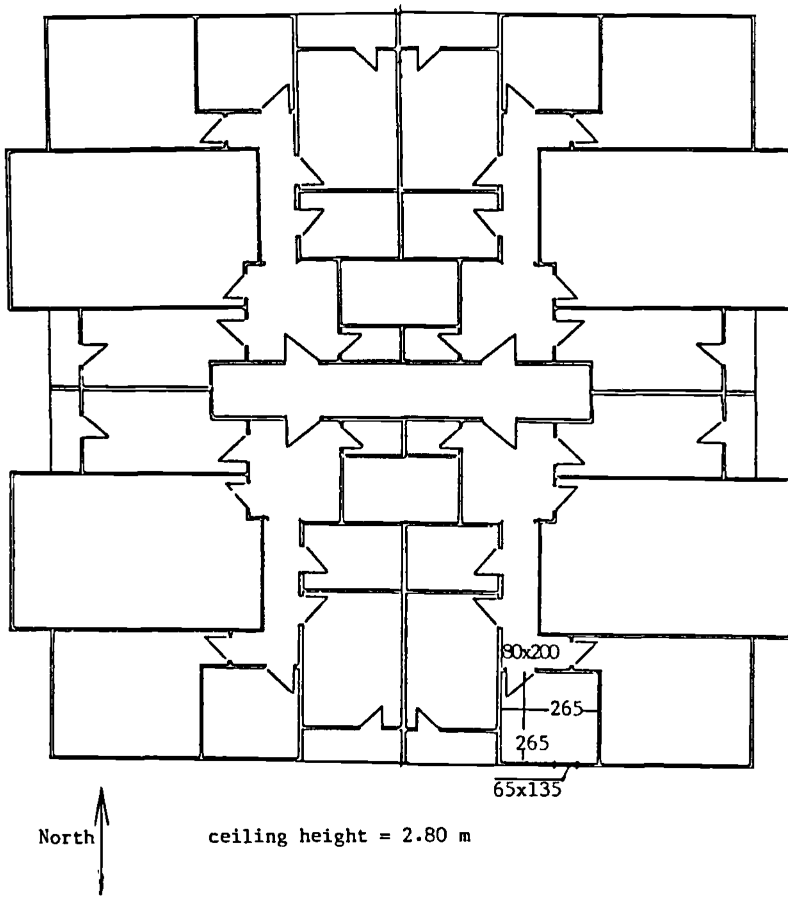


FIG. 6—*Floor plan of the five-story apartment building constructed by traditional technology in the second site.*

All the windows and the internal doors (80 by 200 cm^2) have wood sashes, and the internal doors are without a threshold in the second site. The buildings in the second site are wind shielded from a terrain point of view.

None of the dwellings tested have a mechanical ventilation system since this is not widely used in Turkey.

Instruments

Two blower doors were used in the airtightness experiments. One was imported from the United States and the other was designed and constructed at the Building Research Institute in the project. Both have similar properties.

The blower door constructed in the project, called, "pressurization test unit" and shown in Fig. 8, can blow 2.5 m^3/s of air at 50 Pa pressure difference by a 500-mm diameter, speed controlled axial fan.

Its flow rate is read from a calibration curve obtained due to ASHRAE standard 51–74

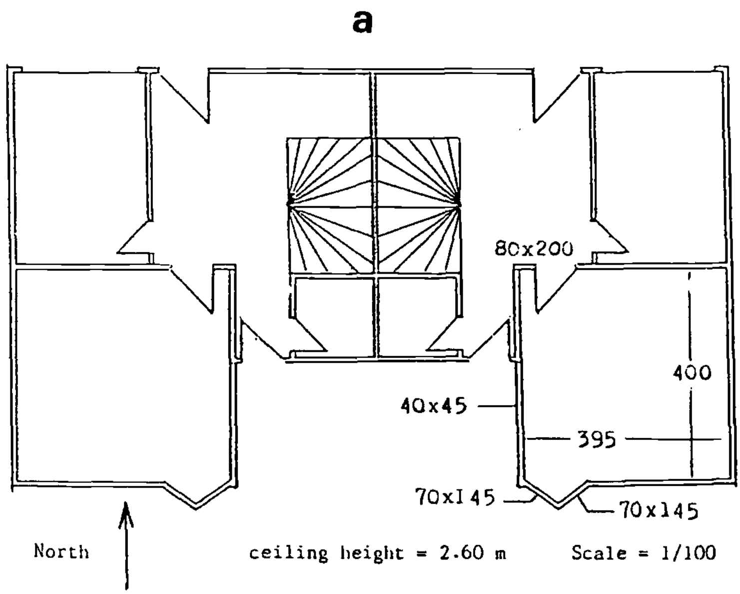


FIG. 7—*Bottom floor plan of the three-story dwelling in the second site.*

about Laboratory Testing of Fans for Rating. Indoor-outdoor air pressure difference and the head of the fan are read from inclined manometers filled with ethanol. The manometers have an accuracy of ±2 Pa.

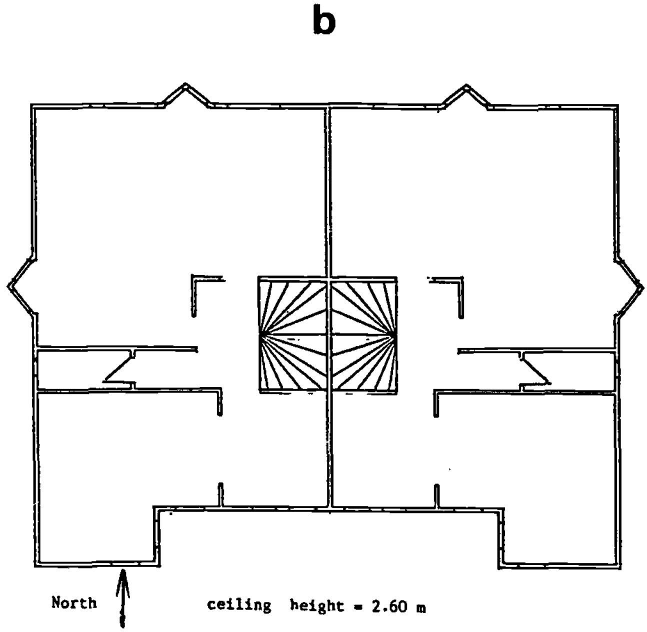
Tracer gas experiments were made using nitrous oxide with an infrared gas spectroscope that has a range of 6000 ppm by volume. Its accuracy is ±10 ppm.

Field Tests

Blower door experiments were made according to the Canadian Standard "CAN2.149.10-M84. Determination of Equivalent Leakage Areas of Buildings," but it is similar to ASTM Method for Determining Air Leakage Rate by Fan Pressurization Test (E 779-81). Indoor-outdoor air pressure difference was decremented by 5 Pa from 50 to 15 Pa for pressurization and depressurization of the test room. At each step, the difference between indoor and outdoor air pressures and air flow rate of the fan have been determined. The indoor air pressure tap was placed in the middle of the room, while the outdoor air pressure tap was on the exterior surface of the window that exists in the neighboring room external wall that is coplanar with the external wall of the test room.

Tracer gas experiments were made due to the ASTM Test Method for Determining Air Leakage Rate by Tracer Gas Dilution (E 741-83). The experiment was started by feeding the gas into the space with its door closed. After 45 min of mixing period, concentration of the tracer gas was recorded with 5-min intervals. The samples were taken through the gas analyzer hose whose end is located at the center point of the test room. The 5-min interval was selected due to statistical calculations for 99% reliability of the results [5]. In the test rooms in a dwelling, tracer gas experiments were performed at different times so that tracer gases in different test rooms did not intermix.

During the blower door and tracer gas experiments, outdoor meteorological conditions such as dry bulb temperature, relative humidity, atmospheric pressure, wind speed, and direction at building roof height were measured hourly. Test room dry bulb temperature was recorded before and after the experiments.



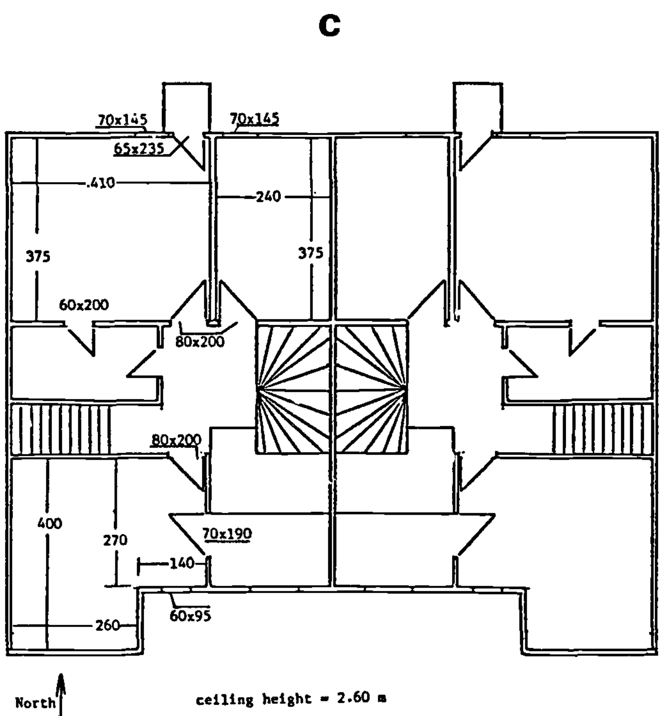


FIG. 7(b,c)—*Middle and top floor plans of the three-story dwelling in the second site.*

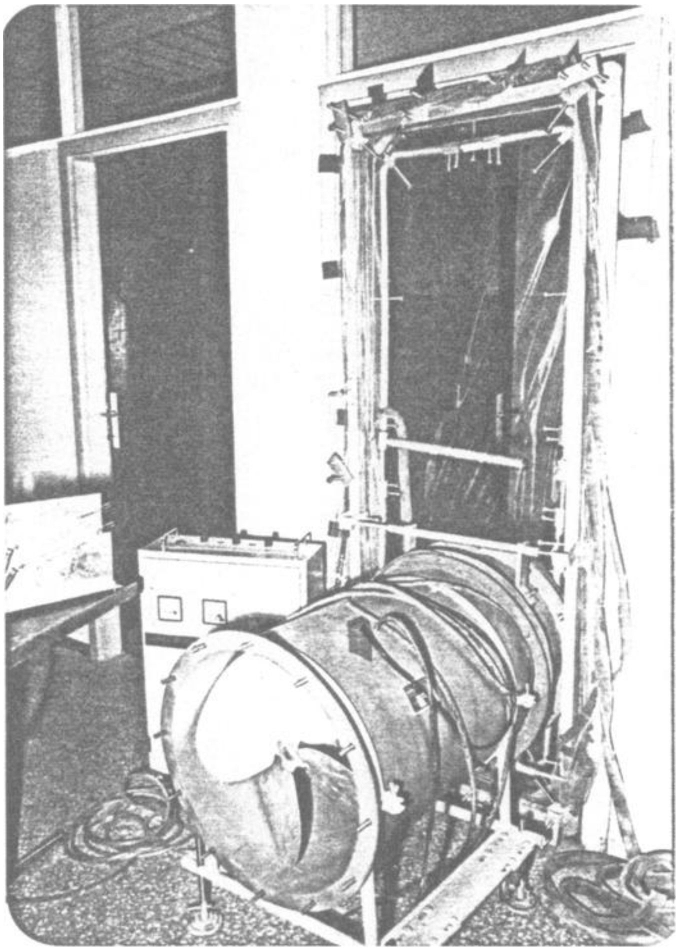


FIG. 8—*Pressurization test unit.*

Results

It was observed that some of the windows permitted rain to enter test rooms through the cracks between the window sash and the frame despite the seals.

The airtightness of the test rooms at indoor-outdoor air pressure difference of 50 Pa varied from 2.64 to 20.54 ACH. Normalized equivalent leakage areas obtained at 10 Pa air pressure difference of indoor and outdoor from blower door experiment results were in the range of 0.57 to 24.45 cm^2/m^2. One can calculate air permeability of windows from the air leakage rate obtained from the blower door experiment at 10-Pa air pressure difference between indoor and outdoor with the assumption that air leakage areas exist only around external windows and external doors. It was found that air permeability of windows with and without seals were about 1.7 to 4.5 $dm^3/s \cdot m$.(see Table 1.)

Plotting the logarithm of the tracer gas concentration with respect to time, the slope of the straight line fitted to the data of a test room gives the air leakage rate due to infiltration of the room. The air change rate of the test rooms was found to be in the range of 0.16 to

TABLE 1—*Some results of tracer gas and airtightness experiments.*

Test Room No.	Story No.	Exterior Wall Direction(s)	Airtightness at 50 Pa, vol/h		Air Infiltration Rate, vol/h	Related Figure(s)	Meteorological Conditions During Tracer Gas Experiment	
			Press	Depress			Wind (m/s) Blowing From	$\Delta T = T_{in} - T_{out}$, °C
31	18	S	1.38	4.08	0.42	1, 9a	0	8
32	18	SW	3.08	2.25	0.74	1, 9b	0.7 N	8
33	18	SE	4.43	4.43	0.4	1, 9a	3 E	12
34	10	NW	2.19	...	0.37	1, 9b	0	11
35	10	NE	2.83	...	0.66	1, 9b	0.7 W	12
36	10	N	1.47	...	0.23	1, 9b	0	10
37	2	NW	3.96	...	1.47	1, 9b	3 SW	7
38	2	NE	3.24	...	1.46	1, 9b	3 SW	7
39	2	N	4.21	2.87	1.26	1, 9a, 9b	3.5 N	19
40	1	S	20.05	20.14	0.39	2a, 9a, 9b	0.5 SW	4.5
41	1	N	6.43	6.33	0.46	2a, 9a, gb	0.6 E	1
42[a]	Bottom	SW	43.6	35.11	0.75	7a, 9a, gb	0	−1
43	3	SW	19.63	22.96	0.75	7c, 9a, 9b	0.7 NW	10
44[a]	4	SE	11.53	10.98	0.87	3, 9a, 9b	0.1 W	0
45[a]	Bottom	S	5.33	5.09	0.41	5, 9a, 9b	1.5 SE	−1
46[a]	Bottom	S	5.01	4.1	1.89	4, 9a, 9b	4 NW	−7
47[a]	Bottom	S	3.51	3.79	0.32	6, 9b	4 N	−9

[a] Without heating (the heating system was not operating during the experiments).

1.99 ACH with wind speed up to 5 m/s from several directions and for indoor-outdoor air temperature differences of about 15 K.

Discussions

Penetration of rain through window cracks despite the seals shows that the crack areas around window sashes are important. Large values of air leakage rate obtained from blower door experiments support this idea. On the other hand, leakage areas between window frame and wall most probably contribute to these values as well.

Investigation of leakage areas mentioned in the literature showed that in the test rooms selected, the only leakage areas were around windows. Although the buildings were constructed by prefabrication techniques, due to the location of the test rooms in buildings there were no leakage areas at the intersection of ceilings, walls, and floors. Each electrical outlet was in a metal box whose surfaces were covered by paper and embedded in the wall. So, air leakage paths through electrical outlets were not to be of great importance. Thus, the only important leakage areas were between window sash and frame and window frame and exterior walls holding the frame. The walls themselves were taken as airtight as well. Based on these observations and determinative assumptions, pressure balancing in neighboring rooms was not maintained during the blower door experiments. Air permeabilities of windows were calculated, due to the above discussion, from air leakage rate obtained at 10 Pa of indoor-outdoor air pressure difference in blower door experiments. Air permeabilities of the windows in the test rooms were found to be higher than those mentioned in the standards and than those obtained in experiments made abroad, as shown in Figs. 9*a* and 9*b* [*6,7*]. Comparison normalized of equivalent leakage area values obtained from the results of blower door experiments at an indoor-outdoor air pressure difference of 10 Pa with the results obtained abroad showed that the results in Turkey were scattered through the range obtained in other countries as shown in Fig. 10 [*8*].

Repeated blower door experiments assured the reliability of results. It can be said that demand in Turkey, being larger than the supply of buildings, gives rise to ignoring standards and to poor quality of material and workmanship. Mistakes in the application of prefabrication technologies certainly affect the results as well.

To compare with the air permeabilities calculated from the results of blower door experiments, direct measurement of air permeability of exterior windows was not possible due to the restriction of not harming the test rooms established by the landlords of the dwellings.

Preferring nitrous oxide in the tracer gas test was due to availability of the gas in Turkey. Simultaneous detection of the tracer gas at several locations in test rooms showed that mixing of the tracer gas and air was satisfactory in the rooms. So, taking samples only from the central point of test rooms was adequate. Turkish standards for air renewal of spaces in dwellings other than kitchens and toilets have not been issued yet. Compared with available standards and test results in the literature, the air renewal rate of test rooms obtained were rather high so as to assure high air permeabilities of windows calculated from blower door experiment results.

Conclusion

The blower door experiments of the test rooms showed that their airtightness and related properties have rather high values. Results of tracer gas experiments support this conclusion as well. Based on the German standard DIN 4701, the current Turkish standard underestimates the heating load item due to infiltration. On the other hand, the test lot should be increased to make more rigid and reliable comments leading to revision of related Turkish standards.

a

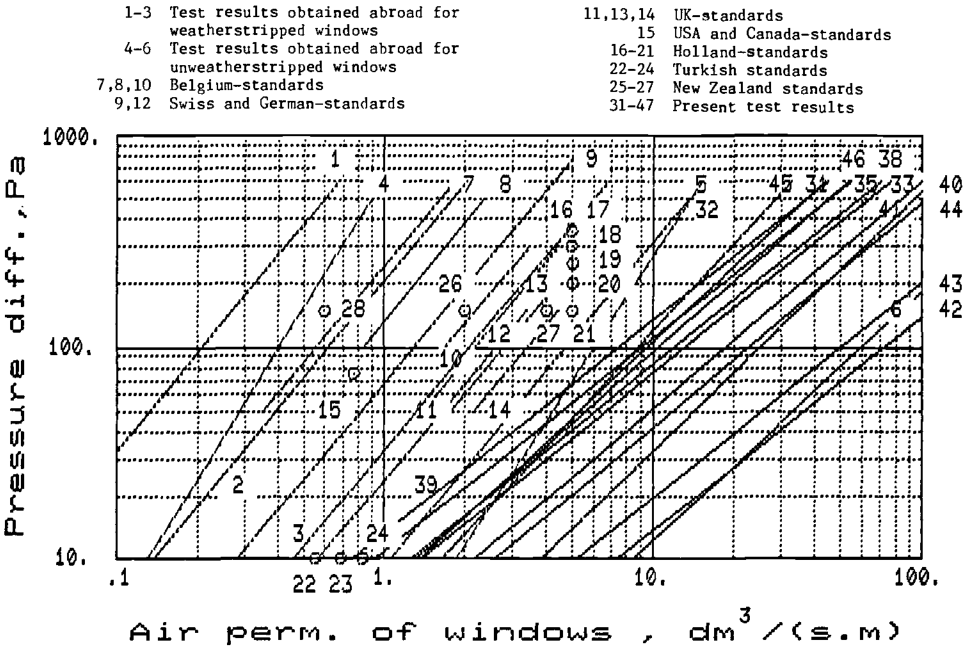
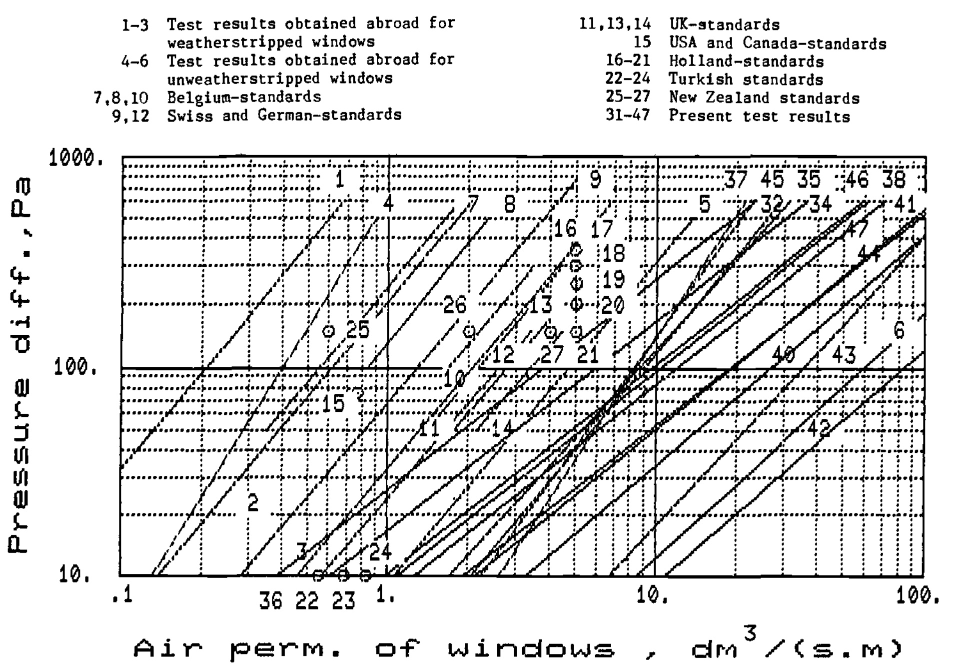


FIG. 9—(a)*Air permeability values for depressurization;*

b



(b) *air permeability values for pressurization.*

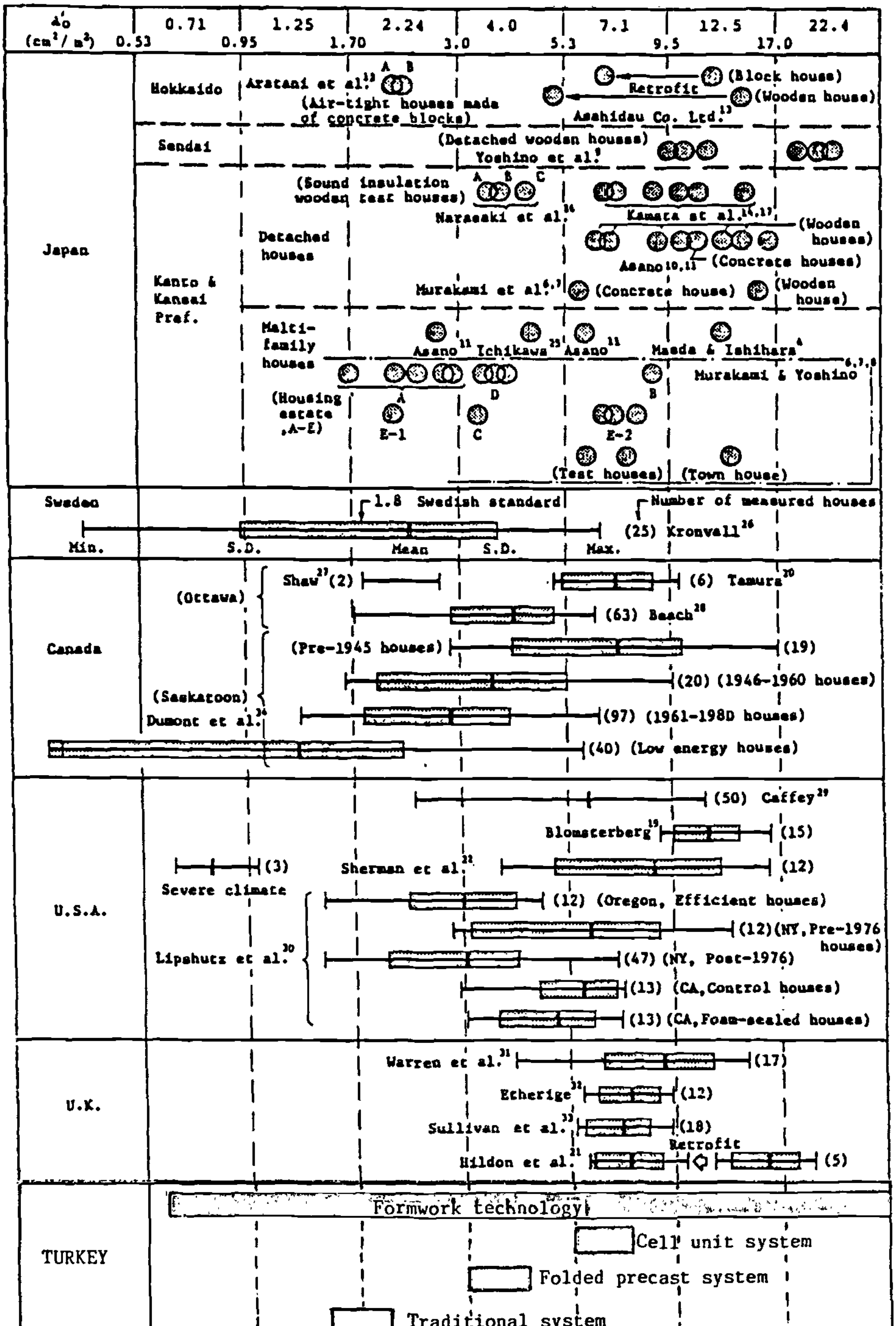


FIG. 10—*International normalized equivalent air leakage areas of spaces* [8].

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Multizone Leakage

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Investigation of a Fan-Pressurization Technique for Measuring Interzonal Air Leakage

REFERENCE: Modera, M. P. and Herrlin, M. K., **"Investigation of a Fan-Pressurization Technique for Measuring Interzonal Air Leakage,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 183–193.

ABSTRACT: Although the prediction of airflow through single-zone buildings has improved significantly during the past ten years, the more complex problem of predicting airflows in a multizone building has seen relatively little progress. One impediment to the solution of this problem has been the lack of reliable measurements of the flow resistances between the zones of such a building. This report analyzes a fan-pressurization technique for measuring the interzonal leakage (inverse flow resistance) in a multi-zone building. The technique involves two blower doors, one in each of the two zones between which the leakage is being measured. The evaluation of the technique is based upon simulations using MOVECOMP, a multizone infiltration and ventilation simulation program, which is used to determine what data would be recorded when using the procedure in a multifamily building under typical wind conditions. These simulations indicate that wind-induced uncertainties in the determined leakage parameters do not exceed 10% for wind speeds lower than 5 m/s. By performing additional simulations, the effects of wind conditions, building location, and measurement protocol on the uncertainties in the measured leakage parameters are examined in detail. These examinations highlight the importance of using an appropriate reference for the pressure difference across the primary-zone envelope.

KEY WORDS: building, leakage, airtightness, multizone, fan pressurization, simulation, measurement, infiltration

Although the prediction of airflow through single-zone buildings has improved significantly during the past ten years, the more complex problem of predicting airflows in a multizone (e.g., apartment) building has seen relatively little progress. One impediment to the solution of this problem has been the lack of reliable measurements of the flow resistances between the zones of such a building [*1*].

Several multizone leakage measurement techniques have been tried over the past several years, some of which determine only the effective leakage area (ELA) of the interzonal path, while others determine both the flow coefficient and flow exponent needed in power-law models of crack flow. One technique used six blower doors simultaneously to measure the total envelope leakage area of a six-unit building and used single-zone blower-door measurements to measure the total leakage area of each apartment, which in combination were used to determine the split between exterior-envelope and interzonal leakage. The data taken with this technique were used in a multizone infiltration model by apportioning

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the interzonal leakage area by surface area and assuming a constant flow exponent [2]. Another technique used two blower doors simultaneously to measure each interzonal flow path, measuring the flow required to maintain several nominal differential pressures between the primary zone and outdoors, with and without pressurizing the secondary zone to the same pressure as the primary zone. With this technique, the leakage area of the primary zone could be determined with and without the interzonal path, or the flows at each nominal pressure differential could be subtracted and used to obtain the flow exponent and coefficient of the interzonal path [3].

Based upon the authors' personal experiences with multizone leakage measurement techniques, the measurements seem to be more sensitive to wind than standard single-zone blower-door techniques. This increased wind sensitivity has been attributed to a number of effects, most notable the fact that any wind-induced uncertainties in the measured blower-door flow rates are compounded by the flow subtractions used in multizone techniques and also the fact that multizone buildings are usually taller than single-family residences and are therefore subjected to higher wind speeds. We therefore decided to make a systematic evaluation of the effects of wind on multizone leakage measurements made with a two blower-door technique. However, due to the considerable expense, logistical difficulties, and the uncontrolled nature of field experiments, we decided to evaluate the effects of wind using a detailed multizone airflow network model.

Multizone Measurement Technique

The multizone leakage measurement technique that we examined utilizes two blower doors, one in each of the zones adjacent to the leakage path being measured. The technique is to maintain a constant indoor-outdoor pressure differential in one zone (e.g., 50 Pa), while simultaneously varying the pressure in the second zone. Thus, for a series of differential pressures (e.g., between 0 and 50 Pa) between the primary and secondary zones, the flow rates required to maintain the constant pressure differential between the primary zone and outdoors are recorded. This technique was chosen because of two potential advantages over the techniques that have been examined in the past. First, because the primary zone is kept at a constant large pressure differential relative to outdoors, the effects of wind on the measured flow should be reduced. Also, because the pressure differential across the leakage path is measured directly and need not be specified precisely, the uncertainties associated with controlling two fans to maintain a zero pressure differential across the leakage path while maintaining a specified pressure differential between the primary zone and outdoors are eliminated.

Assuming that the flow from the primary zone to adjacent zones and outside is maintained constant, the flow through the fan pressurizing the primary zone can be expressed as

$$Q_p = Q_{pout} + k_{ps}\,\Delta P_{ps}^{n_{ps}} \tag{1}$$

where

Q_p = the total flow into the primary zone (i.e., measured by the fan), m^3/s,
Q_{pout} = the flow from primary zone to outside and to all zones except the secondary zone (assumed to be constant),m^3/s,
k_{ps} = the flow coefficient of the leakage path between the primary and secondary zones, $m^3/s\ Pa^n$,
ΔP_{ps} = the pressure difference between the primary and secondary zones, Pa, and
n_{ps} = the flow exponent of the leakage path between the primary and secondary zones, dimensionless.

Equation 1 relates the fan flow to the leakage-path pressure differential via three parameters, Q_{pout}, k_{ps}, and n_{ps}. Thus, by performing a nonlinear search for the three parameters based upon a series of pressure-difference/fan-flow pairs, both the flow exponent and coefficient are obtained.

In addition to Eq 1, there are a number of methodology options associated with using this technique, many of which have significant implications for the uncertainty associated with the leakage characteristics determined. The options which have to be addressed by any examination of the technique include: (1) what pressure differential to maintain between the primary zone and outdoors; (2) how to choose the outside pressure upon which to base the pressure differential between the primary zone and outdoors, (3) how to specify the leakage conditions of the adjacent zones (i.e., open or closed windows), (4) how many pressure-differential/fan-flow pairs to use for a measurement, and (5) what operator technique and instrumentation to assume for obtaining the pressure-differential/fan-flow pairs. The reference technique examined was chosen based upon a combination of uncertainty-reduction and practical-application considerations. The chosen configuration uses 50 Pa as the primary-zone/outside pressure differential (due to practical limitations of fan size), uses a pressure-averaging probe covering the three exterior facades of the primary zone for the outside pressure (to reduce uncertainty), assumes that the windows and doors of adjacent zones are closed during the test (based upon the practical difficulties associated with having all windows in an apartment building open at the same time), and uses six pressure-differential/fan-flow pairs (to conform with customary measurement practices). To gauge the sensitivity of our results to these assumptions, the effects of each of these choices on measurement uncertainty are examined individually at a typical wind condition. In addition, to obtain each pressure-flow pair it is assumed that the operator adjusts the fan flow so as to maintain the 50-Pa differential between the primary zone and outdoors and then records the fan-flow and interzone pressure differential simultaneously. It is further assumed that the observed pressures are not affected by wind speed fluctuations at frequencies higher than 0.25 Hz (period < 4s) or at frequencies lower than 1.67×10^{-3} Hz (period > 10 min).

Test Conditions

As for any simulation-based study, a number of decisions had to be made in choosing the conditions under which to examine the technique. These conditions included: the type of building, the choice of primary zone, the choice of leakage path, the total and interzonal leakage levels, the degree of shielding, and the type of wind. Due to the limited scope of this paper we decided not to include the uncertainties stemming from the pressure and flow measurement equipment. The effects of these uncertainties on the determination of the leakage characteristics can be included in the simulations in a manner similar to that used for the wind. The reference set of test conditions chosen and the reference technique described above are summarized in Table 1.

The building chosen for the reference simulation is typical of those built around the turn of the century in many U.S. cities, similar to the buildings measured by Modera [*2*] and Diamond [*3*]. The range of wind speeds was chosen to bracket the typical average wind speed of 4 m/s and to show what kind of improvement can be expected at lower wind speeds. This examination of lower wind speeds necessitated the use of a positive definite wind speed distribution, in this case lognormal. The wind variance was chosen to conform with a small city environment and as a compromise between unstable (clear sky) and neutral (overcast) wind conditions [*4*]. The choice of wind variance was assumed to be an important issue as the variation in wind speed over the course of a test is what creates the measurement uncertainties described below. Assuming perfect instrumentation accuracy as we have, mea-

TABLE 1—*Reference simulation description.*

Building type	Three-story multifamily with two units/floor
Primary zone	Second-story apartment
Leakage path	Between two second-story apartments
Total leakage	Relatively high, specific leakage area = 10 cm^2/m^2, flow coefficient k = 0.017 m^3/s Pa^n per surface, flow exponent n = 0.65
Interzone leakage	17% of total (i.e., equal leakage for all six surfaces)
Shielding	Average of unshielded and surrounded by similar-height buildings
Mean wind speed	1 to 6 m/s
Wind distribution	Lognormal
Wind variance	Average variance of unstable and neutral conditions
Wind directions	Towards primary zone, towards secondary zone, parallel to common wall
Primary zone pressure	50 Pa
Outdoor pressure reference	Linear average of three facade pressures
Adjacent apartments	Closed windows and doors
Measurements	6 pressure-difference/fan-flow pairs (0, 10, 20, 30, 40, 50 Pa)

surements made during a constant wind speed have no uncertainty. Table 2 contains a summary of the wind variances used for the simulation.

Network-Model Simulation

The principal method used to examine the wind-induced uncertainties associated with the multizone leakage measurement technique was to simulate the measurements that would be made under field conditions. These simulations were based upon MOVECOMP, a multizone infiltration and ventilation simulation program, the major features of which are described in the *Air Infiltration Review* [5,6]. The program is based on a steady state model; however, the quasisteady analysis utilized is justified by the fact that the time constant of the zone being tested is on the order 0.01 s. Due to the flexibility and speed of the program, the leakage-measurement technique could be examined under a large range of conditions.

Given the reference technique and reference measurement conditions, the simulation proceeds as follows. For each mean wind speed and wind direction, 200 measurements of the leakage coefficient (k) and the leakage exponent (n) are simulated. Each of these measurements is obtained from six pressure-flow pairs, one for each of six interzonal pressure differentials (i.e., ΔP_{ps} = 0,10,20,30,40,50 Pa). To obtain each pressure-flow pair, a wind speed is chosen at random from a lognormal distribution with the specified mean and variance. As using 200 simulated leakage measurements was found to provide repeatable values for the bias and uncertainties in the leakage parameters, a new random set of 1200 wind speeds was generated for each mean wind speed. At each wind speed, surface pressures

TABLE 2—*Wind variance.*

Mean Wind speed, m/s	Unstable Wind Standard Deviation, m/s	Neutral Wind Standard Deviation, m/s	Reference Standard Deviation, m/s
1	0.83	0.30	0.57
2	1.19	0.60	0.90
3	1.36	0.90	1.13
4	1.50	1.20	1.35
5	1.65	1.50	1.58
6	1.90	1.80	1.85

are computed for the entire building using one pressure coefficient for each facade: windward wall = 0.40, leeward wall = −0.35, parallel wall = −0.45, roof = −0.55. Then, based upon the pressure differential to be maintained between the primary zone and outdoors, the nominal pressure differential between the primary and secondary zones, and the known wind-induced facade pressures, the network model iterates to find the primary-zone and secondary-zone flows required to maintain the specified pressure differentials and the resulting pressures in all zones of the building.

Based upon the reference simulation conditions described in Table 1, the uncertainty and the bias in the measured characteristics of the interzonal leakage path were estimated. Simulations were also performed to examine the sensitivity of the results to the chosen methodology and test conditions.

Simulation Results

Based upon the reference simulation, the bias and uncertainty in the flow coefficient and flow exponent of the interzonal leakage path are summarized for six mean wind speeds in Table 3.

The results in Table 3 indicate a small bias in the measured interzonal flow coefficients and exponents at all wind speeds. The bias in the flow coefficient changes sign, whereas the bias in the flow exponent is consistently positive. This consistent bias in the flow exponent can be explained by the fact that the windows were assumed to be closed during the measurements. When the windows are closed, increasing the pressure in the secondary zone increases the pressure in adjacent zones and thereby reduces the flow from the primary zone to the adjacent zones, implying that this flow is not truly constant. Thus, as increasing the pressure in the secondary zone decreased the pressure difference across the leakage path, the apparent flow through the leakage path will appear to increase disproportionately with the pressure difference across it, thereby causing an overprediction of the flow exponent.

Table 3 also indicates that the uncertainty induced by the wind, as indicated by the standard deviation of the results, remains smaller than 10% up to a wind speed of 5 m/s. Although this result is encouraging, we must remember that this assumes perfect measurements of pressure and flow and therefore represents a lower limit on the total uncertainty. Also, Table 3 represents the uncertainty to be expected with no knowledge of wind direction. Figure 1 presents the data from the three wind directions used to generate Table 3 and shows the significant variations in uncertainty with respect to wind direction. Examining Fig. 1, it seems that the uncertainties for all three wind directions increase linearly with wind speed up to 5 m/s. When the primary zone is completely on the leeward side of the building (Direction 3), the uncertainties continue to increase linearly with wind speed above 5 m/s, whereas the uncertainties seem to increase dramatically above 5 m/s for the other

TABLE 3—*Results of reference measurement technique simulation.*[a]

Mean Wind speed, m/s	Flow Coefficient, k: Bias, %	Flow Coefficient, k: Standard Deviation, %	Flow Exponent, n: Bias, %	Flow Exponent, n: Standard Deviation, %
1	1	1	1	0
2	1	3	1	1
3	0	6	1	2
4	−1	7	2	3
5	−2	10	2	4
6	1	34	2	9

[a] Average of four wind directions.

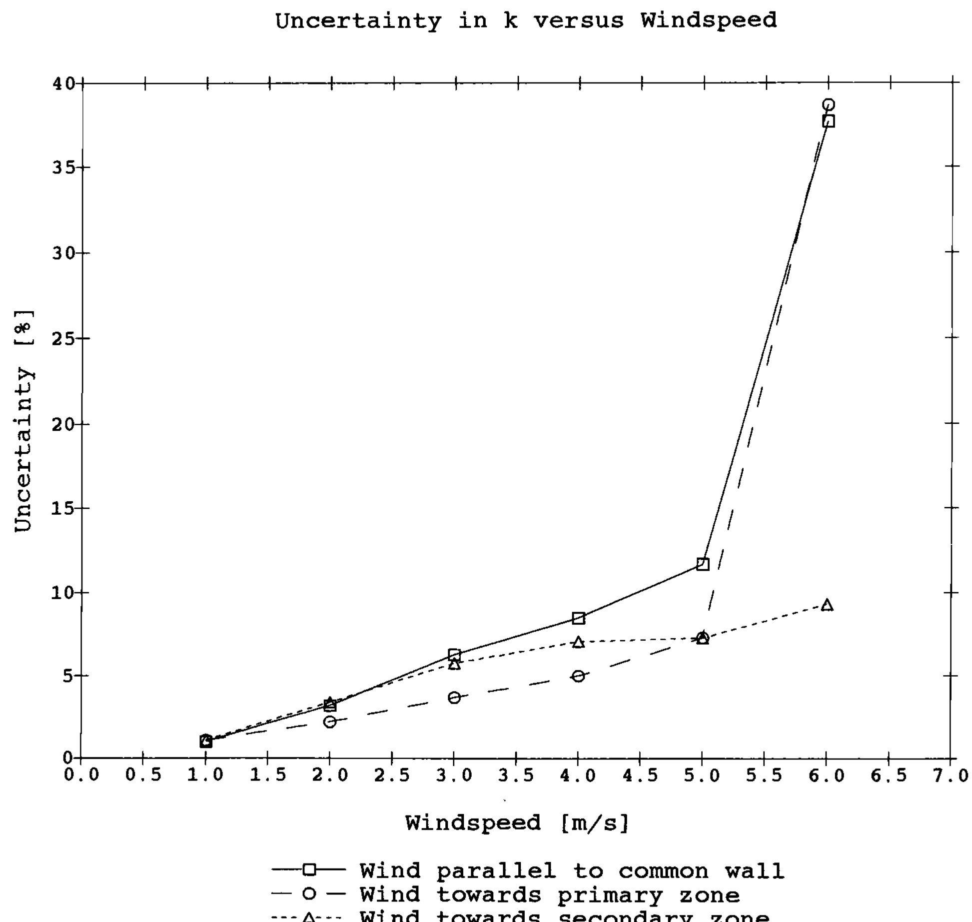

FIG. 1—*Uncertainty (scatter) in the measured leakage coefficient of the common wall between two apartments as a function of wind speed for three different wind directions (based upon reference simulation).*

two directions. This indicates that the wind-induced uncertainty cannot be assumed to simply scale with the dynamic pressure of the wind, but rather must also depend upon other factors. One potential factor is the interaction between the pressurization of the primary and secondary zones, the nonlinearity of the building leaks, and the wind-induced facade pressures.

A more careful examination of the raw simulation results indicated that the flow exponent and flow coefficient were negatively correlated. Thus, although the input to most multizone infiltration models includes both the flow coefficient and exponent, a single parameter which takes into account both the flow exponent and flow coefficient should have less uncertainty. From another point of view, the flow coefficient k can be interpreted as the leakage at 1 Pa, which is at the lower end of our measurement range and therefore has much larger uncertainty. As noted by Persily, to reduce uncertainty, the most logical choice for a single parameter is the leakage (flow) at 25 Pa [7]; however, from the point of view of applicability to actual flow conditions, the most reasonable choice for a single parameter is probably the effective leakage area (ELA). The ELA, defined as in Eq 2, is directly proportional to the leakage at 4 Pa and is used extensively to characterize single-zone leakage [8]

$$\mathrm{ELA} = k\sqrt{\frac{\rho}{2}\Delta P_{\mathrm{ref}}^{\,n-1/2}} \tag{2}$$

where

ρ = the density of air, kg/m^3, and
ΔP_{ref} = the reference pressure differential, 4 Pa.

The bias and standard deviation of the ELA and the leakage at 25 Pa, computed with the same data used to generate Table 3, are compared with the bias and standard deviation of the flow coefficient in Table 4.

The results presented in Table 4 are consistent with those presented by Persily for single-zone fan pressurization measurements. Namely, the determination of a flow in the middle of the measurement range has the least uncertainty, while predicted flows become more uncertain as they move towards the lower extreme of the measurement range. Although this result is not surprising, it is worth noting that the uncertainties in k, ELA, and $Q_{25\mathrm{Pa}}$ roughly correspond to the uncertainties in the flows predicted with a multizone airflow model at characteristic pressures of 1, 4, and 25 Pa, the flow at 4 Pa having approximately two thirds the uncertainty at 1 Pa and the flow at 25 Pa having approximately half the uncertainty at 4 Pa. Also worth noting in Table 4 is the increased positive bias in the predicted flows at higher pressures, in particular the consistent bias in the flow at 25 Pa. Similar to the systematic overprediction of the flow exponent discussed above, this bias stems from the assumption of closed windows used for the simulation.

The effects of different methodology options on the uncertainty and bias of the measurement technique are summarized in Table 5.

The methodology options in Table 5 are listed in order of decreasing beneficial effect on the uncertainty of the flow coefficient. In general, most of the options examined have negative impacts on the quality of the determined parameters. The only option which has a beneficial effect on measurement uncertainty is the use of 12 pressure-flow pairs to determine the flow coefficient and exponent. This option corresponds to taking twice as much data in the field and results in a one percentage point improvement in the uncertainty in the flow coefficient, flow exponent, and effective leakage area.

Somewhat surprisingly, the use of 100 Pa as the reference pressure in the primary zone has virtually no effect on the parameter uncertainties. Although a higher primary-zone pressure is expected to decrease the effect of wind on flow measurements, this beneficial

TABLE 4—k, *ELA and flow at 25 Pa from measurement technique simulation.*[a]

	k		Effective Leakage Area (ELA)		Leakage at 25 Pa	
Mean Wind speed, m/s	Bias, %	Standard Deviation, %	Bias, %	Standard Deviation, %	Bias, %	Standard Deviation, %
1	1	1	2	1	3	0
2	1	3	2	2	3	1
3	0	6	1	4	3	1
4	−1	7	1	5	3	2
5	−2	10	0	7	3	3
6	1	34	2	20	3	7

[a]Average of four wind directions.

TABLE 5—*Effects of methodology changes on measurement technique results.*[a]

	Flow Coefficient, *k*		Flow Exponent, *n*		ELA	
Condition	Bias, %	Standard Deviation, %	Bias, %	Standard Deviation, %	Bias, %	Standard Deviation, %
Reference	**−1**	**7**	**2**	**3**	**1**	**5**
12 data pairs	−1	6	2	2	1	4
100 Pa primary pressure	1	7	1	3	2	5
Open windows	1	9	0	4	0	6
Four-Facade average pressure	7	56	3	17	4	33

[a]Average of four wind directions at mean wind speed of 4 m/s.

effect does not appear in the simulated uncertainties. The uncertainties obtained with a 50-Pa primary-zone pressure were also compared with the 100-Pa uncertainties at an average wind speed of 6 m/s, at which point the 100-Pa uncertainties were half the 50-Pa uncertainties, consistent with expectations. Apparently, the benefits of increasing the primary-zone pressure do not become significant until the wind speed exceeds 4 m/s. As mentioned above, this behavior most likely stems from interactions between the internal building pressures, the nonlinearity of building leaks, and the fact that wind-induced pressures scale with the square of the wind speed.

Opening the windows in the adjacent zones, although it apparently eliminates the bias in the flow exponent and effective leakage area, increases the uncertainty associated with all parameters. This result is not surprising, as opening the windows implies larger pressure fluctuations in the adjacent zones and therefore larger fluctuations in the measured primary-zone fan flow.

The most significant methodology change is the use of a four-facade rather than a three-facade pressure average, which increases the parameter uncertainties by approximately a factor of five. An even more dramatic increase was found when using a single-facade pressure probe for the outside pressure. For one wind direction, the use of a single facade pressure results in biases as high as 80% and uncertainties over 100%. Although the results for other wind directions were not as severe, as one cannot specify wind direction when making a measurement, this technique has to be considered unworkable. Both these results highlight the importance of using a primary-zone pressure reference that is representative of all the pressures affecting the flow out of the primary zone. One better technique would be to average the pressures on the opposite sides of all walls of the primary zone, including all interapartment walls except the wall to the secondary zone. However, this is somewhat impractical in the field. Overall, the results in Table 5 indicate that the choice of reference methodology seems to have been serendipitous.

The uncertainty and bias implications of several of the reference simulation assumptions are summarized in Table 6.

Similar to Table 5, the simulation assumptions in Table 6 are listed in order of decreasing beneficial effect on the uncertainty of the flow coefficient. Also similar to Table 5, the results in Table 6 indicate that the choice of reference simulation assumptions was serendipitous, apparently corresponding to a lower limit on the uncertainties to be expected. The only improvement in measurement uncertainty occurs by assuming that the building was well shielded from the wind. Somewhat surprisingly, going from average wind variance to neutral wind variance does not have a significant effect on the measurement uncertainty. This result, combined with the significant increase in uncertainty associated with assuming unstable wind, seems to indicate that the effects of wind turbulence on measurement uncertainty do not scale linearly with turbulence intensity, but rather result from complex interactions between the internal building pressures, the nonlinearity of building leaks, and the fact that wind-induced pressures scale with the square of the wind speed. The nonlinear dependence of measurement uncertainty on the pressure variations is further illustrated by the significant increases in uncertainty associated with assuming that the building is unshielded.

Not surprisingly, the determined biases and uncertainties in the measured parameters do not depend on the absolute level of leakage in the building (remember we are not including instrumentation uncertainties), but do show approximately linear dependence on the relative size of the leakage path being measured. This latter result suggests a constant absolute uncertainty in the parameters being determined.

TABLE 6—*Effects of simulation assumptions on measurement technique results.*[a]

	Flow Coefficient, k		Flow Exponent, n		ELA	
Assumption	Bias, %	Standard Deviation, %	Bias, %	Standard Deviation, %	Bias, %	Standard Deviation, %
Reference	**−1**	**7**	**2**	**3**	**1**	**5**
Well shielded	0	5	1	2	1	3
Neutral wind	0	7	2	3	1	5
Smaller total leakage, 3.3 cm^2/m^2	0	7	2	3	1	5
Smaller interzone leakage, (9%)	−2	15	4	6	1	10
No shielding	0	16	2	6	1	10
Unstable wind	0	18	2	6	1	9

[a]Average of four wind directions at mean wind speed of 4 m/s.

Conclusions

Several conclusions can be drawn based upon the results presented in this report. First, it is clear that the wind plays an important role in the uncertainties associated with interzonal leakage measurements, and that at wind speeds above 5 m/s even perfect pressure and flow measurements cannot provide uncertainties smaller than 10%. On the other hand, the reference methodology examined seems to have the potential for providing results significantly better than those obtained in earlier studies. Based upon these results, it seems that more rigorous field tests of this technique are warranted.

Perhaps the most significant finding is the observed importance of choosing an outdoor pressure reference for the primary zone pressure that minimizes variations in the flow from the primary zone to other zones or outdoors, which is assumed to be constant. Using a three-facade pressure average improves measurement uncertainty by a factor of five compared to using a four-facade pressure average or a single-facade pressure. In addition to this important result, the simulations also demonstrated the relative importance of other subtleties in the measurement protocol, the leakage distribution, and the type of wind under which the measurements are made.

Finally, within the chosen framework, the reference methodology and simulation assumptions appear to be close to a lower limit on the uncertainties induced by the wind. A number of options for reducing uncertainty, such as temporal averaging or filtering of pressure signals, were specifically not considered. It seems that such options should be considered in conjunction with simulations that take into account the effect of instrumentation uncertainties. It is the authors' opinion that such an analysis would be an important first step in the development of a standardized interzonal leakage measurement technique with acceptable uncertainty.

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DISCUSSION

W. De Gids[1] *(written discussion)—How many nodes,* C_p's, and leakage paths were there in your simulations?

M. Modera (author's closure)—The simulations presented in the paper were based on one pressure coefficient (C_p) per face, which makes a total of five including the roof. Including one pressure node for each of the six apartments, the total number of pressure nodes therefore adds up to eleven. Including all internal and external walls, there were a total of 27 leakage paths modelled for the six-apartment buildings.

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James A. Love[1]

Airtightness Survey of Row Houses in Calgary, Alberta

REFERENCE: Love, J. A., "**Airtightness Survey of Row Houses in Calgary, Alberta,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067*, M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 194–210.

ABSTRACT: While many reports are available on the airtightness of detached dwellings, little information is available on multifamily housing. In this study, airtightness characteristics of 42 row dwellings from nine housing complexes were obtained by depressurization [CGSB "Determination of Airtightness of Buildings by the Fan Depressurization Method" (CAN2-149.10)]. For 24 of the houses, airtightness was also determined with party wall leakage offset by simultaneous depressurization of dwellings adjacent to the test unit. The houses were built between 1965 and 1982 using wood-frame exterior wall construction; airtightness characteristics of exterior envelopes were found to be similar to those of detached dwellings of the same age and envelope construction. Airtightness characteristics of party walls were found to be similar to those of the exterior envelope.

KEY WORDS: air leakage, airtightness, effective leakage area, fan pressurization, row housing

Nomenclature

C	Flow coefficient for dwelling unit, L/(s·Pa^n)
ELA	Effective leakage area, m^2
n	Flow exponent
Q	Air leakage value, L/s
ρ	Density of air, 1.2 kg/m^3, at room temperature
ΔP	Pressure difference across exterior wall, Pa
ΔP_{ref}	Reference pressure difference across exterior wall, Pa, taken to be 4

This paper presents data on the airtightness of row dwellings in Calgary, Alberta as determined by pressure testing with blower doors. The study was undertaken for two reasons. Two row houses used to test retrofit measures in an earlier project were found to have much leakier envelopes than detached dwellings of comparable age and construction [*1*] (included as Row House Complex 8 in this study). This raised the question as to whether row houses were generally leakier than single family dwellings. At the time the study was started, only Harrje's data on the airtightness of attached dwellings had been published [*2*]. While Sherman, Wilson, and Kiel were able to obtain complete pressure test data on 489 detached dwellings in North America by 1986 [*3*], less than 100 airtightness measurements for row dwellings were found by the author [*2,4,5*]. None of the published material on row houses provided data such as flow coefficient and flow exponent, which were required for inclusion of detached dwellings in the Sherman data base.

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Evaluation of airtightness of row houses is much more complicated than is the case for detached dwellings since, apart from leakage across exterior walls, one or more party walls must be considered. Differentiating party wall leakage from exterior envelope leakage has commonly been done with two or more blower doors, although some work has been done on single door techniques [6].

The pressure testing technique relies on correlation of measured air leakage values and pressure differences by an expression of the form

$$Q = C\,\Delta P^{n} \tag{1}$$

Envelope leakiness is frequently expressed in terms of effective leakage area (ELA) [3], which can be computed by

$$\text{ELA} = (C\,\Delta P_{\text{ref}}^{n-0.5}/1000)\,(\rho/2)^{0.5} \tag{2}$$

Most of the work on pressure testing of detached dwellings has been directed at improving thermal performance of exterior envelopes, although Verschoor and Haines assessed acoustical benefits resulting from insulation and air leakage control retrofits [7]. Party wall leakage presents additional problems because it occurs through gaps which increase noise transfer between dwellings and because it permits pollutants, such as tobacco smoke, and odors to travel from one home to another.

Procedure

Information on airtightness was obtained by depressurizing the dwellings with a blower door. Canadian General Standards Board Standard CAN2-149.10, "Determination of Airtightness of Buildings by the Fan Depressurization Method," was followed, except that it was not possible to place exterior pressure taps on all sides of the buildings due to their large size.

Where access to homes adjacent to the test unit was permitted, a second test was performed with party wall leakage offset by simultaneous depressurization of these neighboring homes. Each dwelling adjacent to the dwelling under test was fitted with a blower door. The fan operators communicated by walkie-talkie and maintained the same indoor-outdoor pressure differential at each of the range of test pressures used to determine the values for Eq 1. By eliminating any pressure differential between the test dwelling and adjacent dwellings, air flow between these dwellings was eliminated or reduced to a very low level. The results of the tests with and without depressurization of adjacent homes were used to differentiate leakage through party walls from leakage through the exterior envelope.

Housing complexes were selected for testing through a variety of contacts with owners and tenants. The sample was not intended to be statistically representative, but an attempt was made to test a variety of dwelling designs and age groups. The complexes tested were scattered throughout the city of Calgary. The number of units tested per project varied from two to eleven. It was felt that at least two units should be tested in each complex, and as many adjacent units were tested as we could arrange access to on a given test date. Public housing projects were selected in consultation with the City of Calgary Housing Authority. Cooperatives and rental projects were found through tenants or owners known to the author or the author's students. The opportunity to acquire test results, including discussion of leakage points and comparative performance, motivated many of the people who cooperated. Occupant consent was sought in advance for every unit to be entered as part of the testing program.

Results

Testing often required repeat visits to sites or abandonment of units selected for testing because of:

1. Changing wind conditions.
2. Occupant failure to provide for access despite prior arrangement (changing mind about participation, forgetting to leave key with neighbor, simply not home).

These factors, as well as occasional failure to gain consent to enter adjacent units, meant that several units could not be tested with correction for party wall leakage. For instance, the three units tested in Complex 4 were scattered throughout the site because the owner of the complex would only permit testing at month end in those rental dwellings which were changing hands.

Usable test data were obtained for nine complexes. Dwellings tested in two complexes were not included in the sample because they were so leaky that a reasonable range of pressure differentials could not be induced with the available equipment. These units were condominium homes larger (and, ironically, more luxurious) than the other dwellings tested.

Virtually all row housing in Calgary was built after 1965, and most in the 1970s. All the projects visited as part of this study were built between 1965 and 1982. Despite a variety of detailing and layout, all were built with standard 2 by 4 wood-frame exterior construction and had vapor barriers; none had exterior foam insulation sheathing. Construction details for eight of the nine complexes tested are provided in Figs. 1-8. It was not possible to obtain the architectural drawings for Project 9; these units were two-story structures with wood siding much like the units in Projects 4 and 5. Table 1 summarizes information on the test complexes such as unit floor area and date of construction.

The complexes included in the sample of nine were of the following types:

1. Projects given code numbers 1 to 3 were subsidized housing complexes owned by the City of Calgary housing authority,
2. Projects coded 5 to 7 were housing cooperatives.
3. Other projects were privately owned rental housing.

Airtightness data on these projects are summarized in Tables 2–5.

Tables 2–3 contain test results for 24 dwellings for which it was possible to perform blower door tests with and without correction for party wall leakage. Both average and median flow exponents differed little between test conditions. Some changes in effective leakage area were anomalous, increasing or remaining constant between test conditions. These values likely reflect wind effects, a persistent problem in testing at lower pressure differentials. For air changes with a 50-Pa pressure differential across the envelope, a test condition which minimizes wind effects, values were 17 to 52% lower with party wall leakage eliminated.

Table 4 contains results for 19 dwellings for which tests with party wall correction could not be performed. These results are of value because they indicate the representativeness of the smaller sample for which more detailed testing was possible. Comparison of means and standard deviations for flow coefficients, flow exponents, effective leakage area, and air changes per hour at 50-Pa pressure differential show that there is virtually no difference between this group and the 24 for which more complete testing was possible.

Table 5 summarizes statistics on a complex-by-complex basis and shows that considerable variability in airtightness exists within projects. These variations are due, in part, to occupant modifications. Discussions with occupants of three homes in Complex 7 revealed that they had engaged in zealous weatherstripping and caulking efforts, reflected in leakage rates, under equalized conditions, approaching two air changes per hour at a 50-Pa envelope

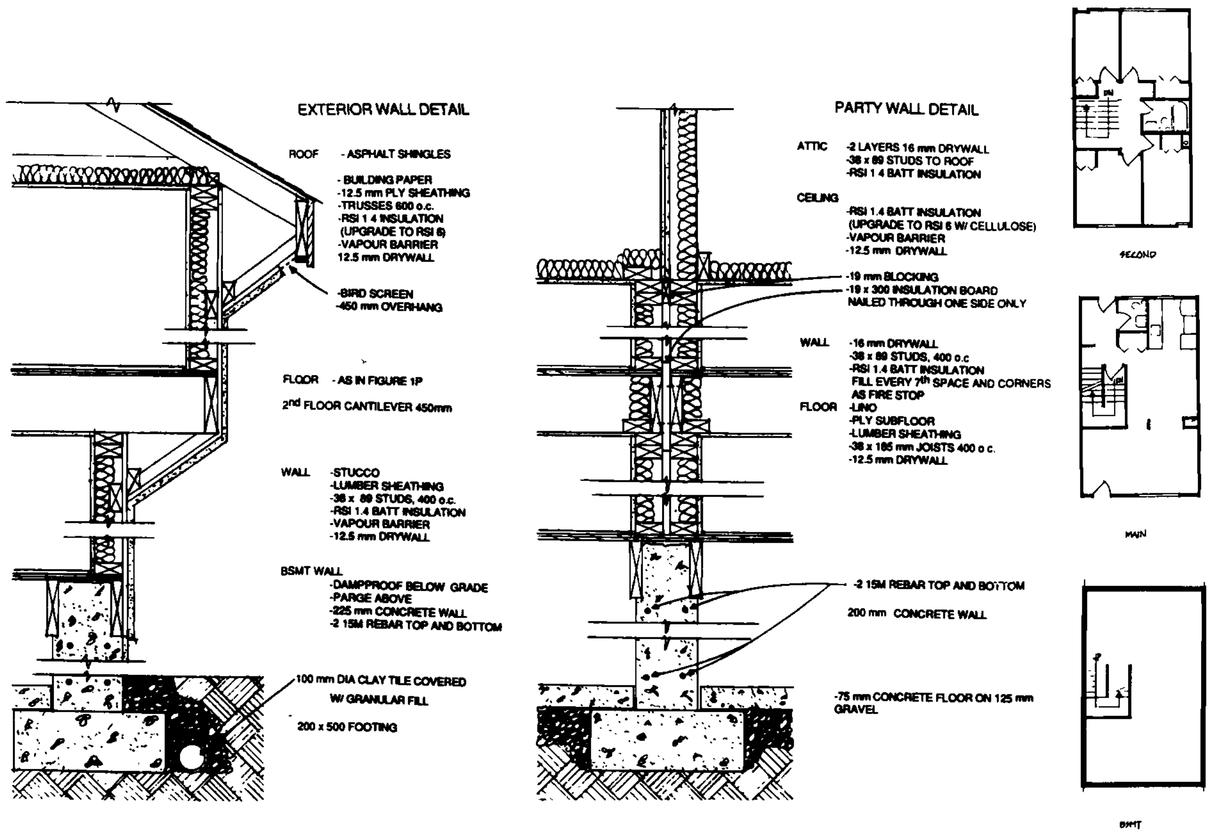

FIG. 1—*Exterior wall section, party wall section, and floor plans for Project 1.*

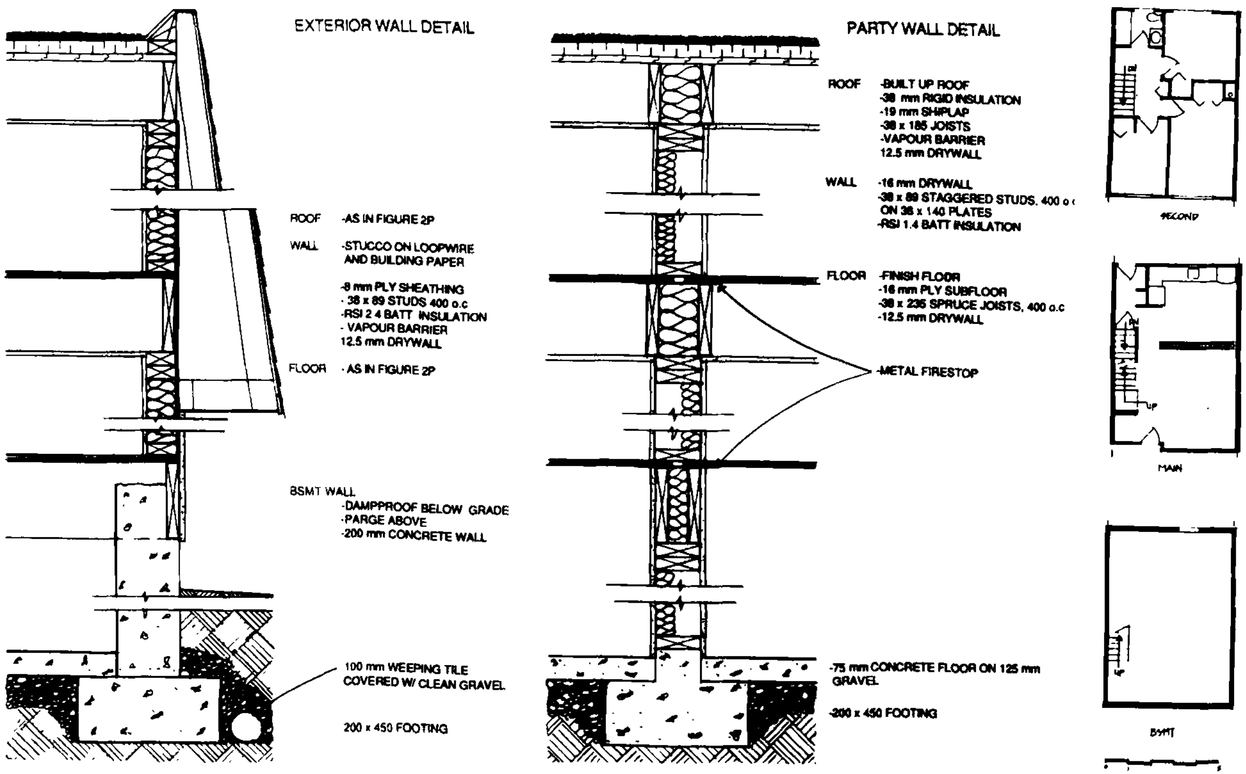

FIG. 2—*Exterior wall section, party wall section, and floor plans for Project 2.*

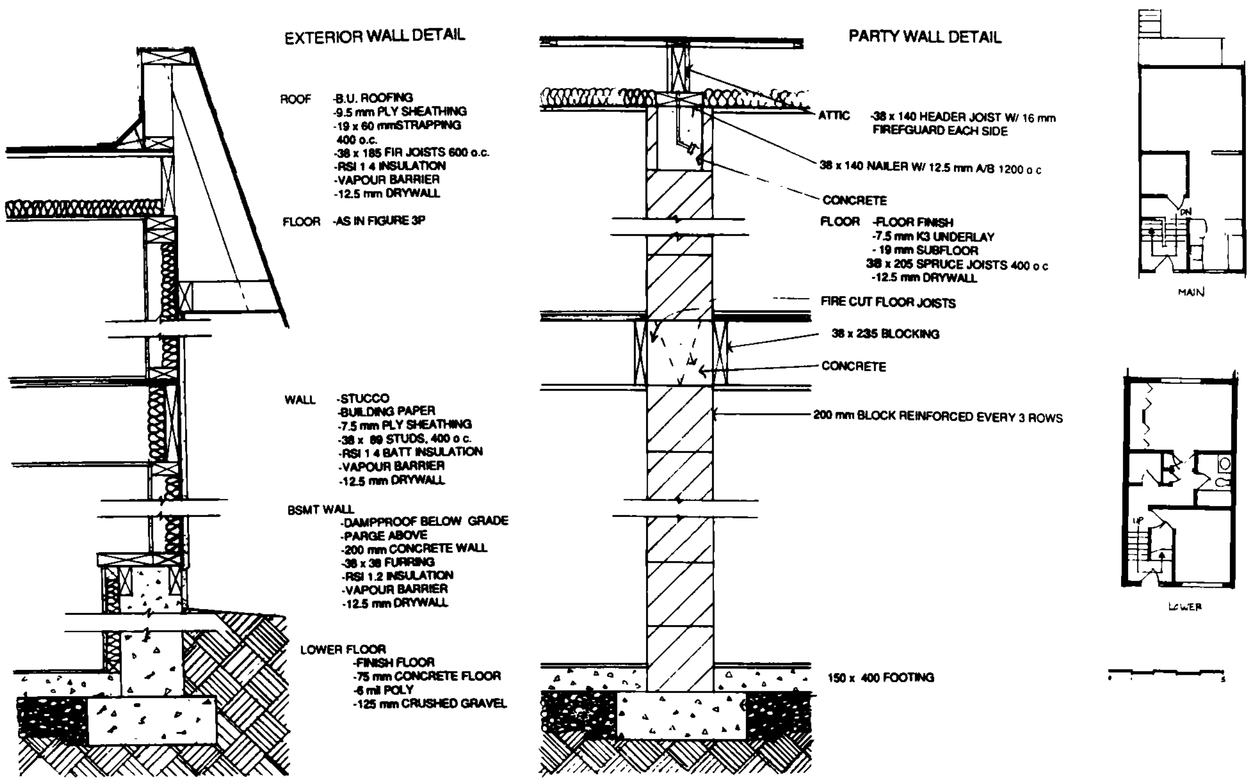

FIG. 3—*Exterior wall section, party wall section, and floor plans for Project 3.*

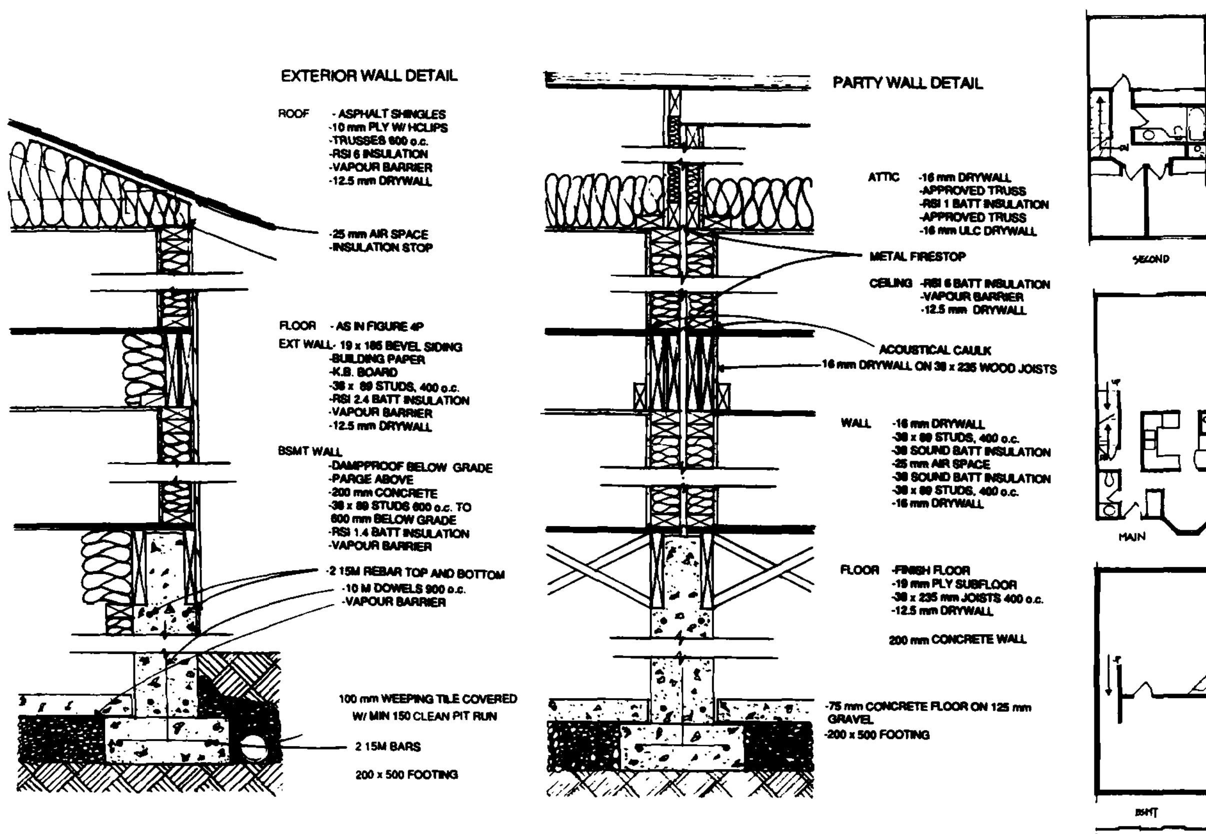

FIG. 4—*Exterior wall section, party wall section, and floor plans for Project 4.*

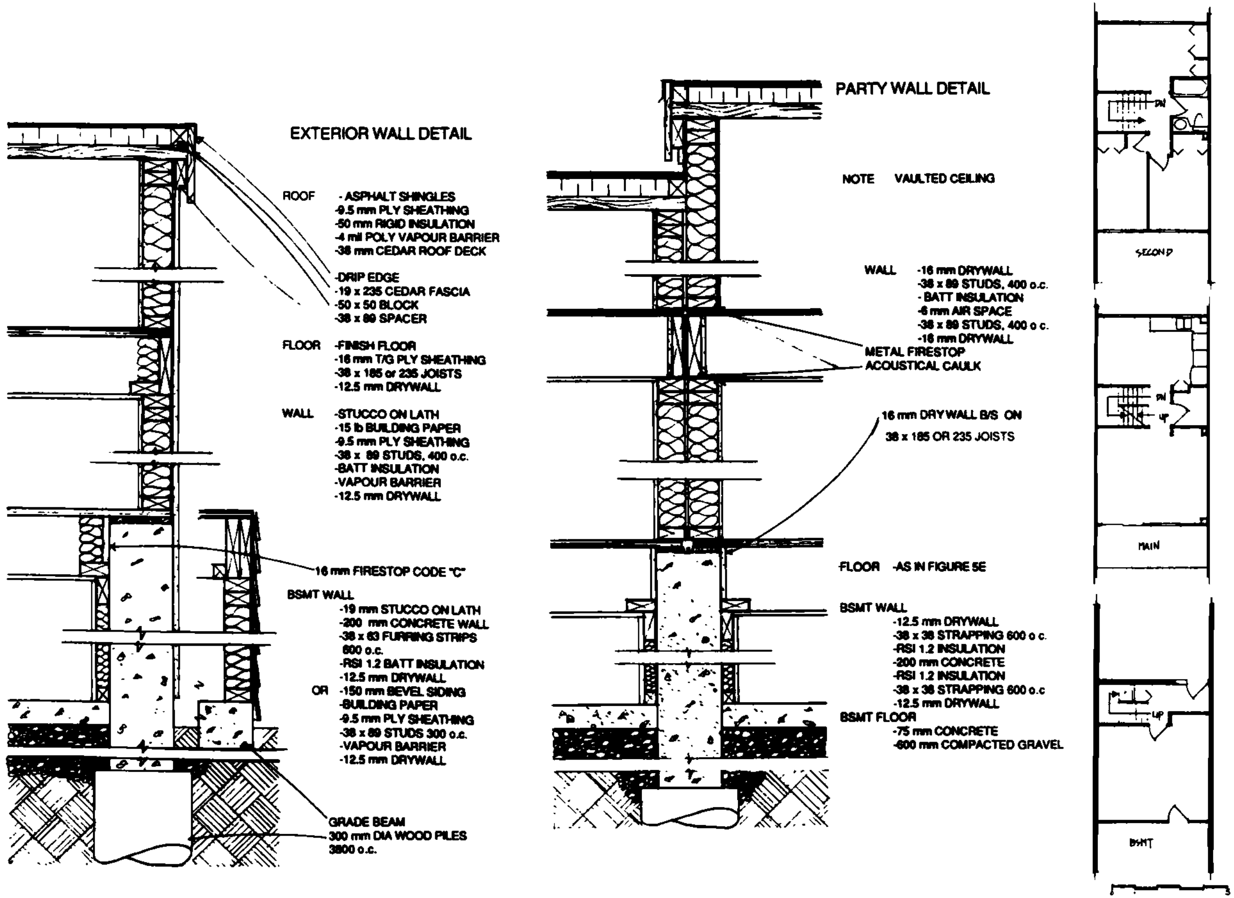

FIG. 5—*Exterior wall section, party wall section, and floor plans for Project 5.*

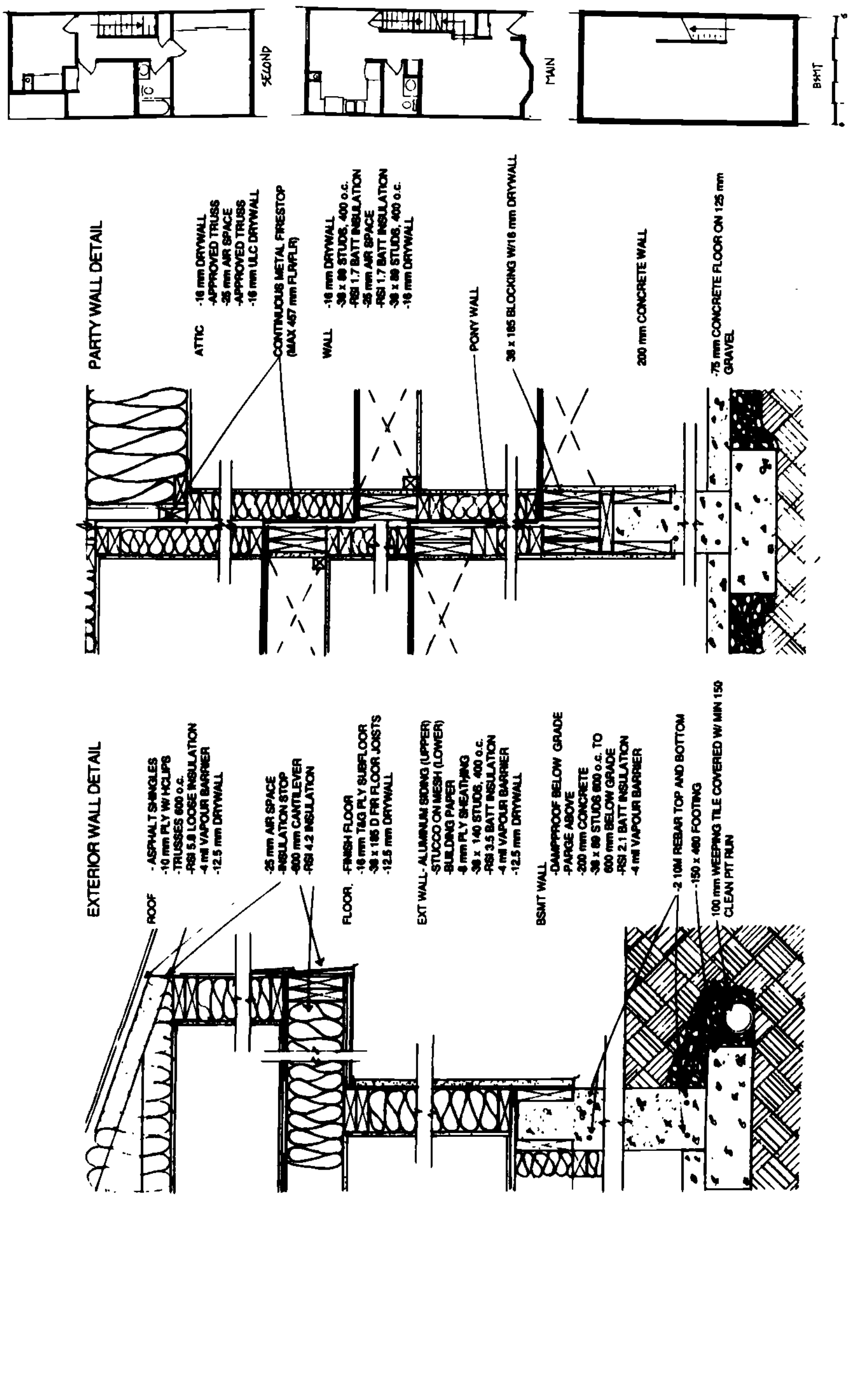

FIG. 6—*Exterior wall section, party wall section, and floor plans for Project 6.*

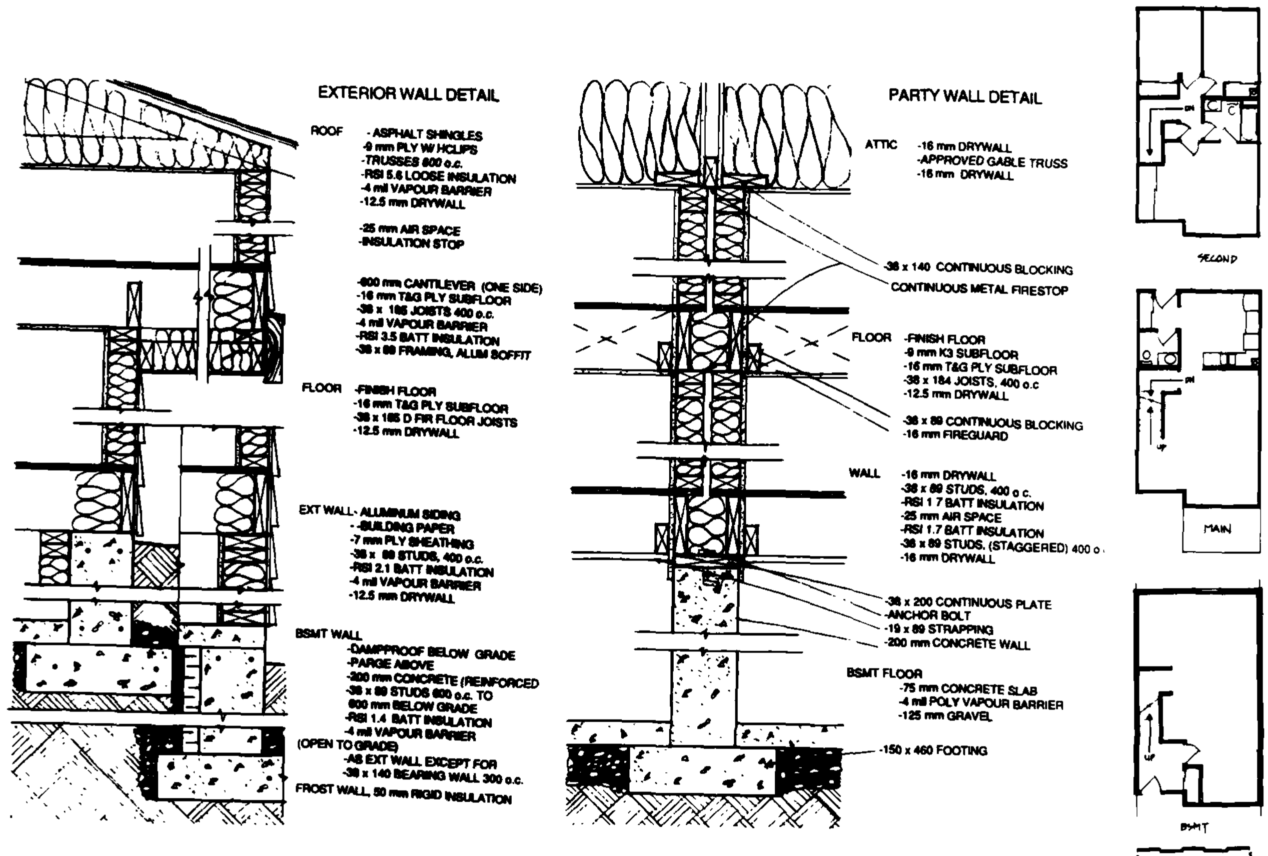

FIG. 7—*Exterior wall section, party wall section, and floor plans for Project 7.*

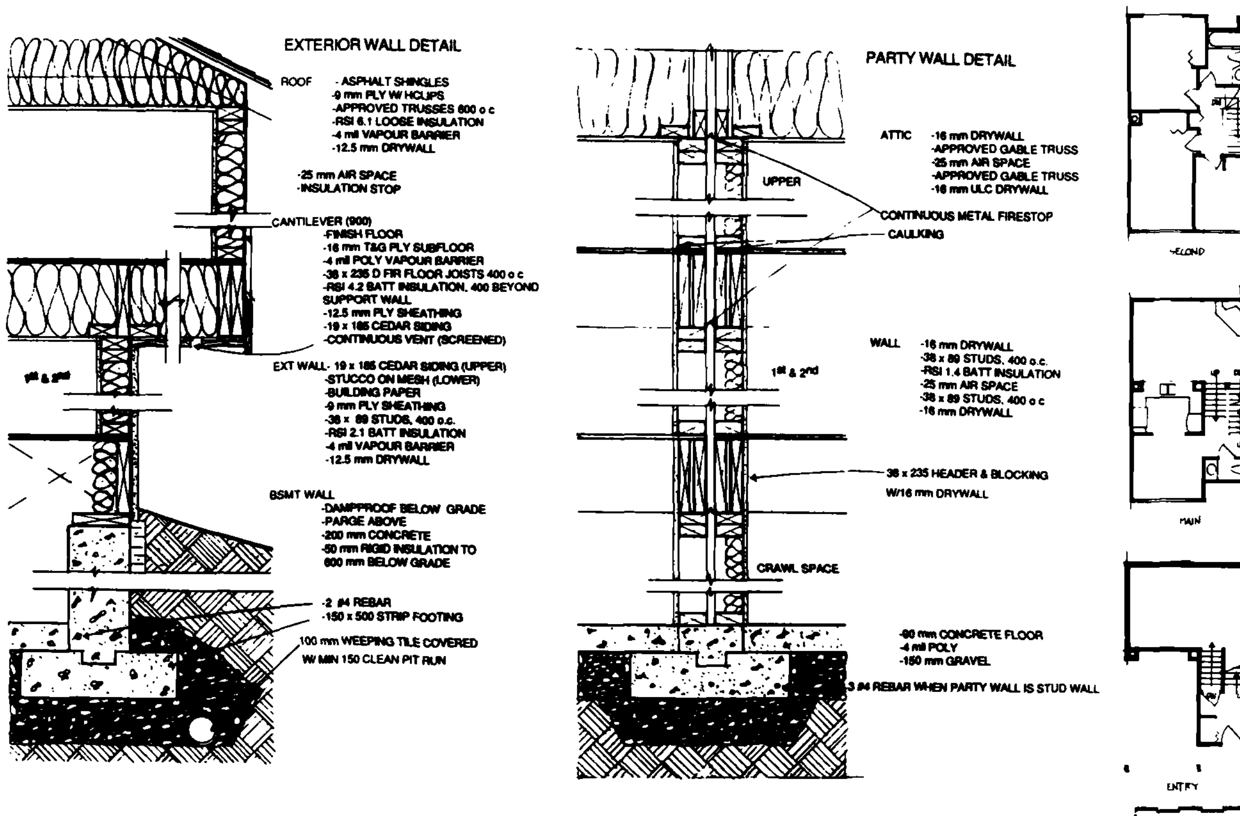

FIG. 8—*Exterior wall section, party wall section, and floor plans for Project 8.*

TABLE 1—*Descriptive information for row housing projects included in the sample: 43 dwellings.*

Housing Project Code	Approximate Year of Construction	Floor Area,[a] m^2	Exposed Surface Area,[a] m^2	Volume,[a] m^3
1[b]	1965–70	98[d]/98[f]	167[d]/121[f]	376[d]/376[f]
2	1965–70	83[d]/83[f]	150[d]/105[f]	323[d]/323[f]
3	1965–70	81[d]/81[f]	113[d]/77[f]	198[d]/198[f]
4[b]	1975–82	106[d]/109[f]	177[d]/134[f]	368[d]/375[f]
5[b,c]	1975–82	102[d]/90[f]	178[d]/147-157[f]	102[d]/90[f]
6[b]	1975–82	96[d]/94[f]	151[d]/115-122[f]	356[d]/354[f]
7[b]	1982	100[d]/100[f]	205[d]/178[f]	372[d]/372[f]
8[c]	1982	91-99[e]/-[g]	111-115[e]/-[g]	294-397[e]/-[g]
9	1982	91[d]/91[f]	131[e]/96[f]	331[d]/331[f]

[a] Dimensions shown are end unit/interior unit.
[b] Some units staggered.
[c] Dwelling extends over partial car port at grade.
[d] Value for end units.
[e] Range of values for end units.
[f] Value for interior units.
[g] No interior units tested.

pressure differential. To put this in perspective, the Canadian "R2000" super-energy efficient home program stipulates a maximum air change rate of 1.5 air changes per hour under test conditions! The public housing units (Projects 1–3) that were tested were also found to have very tight exterior envelopes, in some cases close to the performance of the occupant retrofitted units of Project 7. All of the public housing units had a stucco finish, while the rental and coop units had lapped wood siding or, in one case, vinyl siding. The public housing units were also the oldest and most airtight, but it is difficult to draw even tentative conclusions about relationships between airtightness, date of construction, construction type, and type of developer due to the number of variables involved. A number of significant defects in workmanship were noted in both rental and cooperative housing built between 1975 and 1982, during which Calgary experienced a boom in housing construction. Most notable were gaps in certain junctions at exterior walls in Projects 6 and 8, and at party wall-ceiling junctions in Project 6. Because different numbers of units were studied in each project, the means of the project means were computed to see whether differences in project contributions were affecting overall results; in fact, there was close agreement between the means of the project means and the mean values for all row dwellings studied (the latter being weighted by the number of units tested in each complex).

Comparison with Results of Other Studies

The comparison of averaged data with results of other studies must be tempered with the caution that, as was noted above, usable results could not be obtained for units in two projects due to excessive leakiness.

A pioneering study by Harrje found an air change rate at 50 Pa of 12.2 ± 1.5 for ten row houses in Twin Rivers, New Jersey (dwellings adjacent to the test units were not depressurized) [*2*]. For 42 Calgary row houses, the air change rate at this pressure differential was 5.5 ± 1.8. Lagus and King published effective leakage area for units in four sixplexes at Norfolk, Virginia, obtaining a mean of 0.041 ± 0.008 m^3 with pressure differentials eliminated between adjacent units [*4*]. The effective leakage area for 24 Calgary row houses was 0.024 ± 0.006 m^3 under the same conditions. Verschoor and Collins review airtightness data on Navy family housing, much of which was row housing, but provide only aggregate

TABLE 2—*Flow coefficients and flow exponents obtained with and without party wall leakage offset by simultaneous depressurization of houses adjacent to test unit: 24 row dwellings.*

Dwelling Code[a]	Flow Coefficient, L/s · Pa^n			Flow Exponent		
	With Party Wall Leaks	Without Party Wall Leaks	Difference	With Party Wall Leaks	Without Party Wall Leaks	Difference
1-1E	38	19	−19	0.64	0.75	+0.11
1-4E	32	28	−4	0.69	0.65	−0.04
1-5	29	12	−17	0.69	0.77	+0.08
2-1E	37	36	−1	0.52	0.54	+0.02
2-2E	20	13	−7	0.70	0.72	+0.02
3-1	30	33	+3	0.63	0.52	−0.11
5-1	47	13	−14	0.70	0.90	+0.20
5-2	51	25	−26	0.66	0.72	+0.06
5-3	57	32	−25	0.69	0.71	+0.02
6-2	49	38	−11	0.61	0.54	−0.07
6-3	Unknown	20	Unknown	Unknown	0.62	Unknown
7-2	25	34	+9	0.80	0.63	+0.17
7-3	40	19	−21	0.71	0.83	+0.12
7-4E	38	19	−19	0.69	0.77	+0.08
7-5E	31	25	−6	0.72	0.72	0.00
7-6	32	18	−14	0.69	0.66	−0.03
7-7	48	31	−17	0.66	0.65	+0.01
7-8	40	24	−16	0.73	0.75	+0.02
7-9	49	12	−37	0.56	0.78	+0.22
9-1E	32	27	−5	0.66	0.68	+0.02
9-2	30	22	−8	0.73	0.71	−0.02
9-3	39	33	−6	0.68	0.61	−0.07
9-4	35	31	−4	0.64	0.58	−0.06
9-5	45	38	−13	0.61	0.58	−0.03
Mean	38	25	−13	0.65	0.68	+0.03
Standard deviation	9	8	10	0.06	0.10	0.08
Median	38	26	−13	0.69	0.70	+0.02

[a]Dwelling codes are comprised of a complex code followed by the unit code. End units are denoted by an E.

TABLE 3—*Effective leakage area and air changes per hour obtained with and without party wall leakage offset by simultaneous depressurization of houses adjacent to test unit: 24 row dwellings.*

	Effective Leakage Area, m^2			Air Changes Per Hour With a 50-Pa Pressure Differential Across the Exterior Envelope		
Dwelling Code[a]	With Party Wall Leaks	Without Party Wall Leaks	Difference	With Party Wall Leaks	Without Party Wall Leaks	Difference
1-1E	0.035	0.020	−0.015	4.5	3.4	−1.1
1-4E	0.032	0.026	−0.006	4.5	3.4	−1.1
1-5	0.029	0.013	−0.016	4.1	2.4	−1.7
2-1E	0.027	0.027	0.000	3.4	2.8	−0.6
2-2E	0.021	0.014	−0.007	3.4	2.5	−0.9
3-1E	0.026	0.026	0.000	6.3	4.6	−1.7
5-1	0.047	0.017	−0.030	8.6	5.4	−3.2
5-2	0.048	0.026	−0.022	8.8	5.7	−3.1
5-3	0.055	0.032	−0.023	10	6.1	−3.9
6-2	0.043	0.031	−0.012	5.4	3.2	−2.2
6-3	Unknown	0.020	Unknown	Unknown	2.9	Unknown
7-2	0.029	0.032	+0.003	5.5	3.9	−1.6
7-3	0.041	0.023	−0.018	6.4	4.8	−1.6
7-4E	0.039	0.022	−0.017	5.6	3.8	−1.8
7-5E	0.032	0.026	−0.008	5.2	4.1	−1.1
7-6	0.030	0.016	−0.014	4.6	2.2	−2.4
7-7	0.046	0.029	−0.017	6.1	3.8	−2.3
7-8	0.042	0.025	−0.017	6.6	4.4	−2.2
7-9	0.042	0.014	−0.028	4.3	2.3	−2.0
9-1E	0.027	0.031	+0.004	4.5	3.8	−0.7
9-2	0.032	0.023	−0.009	5.8	3.9	−1.9
9-3	0.038	0.029	−0.009	5.9	3.9	−2.0
94	0.033	0.027	−0.006	4.8	3.3	−1.5
9-5	0.040	0.032	−0.008	5.2	4.0	−1.2
Mean	0.036	0.024	−0.012	5.6	3.8	−1.8
Standard deviation	0.010	0.006	0.009	1.7	1.1	0.8

[a]Dwelling codes are comprised of a complex code followed by the unit code. End units are denoted by an E.

TABLE 4—*Airtightness data obtained with only measurement unit depressurized for dwellings for which test data were not obtained with party wall pressure differential eliminated: 19 row dwellings.*

Dwelling Code[a]	Flow Coefficient, L/s · Pa^n	Flow Exponent	Effective Leakage Area, m^2	Air Changes Per Hour at 50-Pa Pressure Differential
1-2	63	0.59	0.056	6.2
1-3	47	0.63	0.044	5.3
1-6	66	0.61	0.059	6.9
2-3	36	0.62	0.032	4.6
2.4	44	0.64	0.040	6.0
3-2	29	0.62	0.028	6.7
4-1E	41	0.66	0.039	5.3
4-2	27	0.72	0.027	4.3
4-3	20	0.80	0.024	4.6
5-4	68	0.59	0.057	8.3
6-1	16	0.75	0.016	3.0
6-4	30	0.64	0.027	3.6
6-5	27	0.71	0.028	4.5
6-6	31	0.68	0.030	4.5
7-1E	32	0.75	0.036	5.7
7-10E	25	0.84	0.031	6.5
7-11	25	0.80	0.028	5.5
8-1E	50	0.51	0.027	9.2
8-2E	65	0.67	0.032	11
Mean	39	0.67	0.035	5.4
Standard deviation	16	0.08	0.012	2.0

[a] Dwelling codes are comprised of a complex code followed by the unit code. End units are denoted by an E.

data [5]. These results show that the Calgary row dwellings are twice as airtight as the Navy row dwellings. Information on construction was not provided for either the Twin Rivers or the Norfolk samples.

Party wall leakage, expressed as a percentage of overall leakage at 50 Pa pressure differential, ranged from 7 to 24% and averaged 14% for the Norfolk row houses. For 24 Calgary row houses, party wall leakage ranged from 17 to 52% of overall leakage and averaged 37%. If party wall leakage were the same for row houses in both locations, one might expect the Calgary fraction to be double the Norfolk fraction because of the greater tightness of the exterior envelopes.

The data on almost 500 single family dwellings summarized by Sherman, Wilson, and Kiel indicate many similarities in performance between the single family and row dwellings tested. They commented that a "mean flow exponent of 0.67 confirms the widely held assumption that a flow exponent near 0.65 is typical of air infiltration leakage sites." A mean flow exponent of 0.68 was obtained for 24 Calgary row houses with zero pressure differentials across party walls. With only the test dwellings depressurized, a mean flow exponent of 0.66 was obtained for 42 Calgary row houses, so the inclusion or exclusion of party walls appears to have little effect on the range of flow exponent values.

A more recent study by Sulatisky included results for 184 recently built detached dwellings from across Canada [8]. Air changes per hour at 50-Pa pressure differential averaged 4.8,

TABLE 5—*Airtightness data grouped by housing project (obtained with only measurement unit depressurized): 42 dwellings.*

Housing Project Code	No. of Dwellings in Sample	Flow Coefficient, L/s · Pa^n	Flow Exponent	Effective Leakage Area, m^2	Air Changes Per Hour at 50-Pa Pressure Differential
All	42	38 ± 12	0.66 ± 0.07	0.035 ± 0.010	5.5 ± 1.8
1	6	45 ± 15	0.64 ± 0.04	0.042 ± 0.013	5.2 ± 1.1
2	4	34 ± 10	0.62 ± 0.07	0.030 ± 0.008	4.4 ± 1.2
3	2	30 ± 1	0.62 ± 0.01	0.027 ± 0.002	6.5 ± 0.3
4	3	29 ± 11	0.73 ± 0.07	0.030 ± 0.008	4.7 ± 0.5
5	4	56 ± 8	0.66 ± 0.05	0.052 ± 0.005	8.9 ± 0.7
6	5	31 ± 12	0.68 ± 0.05	0.029 ± 0.009	4.2 ± 0.9
7	11	35 ± 8	0.72 ± 0.08	0.036 ± 0.006	5.6 ± 1.0
8	2	58 ± 11	0.59 ± 0.11	0.030 ± 0.004	10 ± 1.3
9	5	36 ± 6	0.66 ± 0.04	0.034 ± 0.005	5.2 ± 0.6
mean of project means		39 ± 11	0.66 ± 0.05	0.034 ± 0.008	6.1 ± 2.0

[a]Dwelling codes are comprised of a complex code followed by the unit code. End units are denoted by an E.

but ranged from 2.1 for 20 houses in the province of Manitoba to 9.3 for 20 houses in British Columbia. Sulatisky computed an average normalized leakage area (cm^2 of equivalent leakage area per m^2 of exposed envelope area) of 3.2 for his sample, the same value that was obtained for the Calgary row houses with party wall leakage offset.

Another measure computed by Sherman, Wilson, and Kiel was specific leakage area, defined for convenience as the effective leakage area or ELA (expressed in cm^2) divided by the floor area (expressed in m^2) of the home. Applying this measure to results from row houses with party wall leakage eliminated would underestimate wall leakiness. An "adjusted" specific leakage area was calculated to correct for party walls. This involves adding 25% to the specific leakage area of end units (exposed wall and ceiling area is about 0.80 of total wall and ceiling area) and 67% to the leakage area of interior units (exposed wall and ceiling area is about 0.60 of total wall and ceiling area). The adjusted specific leakage area for 24 row houses was 3.6 ± 1.1 cm^2/m^2 compared with 3.5 ± 3.2 cm^2/m^2 obtained for 554 data points of 1961–1983 vintage in the Sherman study (the raw specific leakage for the row houses was 2.5 ± 7 cm^2/m^2). The specific leakage area, including party wall leakage, for 42 row houses was 3.7 ± 1.0 cm^2/m^2.

Discussion

Adjusted specific leakage for the Calgary row houses with party wall leakage eliminated was found to be very close to specific leakage including party wall leakage. It may be that party wall airtightness is similar enough to exterior wall leakage to obtain a reasonable measure of specific leakage area without eliminating party wall leakage when sampling row housing. This would save a great deal of time, effort, and expense. A larger sample of complete data is required to establish the validity of such an approach.

For new multifamily housing, a case could be made for including all leakage in tests of envelope airtightness. While party wall holes may not significantly affect thermal performance, they are a concern in terms of air quality and noise transmission.

ASTM method for Determining Air Leakage Rate by Fan Pressurization Test (E 779), followed by Lagus and King, requires both pressurization and depressurization of dwellings. Sherman et al. found that there is little systemic difference between pressurization and depressurization; differences were significant in some individual cases. Sherman et al. also noted that differences could arise between Canadian and American test results because the Canadian testing standard requires that intentional ventilation points be taped while the American standard merely requires that dampers be closed.

Conclusion

The airtightness characteristics of row housing envelopes tested by the author are similar to those of detached dwellings tested by other researchers. Airtightness characteristics of party walls are similar to those of exterior envelopes. Row houses tested by the author are twice as airtight as those tested in the United States.

Acknowledgements

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Airtightness Measurements in Two UK Office Buildings

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ABSTRACT: A major factor in the ventilation of buildings is the leakiness of the building envelope. In housing, it has been possible for some time to measure leakiness quickly and easily by using a fan (sealed in place of the front door) to pressure/depressurize the building. Until now, this has not been done in larger buildings either in the UK or elsewhere in Western Europe.

The Building Research Establishment (BRE) designed and built three fan units which can be used together to pressurize large nonresidential buildings. A novel feature of the *pressurization* rig is that the fans are powered from conventional 13-A ring mains. This is in contrast to the techniques used in North America of either using a building's mechanical ventilation system (not possible in the UK since most buildings are naturally ventilated) or a large, bulky, trailer-towed fan with its own generator.

Envelope leakage tests have been carried out in two medium-sized (approximately 5500 m^3) office buildings. Pressure differences of well over the accepted target of 50 Pa between inside and outside were reached easily.

Results showed that one of these buildings, of conventional construction, was twice as leaky as those found (on average) in North America. The other, built specifically as a low-energy office at BRE, was found to be as tight as the North American buildings. BRE will carry out measurements in further buildings as an aid to understanding and developing air leakage control from the viewpoint of natural ventilation.

KEY WORDS: pressurization, air leakage, leakage area, airtightness, fan pressurization, pressurization testing, large building, nonresidential building, commercial building, office building, multistory building

A major factor in the ventilation of buildings is the leakiness of the building envelope. It is usually quantified by measuring the whole building air leakage rate at appropriate applied pressure differentials between inside and outside. In small buildings, this is most conveniently done by using the fan pressurization technique [*1*], whereby a portable fan assembly is sealed into the doorway of a dwelling and the airflow rates required to maintain a series of pressure differences measured.

The fan pressurization technique is a powerful diagnostic and research tool for measuring airtightness in buildings. Over the last decade, use of this technique has increased, but mainly with respect to dwellings rather than bigger, more complex buildings like offices. Problems of scale and the lack of appropriate equipment have deterred investigations of bigger buildings, especially those which are naturally ventilated.

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In the United States, whole building leakage rates have been measured [*2*] in some mechanically ventilated buildings using the system fans to pressurize the building envelope. This technique cannot be widely used in the UK since most buildings are naturally ventilated. An alternative approach, utilized in Canada [*3*], employed a greatly scaled up version of the equipment used in dwellings and consisted of a trailer-towed 2-m-diameter fan with its own electric generator as a power supply. This is a quite feasible approach to use in the UK, but it lacks true portability and, more importantly, lacks flexibility to accommodate buildings of different sizes or leakiness.

This paper initially describes briefly the design and construction at the Building Research Establishment (BRE) of three fan units which can be used together to pressurize large nonresidential buildings. The units are portable, can be easily assembled and used by a minimum of personnel, and can be operated using conventional 13-A electrical power points. In addition, the fans are chosen to accommodate a wide range of building sizes and air leakage rates while maintaining reasonable flow measurement accuracy.

Using this equipment, field measurements of the envelope leakage characteristics of two UK office buildings are then described. The paper concludes by comparing the results obtained with those from a sample of North American buildings to draw some preliminary conclusions as to the airtightness of UK office buildings.

Design and Construction of Pressurization System

Three pressurization units, each drawing less than 3 kW of electrical power from conventional 13-A sockets, were designed and built [*4*]. Each unit consists of a fan, a single- to three-phase inverter-type speed control, and nozzles to measure the airflow rates. The fans are 762 mm (30 in.) in diameter and are of the direct drive, single stage, and axial flow type. Each fan will generate at least 180 Pa (static, unstalled) and provide a flow rate in excess of 6 m^3/s with free delivery.

The strategy which governed the design of these units was that, on any particular building, only a sufficient number of fans would be used to achieve the target envelope pressure difference. Problems of fan control stability can arise, however, when multiple fans are used, which results in one fan stalling while the other surges in speed, then reversing this sequence, and so on. This was solved by using single- to three-phase (variable frequency inverter-type) speed controllers to drive the fan motors [*4*].

Airflow through each fan was measured using nozzles [*5*]. These were chosen because they could be used without calibration, had known measurement uncertainties, and offered no extra system pressure losses. Two straight-duct sections were also made to provide the required [*5*] system length. Using toggle clamps, each conical inlet was connected (via the straight ducts) to a fan. This made it easy to transport each of the units which, when assembled, had an overall length of about 3.2 m. System pressure losses, over and above the 50 Pa required across the building envelope, were estimated at about 130 Pa for a 6 m^3/s flow rate through each fan.

Experimental Arrangements

Buildings

Whole-building pressurization tests were carried out in two medium-sized office buildings located at the BRE site in Garston. Building A, with a volume of 6254 m^3, is naturally ventilated. In plan, it is T-shaped and consists of a two-story block linked at one end to a four-story block (Fig. 1) with a stairwell at that end providing common access to all four levels. At the other end, another stairwell also links the two levels of the two-story block. The outer face of the building consists of single-glazed steel-framed windows and 13-mm

FIG. 1—*South face of Building A.*

insulated infill panels. Behind each panel, there is a 114-mm air gap followed by a 114-mm thick brick wall lined with 16 mm of plaster on the inside. The external surface area (walls and roof) was estimated to be 2195 m^2.

Building B (Fig. 2) consists of three-stories and was built as a low-energy office [*6*] and incorporates a number of energy saving features. Among these is a mechanical ventilation system which allows a varying amount of fresh air to be taken into the building, depending upon the setting of mechanical dampers at the air handling unit (AHU). The occupants are free to open the windows whenever they choose.

The building is rectangular (60 by 12 m) in plan, and the floor-to-ceiling height of each story is 2.6 m. Offices are located on each floor along either side of a central corridor. The total volume of the building is 5315 m^3 and the estimated external surface area is 1750 m^2. Windows are all double-glazed with aluminum frames, and wall construction consists of 9-mm-thick clay tiles on the outside face followed in succession by 125-mm-thick precast concrete panels (PCP), a 300-mm void filled with blown polystyrene beads, and plaster board (12.5 mm thick) with an aluminum foil vapor barrier.

Test Conditions

Results of three pressurization tests—the first (Test A) in Building A and the last two (Tests B1 and B2) in Building B—are reported here. During the tests, all outside doors and windows were kept shut while all internal doors were wedged open. Wind speed during Test A was estimated to be about Beaufort 1 (0 to 1.5 m/s), occasionally gusting to Beaufort 2 (1.6 to 3.3 m/s). Inside and outside air temperatures were 13.5 and 10.5°C, respectively.

The mechanical ventilation system was switched off during the tests in Building B. Test B1 was carried out with the dampers open (as found during normal operation) on the intake and exhaust of the AHU. These openings to the outside were blanked off with plywood panelling for Test B2. Both tests were carried out on a very still day with the outside air temperature at 4°C and with internal temperatures of 8°C (Test B1) and 12°C (Test B2).

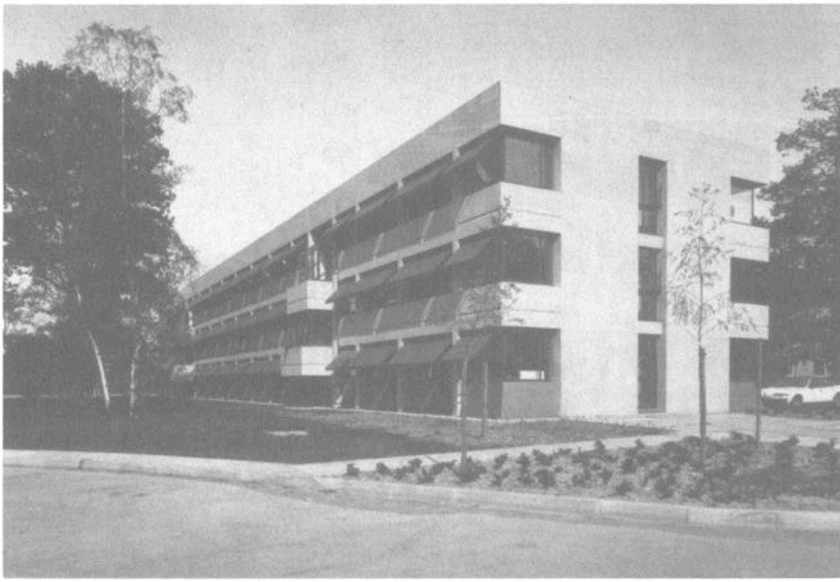

FIG. 2—*View from the southeast of Building B.*

Method of Testing

In use, each pressurization unit was connected, via short lengths of flexible ducting, to false plywood door panels temporarily sealed (Fig. 3) into open external doorways. In each unit, the differential pressure, Δp (Pa), between the conical inlet and an outside reference location (sheltered from the wind) was measured so as to determine the airflow rate, Q (m^3/s), through each fan. This was calculated from the following relationship derived in Ref *5*,

$$Q = C \pi (d^2/4)\sqrt{(2 \Delta p/\rho)}$$

where

d = inside diameter of the conical inlet, m,
ρ = density of air at entry to conical inlet, kg/m^3, and
C = combined flow coefficient for conical inlet.

The coefficient C is a function of the Reynolds number, R, where

$$R = 83\,500\, d \sqrt{\Delta p}$$

such that, $C = 0.960$ for $R > 300\,000$ and $C = 1 - 0.5R^{-0.2}$ for R between 20 000 and 300 000. Conical inlets should not be used for $R < 20\,000$.

Initially, as many fans as were needed (two/three for Building A and two for Building B) were run together to achieve an adequate building pressure differential. Pressure differentials were monitored, and flow rates were calculated. The fan speeds then were reduced evenly to establish new pressure levels, and new measurements were taken. When the stage was reached at which one less fan was needed to maintain the required pressure and flow rate, one fan was shut down and sealed from the building using polyethylene sheeting and masking tape. The remaining fans were then powered up to reestablish the required flow rate and pressure differential, and the test then continued until finally only one fan was left running.

FIG. 3—*Pressurization system installed in the main entrance (north face) of Building B.*

Results

Figures 4 and 5 show the airflow rates plotted against applied pressure differential (at ground floor level) across the outside wall envelopes for Buildings A and B, respectively. Figure 4 for Building A consists of two separate sets of measurements carried out on the same day. One set was generated by using two fan units installed together at the main doorway. The other set was obtained by using a third additional fan installed at a doorway on the opposite end of the building.

Best-fit power-law profiles of the form.

$$Q = K\,\Delta p^n$$

where the coefficient K and the exponent n (lying between 0.5 and 1.0) are constants, were fitted to the data. This was done by transforming the above equation to the form

$$\ln(Q) = \ln(K) + n \ln(\Delta p)$$

and fitting a linear regression line on the transformed variables. The computed coefficients and exponents (with associated 95% confidence intervals), were evaluated, and are as given in Table 1. Note that no confidence interval has been ascribed to the coefficient K since the regression analysis was carried out on the log transform of this coefficient.

Discussion of Results

Leakiness of the Two UK Office Buildings

In dwellings, it is usual for purposes of comparison [7] to calculate the air leakage rate at an applied pressure differential of 50 Pa. For larger buildings, however, this can be a

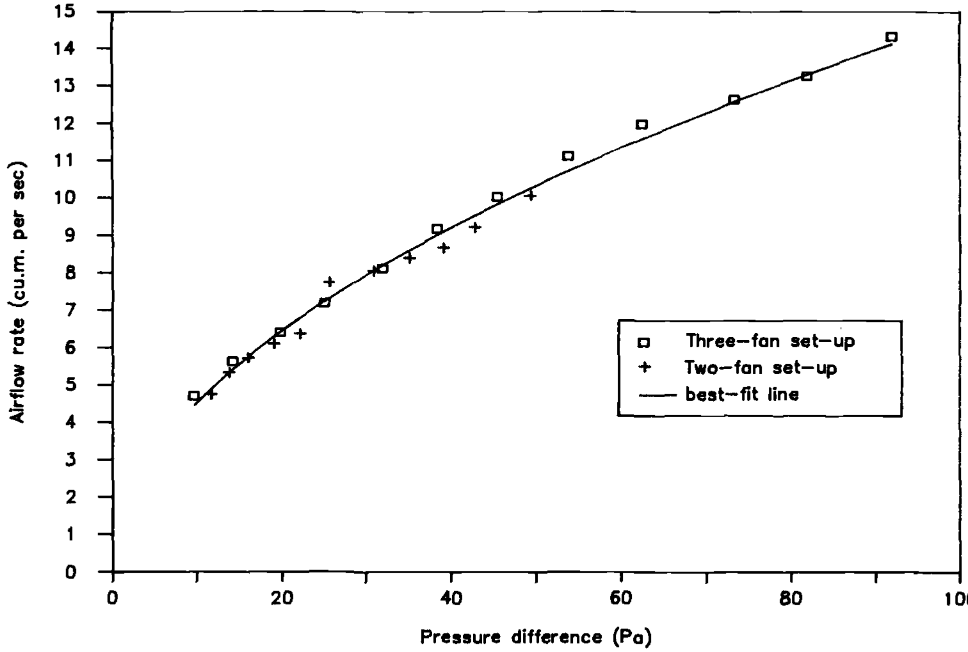

FIG. 4—*Building A pressure test.*

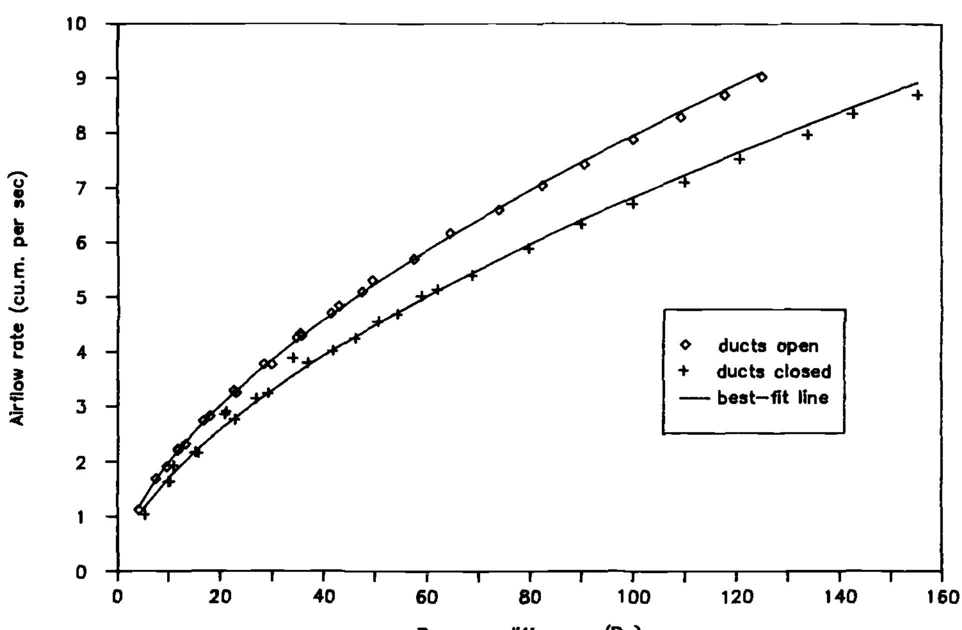

FIG. 5—*Building B pressure tests.*

TABLE 1—*Computed coefficients and exponents.*

Building	Test	ln(K)	Coefficient, K, (m^3/s)/Pa	Exponent, n
A	A	0.328 ± 0.015	1.388	0.51 ± 0.01
B	B1	−0.697 ± 0.005	0.498	0.60 ± 0.00
B	B2	−0.859 ± 0.015	0.424	0.60 ± 0.00

difficult pressure to achieve, and consequently the flow rate, Q_{25}, at a lower pressure of 25 Pa can be used [2].

For Buildings A and B, the overall whole-building leakage rates at any applied pressure differential can be evaluated using the power law constants calculated earlier. At 25 Pa, the air leakage rate is 7.2 m^3/s for the more conventional Building A. This rate is more than halved to 3.4 m^3/s (Test B1) and 2.9 m^3/s (Test B2) for Building B, indicating the relative tightness of this low-energy building. The results also indicate that the envelope leakiness of Building B is reduced by about 15% (at 25 Pa) when the duct openings of the AHU are blanked off.

Leakage Comparison with North American Office Buildings

Published literature was searched to enable a preliminary comparison to be made between the leakiness of the two UK office buildings tested here and those found elsewhere. Two data sets, one from Canada and the other from the USA, were found and the leakage characteristics of the buildings comprising these sets were analyzed statistically (see Appendix) to remove individual variations between buildings.

There is little point in comparing the air change rates (leakage airflow rate, Q, m^3/s, divided by building volume, V, m^3) of buildings with substantially different external surface to volume ratios since such comparisons do not provide any useful information. A more suitable measure is Q_{25}/S (where S is the total permeable external surface area), which can be regarded [7] as an index of the overall permeability of the building envelope to airflow and hence can be considered as a measure of the building's constructional quality.

Figure 6 shows the computed averaged values of the Q_{25}/S index for the North American buildings together with those measured for the two UK office buildings. Results also show that, while the low-energy UK building is relatively tight (when compared with the North American buildings), the more conventional Building A is twice as leaky.

Conclusions

At present, there is a considerable lack of information on the leakage characteristics of UK office buildings. This is because no suitable equipment have been available until now to pressurize these large and mostly naturally-ventilated buildings.

This paper described the design and construction of individual fan units which can be used together to pressurize a large building. Important design constraints included portability of the units and operation from conventional 13-A electrical power points.

Field measurements to determine envelope leakage characteristics were carried out in two medium-sized office buildings, and pressure differentials well over the usually accepted target of 50 Pa were reached. Results showed that one of these buildings, of conventional construction, was twice as leaky as those found (on average) in North America. The other, built specifically as a low-energy office, was found to be as tight as the North American buildings.

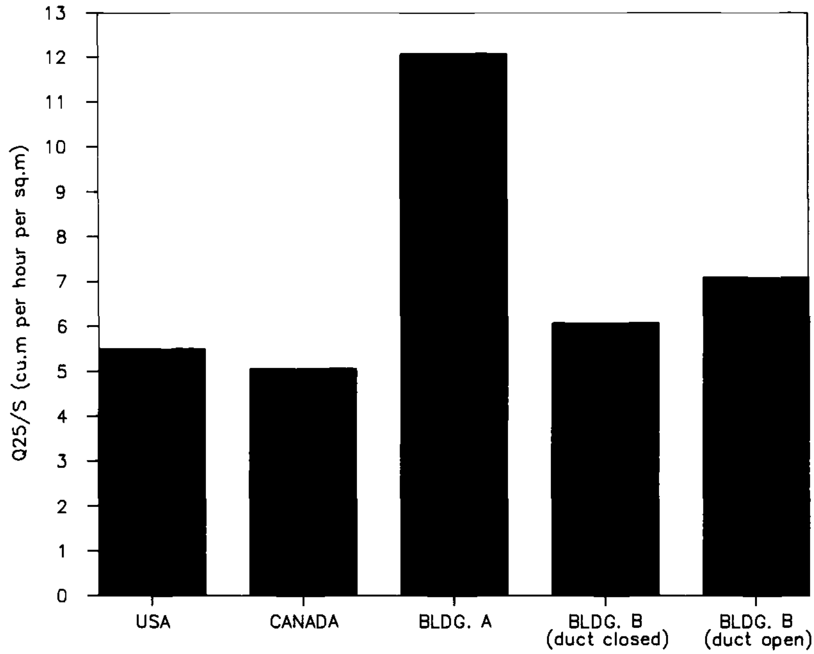

FIG. 6—*Envelope leakage of office buildings.*

Acknowledgments

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

APPENDIX

Leakage Characteristics of North American Buildings

Published literature was searched so as to make a preliminary assessment of the leakage characteristics of the office buildings tested here with those found elsewhere. It was found that the majority of field work has been undertaken either by the Division of Building Research of the National Research Council (NRC) of Canada or the Center for Building Technology, National Bureau of Standards (NBS), USA. All these North American buildings tested were mechanically ventilated, and, in most cases, the ventilation systems were used to pressurize the buildings.

The eleven Canadian Buildings [*8–11*] ranged from 9 to 44 stories in height and had volumes between 48 000 and 246 000 m^3. Wall construction was mainly PCP, even though three buildings had metal-panelled exterior facades. One building was of masonry construction.

The eight office buildings tested [*2, 12–14*] by NBS ranged from 2 to 15 stories in height and had volumes between 8500 to 191 000 m^3. Two of these buildings were built from PCP while the others had walls constructed from either concrete units and brick or from brick and block.

Table A1 sets out the building leakage characteristics of these two sets of buildings with each building being referred to in the same manner as that found in the various references.

TABLE A1—*Leakage characteristics of North American buildings.*

Building	Wall Description,[a] Major Components	S/V, m^2/m^3	Q_{25}, m^3/h	Q_{25}/V, 1/h	Q_{25}/S $(m^3/h)/m^2$	K/S, $\frac{(m^3/h)}{(m^2 \cdot Pa^n)}$	Exponent, n
NBS:							
Anchorage	PCP[b]	0.12	152 460	0.80	6.70	0.94	0.61
Ann Arbor	Concrete masonry	0.21	27 395	0.86	4.10	0.47	0.67
Columbia	Concrete	0.11	83 077	0.67	6.00	1.32	0.47
Huron	Brick/concrete masonry	0.24	12 398	0.45	1.90	0.24	0.64
Norfolk	Brick	0.20	87 476	1.45	7.20	0.67	0.74
Pittsfield	Brick	0.27	8 125	0.95	3.50	1.10	0.36
Springfield	PCP[b]	0.16	82 666	1.43	9.20	0.01	2.09
NRC:							
A	PCP[b] and tile	0.10	83 935	0.58	5.70	0.63	0.69
B	PCP[b]	0.15	55 054	0.80	5.50	1.07	0.51
B (repeat)		0.17	56 514	0.81	4.70	0.24	0.90
C	PCP[b] and concrete block	0.11	65 598	0.55	4.90	0.55	0.68
D	Metal panel and concrete	0.16	48 362	1.00	6.20	0.98	0.57
E	Metal panel	0.13	58 696	0.64	4.80	0.95	0.50
F	PCP[b]	0.12	42 226	0.45	3.80	0.75	0.50
G	PCP[b]	0.12	91 271	0.65	5.60	0.69	0.65
H	Metal panel	0.11	81 852	0.65	5.80	0.82	0.61
I	Slate and concrete	0.12	97 819	0.40	3.33	0.17	0.91
J	Aluminium panel	0.11	114 065	0.46	4.24	0.39	0.73
J (repeat)		0.11	181 858	0.75	6.76	1.02	0.59
K	PCP[b]	0.18	90 202	1.55	8.70	0.36	0.99

[a] All walls have some form of insulation.
[b] PCP represents precast concrete panels.

TABLE A2—*Computed coefficients and exponents, North America.*

Country	ln(K/S)	Coefficient, K/S, $(m^3/h)/(m^2 \cdot Pa^n)$	Exponent, n
USA (6 tests)	−0.329 ± 0.133	0.72	0.60 ± 0.04
Canada (12 tests)	−0.448 ± 0.034	0.64	0.60 ± 0.01

Some of the values shown have either been taken directly from the published results or have been evaluated or inferred from the given information. Leakage characteristics of these two regionally differing sets of buildings then were assessed on a statistical basis to remove variations between individual buildings.

Surface Area to Volume Ratio, S/V

The average values, together with their 95% confidence levels, are as follows:

USA (7 buildings) $S/V = 0.19 \pm 0.06\ (m^2/m^3)$

Canada (11 buildings) $S/V = 0.13 \pm 0.02\ (m^2/m^3)$

The permeable area, S, for the Canadian buildings not only includes wall areas and roof areas but also the floor areas since these buildings were raised on pilotii. For interest, the S/V ratios can be compared with those for dwellings which have been found to lie [7] between values of one and two.

Airflow through Building Envelope, Q_{25}/S

The Q_{25}/S value for the NRC buildings was estimated from a reduced sample of ten buildings since results from a masonry-wall building (nontypical of the other Canadian buildings) was excluded. Results for the two sets of data are as follows:

USA (7 buildings) $Q_{25}/S = 5.51 \pm 2.30\ (m^3/h)/m^2$

Canada (10 buildings) $Q_{25}/S = 5.08 \pm 0.65\ (m^3/h)/m^2$

Comparison of variances ($F_{6,9} = 7.52$, $P < 0.05$) and the Mann-Whitney test ($U_{7,10} = 28$, $P < 0.05$) showed that the sample of Canadian buildings were statistically significantly tighter than those tested in the United States.

Leakage Characteristic Profiles

Using the power-law constants given earlier in Table A1, leakage rate per unit surface area, Q/S, were computed for a range of pressure differentials between 0 and 100 Pa for each building. Results from the Springfield building (NBS study) and Building K (NRC study) were discarded because of anomalies in the data.

From these computed leakage rates, best-fit power-law profiles were fitted (as described in the main text) and the constants (together with their 95% confidence levels) were evaluated as given in Table A2.

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Methods for Measuring Air Leakage in High-Rise Apartments

REFERENCE: Shaw, C. Y., Gasparetto, S., and Reardon, J. T., **"Methods for Measuring Air Leakage in High-Rise Apartments,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 222–230.

ABSTRACT: The balanced fan depressurization method has been modified for application to high-rise apartment buildings in order to measure the overall air leakage and the wall air leakage of an apartment unit simultaneously. The method requires the use of two sets of fan pressurization apparatus. One is installed at the door of an apartment unit for measuring the air leakage rate of the exterior wall, and a much larger apparatus is installed at an exterior door of the building for measuring the overall air leakage rate. The pressures between the test unit and the adjacent units are balanced to minimize the air leakage through the party walls by adjusting the airflow of the larger apparatus and the door opening of the adjacent apartments. The method was successfully applied to two high-rise apartment towers before and after they were retrofitted to improve airtightness of the envelope. In addition, the tracer gas decay method was applied to the same buildings to obtain the infiltration rates of selected apartment units.

The methods used to measure the airtightness values and the air infiltration rates and the test results of the two apartment towers are discussed.

KEY WORDS: leakage, pressure, residential, measurement, fan, tracer gas

Two high-rise senior citizen apartment buildings, Buildings D and V, were experiencing significant deterioration of their exterior masonry. As air leakage was suspected as the major cause for the deterioration, the buildings were retrofitted to improve airtightness. To assess the effectiveness of the retrofit measures, the air leakage rates through the building envelope and through the exterior wall of one individual apartment unit in each building were measured both before and after the retrofit. The balanced fan depressurization technique [*1*] was modified to be able to measure the air leakage rates through the exterior wall of the individual apartment unit and through the envelope of the whole building simultaneously.

A method was developed for use by building consultants and air sealing contractors to estimate the air infiltration rate of an individual apartment unit based on its measured airtightness value and the pressure difference across its exterior wall. Tracer gas decay tests were conducted on two individual apartment units to determine the feasibility of the proposed method. This paper presents the test methods and results.

Test Building

Both buildings were constructed with reinforced concrete frames and double wythe brick masonry cladding. The exterior walls are 20.3-cm (8-in.)-thick masonry panels and are

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insulated on the inside. The 14-story Building D was constructed in 1977. The 17-story Building V, constructed in 1982, incorporates a cavity between the inner and outer wythes, in addition to the interior insulation. The two buildings are connected at the ground floor via a common foyer.

Each floor has seven apartment units on each side of a common corridor. Outdoor air is supplied to each corridor through a central supply-only ventilation system. Exhaust air leaves the building through the exhaust fans in the bath room and the kitchen of each apartment. Each building has two elevators and two stairwells. One stairwell in each building has an outside door at ground level.

Test Methods

Airtightness Measurements

In each building, airtightness values of the building envelope and the exterior wall of one apartment unit were measured both before and after the retrofit. During the test of each building, the connecting ground-level door to the other building was sealed. The test methods are described below.

Overall Airtightness

As shown in Figs. 1 and 2, a large vane-axial fan was used to depressurize the test building. The fan airflow could be adjusted from 0 to 23 m^3/s (0 to 50 000 ft^3/min). The fan inlet was

FIG. 1—*Building test setup showing exhaust fan and duct connection.*

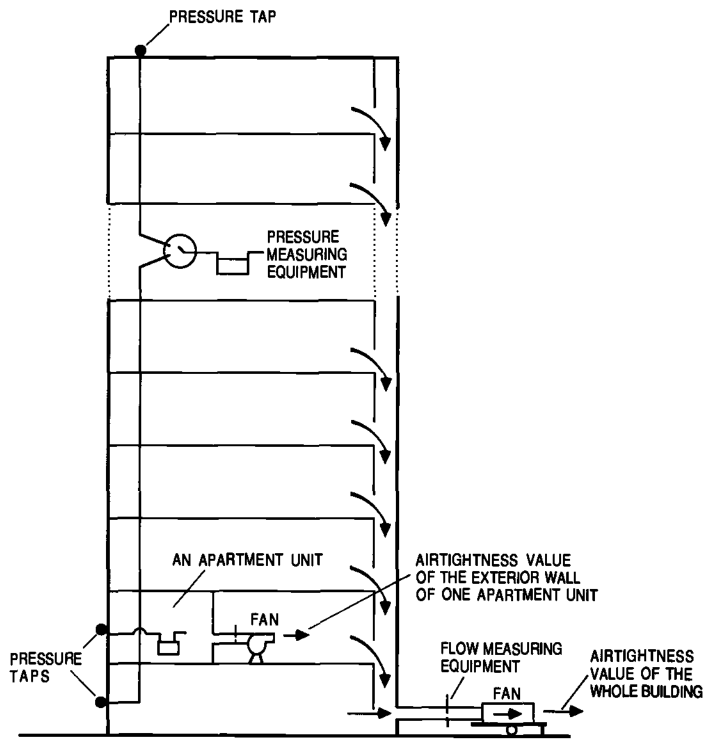

FIG. 2—*Building test setup showing the fan pressurization apparatus for measuring the airtightness values of the whole building and an apartment.*

connected by 12 m (40 ft) of 0.9-m (3-ft)-diameter ducting to a plywood panel temporarily replacing the entrance door to a stairwell. All interior doors to the stairshaft were kept open to provide a free flow path for the air drawn by the fan from the floor spaces, through the stairshaft, to the outdoors.

The airflow rate was measured upstream of the fan intake using a pair of total pressure averaging tubes. Flow rate measurements are accurate to within 5% of the measured values. The pressure differences across the building envelope at both the ground and roof levels were measured using an electronic manometer with a strip chart recorder (accurate to within 5% of the measured values). The average of the two measured values was used to represent the mean pressure difference across the building envelope. Prior to and immediately after each test, the fan was sealed with a plastic sheet and the pressure differences across the envelope at the ground and top levels were measured. The two readings obtained at each location (one before and one after the test) were averaged to give the base readings of the pressure difference for the two locations. These base readings were then subtracted from subsequent pressure difference measurements to minimize weather effects (wind and stack action).

The two buildings were tested without their ventilation systems operating. The window air conditioners in Building D were removed for the tests. Those in Building V were left in place with their outdoor air dampers closed during the tests. In addition, all the windows in each building were closed tightly for each test.

Exterior Wall Airtightness

Figure 2 is a schematic diagram of the test setup to measure the airtightness of the exterior wall of an individual apartment and the airtightness of the whole building's envelope simultaneously. A small fan depressurization apparatus was connected to a plywood panel, replacing the apartment's entrance door, to draw outdoor air through the apartment's exterior wall and exhaust it into the corridor. The entrance doors of the two immediately adjacent apartments were cracked open just enough to make the individual pressure differences between them and the tested unit approximately zero. This adjustment was made to minimize the air leakage through the common walls [*1*] and is fundamental to this technique. The pressure differences between the test unit and the units directly above and below were also measured during the tests to ensure that they were approximately zero. Under this "balanced" condition, the airflow rate measured through the small fan depressurization apparatus is equal to the air leakage rate through the exterior wall of the test unit driven by the pressure difference across the exterior wall [*1*].

The airflow rates through the small fan were measured using a Meriam LFE laminar flow element accurate to within 5% of the measured values. The pressure differences across the exterior wall of the test unit and across the common walls it shares with the adjacent units were measured using an electronic micromanometer and a strip chart recorder. The accuracy of all pressure measurements is within 5% of the measured values.

Air Change Rate Measurement Method for Individual Apartment Units

The air infiltration rate in an individual apartment unit can be estimated with the following equation. It uses the measured airtightness value of the exterior wall and the pressure difference measured across it.

$$q = C \cdot (\Delta P)^n \tag{1}$$

where

q = air infiltration rate, L/s,
C = flow coefficient, L/(s·Pa^n),
ΔP = pressure difference across the exterior wall, Pa, and
n = flow exponent.

In Eq 1, the values of C and n for the test units were obtained from the fan pressurization tests described earlier. The pressure difference in this equation is that measured across the exterior wall of the apartment unit during normal operating conditions, that is, during conditions under which the air infiltration rate is to be estimated.

The method was used to estimate the air infiltration rates in two apartments, one in each building. The pressure differences were measured with the same apparatus used for the fan pressurization tests. The outdoor pressure tap was installed on the exterior surface of the living room window, and the indoor pressure tap was located near the center of the test unit.

For comparison with the estimates, the air change rates in the test apartment units were measured using the tracer gas decay method at the same time as the pressure differences were being measured. The tracer gas concentrations in the surrounding units and the pressure differences across the common walls were also measured during these tests. These data were used to estimate the flow rates and directions of any air exchange between the test unit and its surrounding units.

The tracer gas test procedure was as follows: A small amount of SF_6 gas was injected into the center of the living room. A small desk fan was used to help mix the tracer gas with the indoor air. After allowing 30 min for mixing, 50-mL samples of the indoor air were collected manually, using a syringe, every 10 min at the center of the room for at least 1 h. A total of seven to ten samples were collected for each test.

Each sample was taken as follows: Just prior to the sample time, the 60-mL syringe was purged twice and then, at the sample time, was used to draw in a 50-mL sample of air. The gas sample was then injected into a 20-mL evacuated glass test tube with a rubber septum-type stopper, of the same type used to collect blood samples in medical laboratories. In this way, the sample was stored under pressure. This pressure was relied upon to later drive the sample into an electron-capture gas chromatograph for analysis.

The electron-capture gas chromatograph was calibrated against gases with known concentrations. Four SF_6-air gas mixtures ranging from 1 to 200 ppb were prepared in our laboratory for this purpose (the accuracy of the prepared gas mixtures could not be checked because no certified gas at such low concentrations is available). To check the consistency of the preparation procedure, several gas mixtures of the same concentration were prepared using containers of different sizes so that different proportions of SF_6 and air were used. The agreement among these gases was within 5% of each other.

Results and Discussion

Airtightness Values

The overall airtightness values for both buildings, before and after the retrofit, are shown in Fig. 3. The plotted results have been normalized by exterior wall area. The results indicate that the overall airtightness of each building was improved by the retrofit. They also show that Building V is leakier than Building D.

As the pressure difference across the envelope decreased with the building height due to the large flow resistance in the stairwell, the overall air leakage rate was presented in terms of the mean pressure difference across the envelope. The mean pressure difference was defined to be the average value of the pressure differences at the ground and top levels. To give some indication of the variation of the pressure differences along the building height, the pressure differences at the ground and top levels are given for a fan flow rate (airtightness value) which produced a mean pressure difference of about 50 Pa. For Building D (14 stories), the airtightness value corresponding to a mean pressure difference of 53 Pa was 2.25 $L/s{\cdot}m^2$ (Fig. 3), and the pressure differences at the ground and top levels were 74 and 32 Pa, respectively. For Building V (17 stories), the airtightness value, the mean pressure difference, and the pressure differences at the ground and top levels were 3.39 $L/s{\cdot}m^2$, 50 Pa, 75Pa, and 25 Pa, respectively.

The airtightness values of the exterior walls of the two individual apartment units are shown in Fig. 4. The results indicate that, in both buildings, the improvement in the airtightness of the exterior wall of the tested apartment is much greater than that realized for the whole building. This suggests that the air leakage through the exterior walls for both buildings is not as important as that through their roofs and basements. Visual inspections suggest that some of the major leakage sites in the roof are the elevator shafts (and the smoke dampers in Building V).

A comparison between Figs. 3 and 4 indicates that the normalized overall airtightness value was greater than the normalized exterior-wall airtightness value. This is because the area of the exterior wall used to normalize the overall airtightness value includes the two side walls. The side walls (Fig. 1) are expected to be much more airtight than the front and back walls because the window area to wall area ratio for the side walls is much smaller than that for the other walls. Also, the windows in the side walls are not openable.

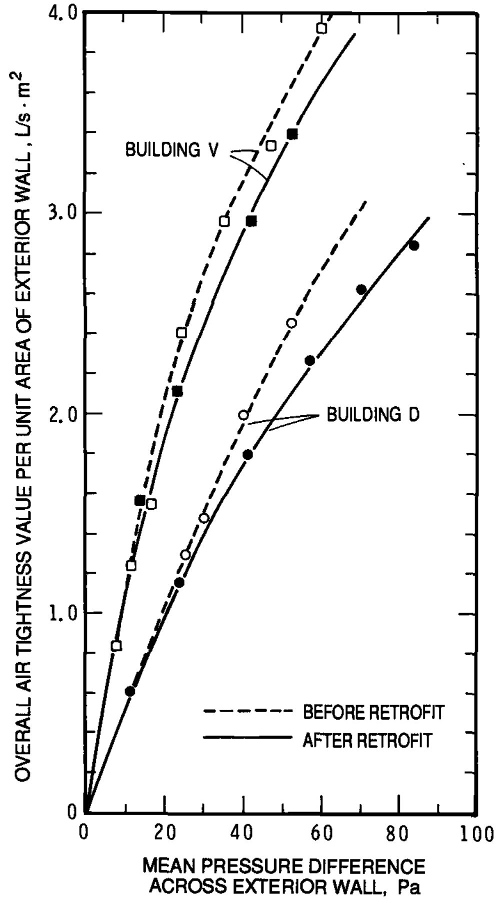

FIG. 3—*Overall airtightness value per unit area of exterior wall.*

Air Change Rates

Figure 5 shows the results of two typical tracer gas tests for each apartment unit, including the concentrations and pressure differences measured in the surrounding units. All four tests shown were made after the retrofits. Arrows are used to indicate the directions of the pressure differences between the test apartment units and their surroundings. The air infiltration rates were calculated from Eq 1. The flow coefficients and exponents used for the calculation were 3.43 L/s·$Pa^{0.61}$ and 0.61 for Apartment Unit 208, and 5.68 L/s·$Pa^{0.5}$ and 0.5 for Apartment Unit 310. The results indicate that there were some interapartment airflows during these tests. A mass flow balance for the unit left apartment in Fig. 5*a*, assuming an air infiltration rate of 19.6 L/s equal to that calculated in Unit 208, was made to estimate the airflow rate from Unit 208. The result of this mass flow balance indicated that the airflow rate from Unit 208 was about 0.1 L/s. Similar observations in the other adjacent units, for all the tests, suggest that these interapartment airflow rates were too small to be measured accurately.

The air infiltration rates of Apartment Units 208 (Building D) and 310 (Building V) were calculated based on the pressure differences across the exterior walls measured under various weather conditions. At the same times that the pressure differences were measured, the air

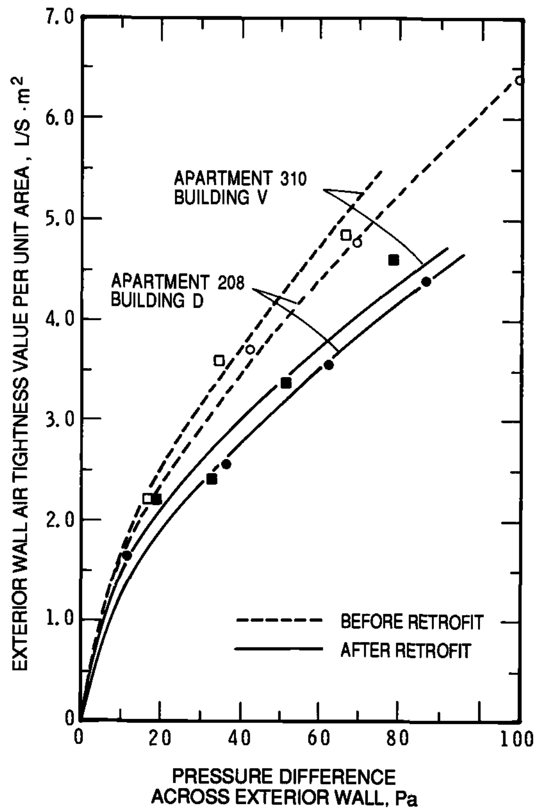

FIG. 4—*Airtightness value of exterior wall per unit area of exterior wall.*

change rates of the two apartment units were also measured using the tracer gas decay method. Although the measured air change rates included the effects of air inflows from the surrounding apartment units, the above discussion suggests that the contributions of the air inflows were negligible. Figure 6 shows a comparison between the calculated and the measured air infiltration rates. The results indicate that, for most cases, Eq 1 estimates the air infiltration rate within 20%.

Conclusions

The balanced fan pressurization method was modified to measure the air leakage rates through the exterior wall of an apartment unit and through the entire building envelope simultaneously. This technique was successfully used to test two high-rise apartment buildings to assess the effectiveness of an airtightness retrofit.

A method was developed to estimate air infiltration rates of individual apartment units using measured airtightness values and measured pressure differences across the exterior walls. A comparison between the air infiltration rates calculated using this method and those measured by the tracer gas decay method indicates that, for most cases, the proposed method estimates the air infiltration rates within 20%.

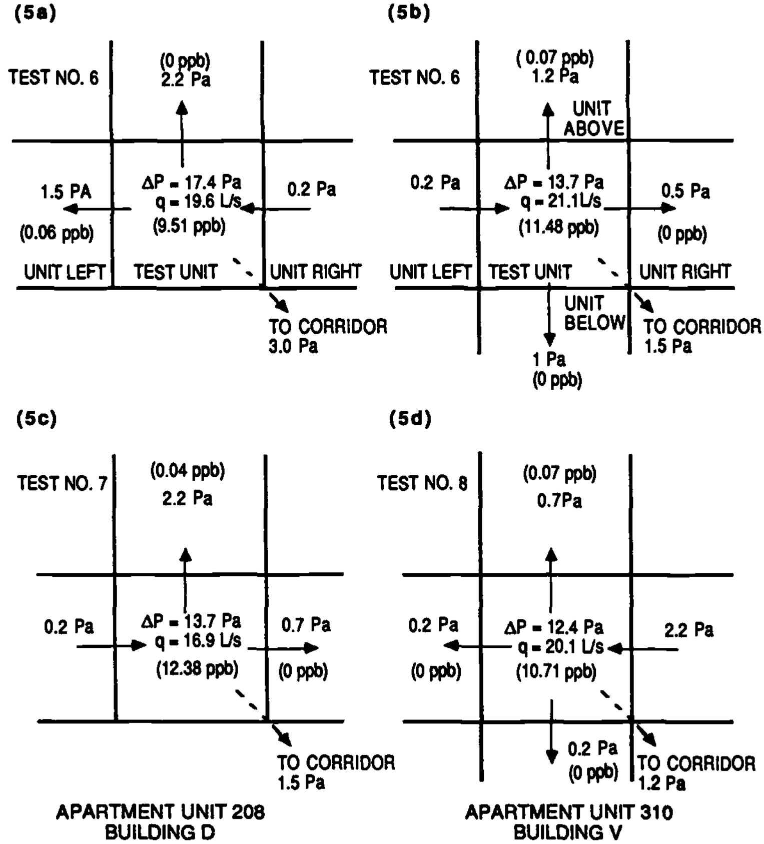

FIG. 5—*Tracer gas concentration, air flow directions, and corresponding pressure differentials.*

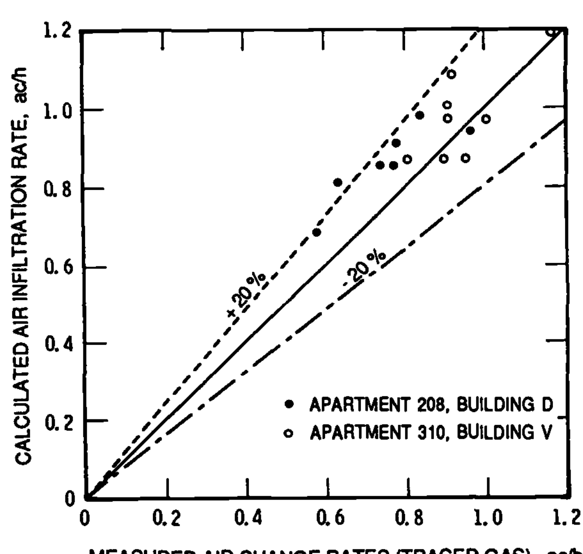

FIG. 6—*Calculated air infiltration rate versus measured air change rate.*

Acknowledgments

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Shin Hayakawa[1] *and Satoshi Togari*[1]

Simple Test Method for Evaluating Exterior Wall Airtightness of Tall Office Buildings

REFERENCE: Hayakawa, S. and Togari, S., **"Simple Test Method for Evaluating Exterior Wall Airtightness of Tall Office Buildings,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067*, M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 231–245.

ABSTRACT: C. Y. Show, D. M. Sander, and G. T. Tamura developed a test method to measure the air leakage characteristics of exterior walls of buildings that utilized an outdoor air supply system of ventilation and air handling, taking into account the influence of the stack effect. They applied this method to eight tall buildings in Ottawa, and results were reported.

However, windows and wall constructions in Japan are so different than those in Canada that those results cannot be used directly. To obtain our own data, the authors developed a simple test method that utilizes buoyancy caused by the stack effect instead of fans for pressurization. To open doors on the ground floor or the window at the bottom part of the building while the stack effect is operative is the same as pressurizing the whole building, and to open an exit door at the roof or the window at the upper part of the building is the same as decompressing the whole building.

This method was applied to three tall buildings of Sendai and Tokyo, whose walls were cast-in-place concrete (Building A), precast concrete panel (Building B), and metal panel (Building C). For the test results, infiltration rates through the exterior wall were estimated by approximate calculation. Of the three, it was found that Building A was the tightest and Building C was the loosest. This paper reports the results of the application for the simple test method we developed.

KEY WORDS: exterior-wall, airtightness, test method, stack effect, tall building

To estimate outdoor air volumes which infiltrate through exterior-wall cracks of a tall building due to the stack effect and wind force, the area method [*1*], crack method [2], etc. have been used as conventional methods for a long time. However, since these methods use window areas and the total length of sashes as parameters, they lack reliability when applied to modern buildings that have many unknown cracks. At present, it is more practical to establish the airtightness of the exterior walls as a whole, rather than parts of the building. On the basis of this concept, C. Y. Shaw et al. [*3,4*] obtained the airtightness of eight tall buildings in Canada in the winter season, when the stack effect was operative, by employing the method of pressurizing the entire building using air-supply fans and utilizing the pressure distribution caused by the stack effect. The above method, however, involved the troublesome considerations of obtaining operators for the fan system and incurring the cost of running the fans at the time of measurement, which occurred mostly during the night when the building was deserted. Further, since the air-supply system's fan was also used, it was not possible to correctly determine the supply air rate. Thus, their method cannot be said to be easily operable by the inexperienced.

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The authors developed a simplified estimation method which uses the stack effect itself as a pressurizing source to take the place of the fans, a method which requires no fans, and applied it to three buildings. Results of the application are reported in this paper [5,6]. The authors call this test method "stack effect method" as compared with pressurizing method.

Airtightness of Exterior Wall

Simplified Measuring Method

Preconditions.

1. Cracks are classified as: the "basement floor plus lobby floor $[(\alpha A)_G]$," "typical floor $[(\alpha A)_T]$," and "top floor $[(\alpha A)_R]$," as shown in Fig. 1. These are expressed by effective area αA where A (m^2) is an area and α is a flow coefficient of a simple opening. Naturally, these expressions are used as expedients; it is also possible to express each crack as

$$q = a\Delta P^{1/n}$$

where

q = flow rate (kg/s),

ΔP = pressure difference (kg/m^2)[2], and

a,n = coefficients.

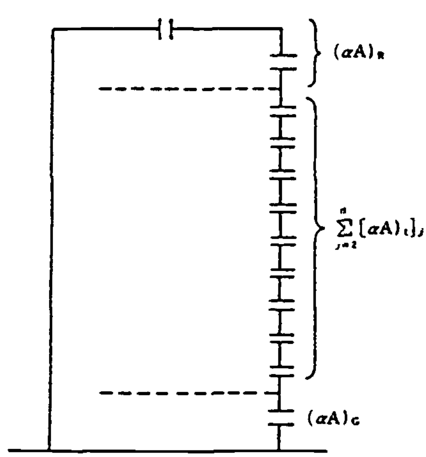

FIG. 1—*Kinds of exterior-wall cracks.*

[2] "kg/m^2" is used instead of Pa as the unit of pressure difference ΔP. The reason is that the crack having the airtightness given by $q = a\Delta P^{1/n}$ can be easily expressed in an equivalent effective area αA of a simple opening using the equation

$$Q = \alpha A\sqrt{2g\gamma\Delta P}$$

where

$\Delta P = 1.0$ kg/m^2.

Conversion can be made by 1 kg/m^2 = 9.8 Pa. Pa is written in parentheses as far as possible.

This matter will be discussed later.

2. Measurements are made in the condition of nearly no wind (1 to 2 m/s or below) in winter.

3. The opening ends of ducts such as air in-take ports and air exhaust ports are closed with air dampers. If possible, they are sealed with vinyl sheets, etc.

4. To permit estimation of the pressure differences of exterior walls of typical floors, exterior pressure differentials at more than three locations and internal temperature distributions at several locations in the height direction are measured. To improve the accuracy of these measurements, the entire building is made into a state of "one room" by keeping open the stair-case doors and partition doors, so that no great air velocity and resultant pressure drop will occur. But even if opening partition doors would not be possible, by measuring the pressure difference across interior doors at the same time exterior pressure differences of another typical floors can easily be estimated.

Measuring Principles. Assuming that there is a neutral zone at the intermediate position of the building as shown in Fig. 2 during an ordinary state (a state in which no window and door are kept open), infiltration rate Q_i through the exterior wall and air leakage rate Q_o (kg/s) have the following relations with inner/outer pressure differential Δp (kg/m^2) and αA

$$Q_i = (\alpha A)_G \sqrt{2g\gamma_o|\Delta P_G|} + \sum_{j=2}^{M-1} (\alpha A)_{T \cdot j}\sqrt{2g\gamma_o|\Delta P_j|}$$

$$Q_o = \sum_{j=M}^{N} (\alpha A)_{T \cdot j}\sqrt{2g\gamma_i|\Delta P_j|} + (\alpha A)_R\sqrt{2g\gamma_i|\Delta P_R|}$$

Since the values in the root mark, denoted by K_G, K_J, and K_R can be obtained as measurement results, and $Q_i = Q_o$ can be assumed, the above-mentioned equations will be

$$K_G\,(\alpha A)_G + \sum_{j=2}^{N} K_j\,(\alpha A)_{T \cdot j} - K_R\,(\alpha A)_R = 0 \tag{1}$$

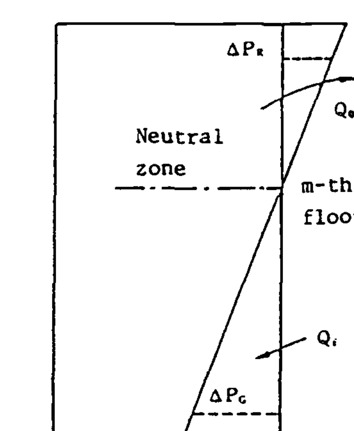

FIG. 2—*Ordinary state.*

where

$$j \leqq M - 1: K_j = \sqrt{2g\gamma_o|\Delta P_j|},$$
$$\text{and } M \leqq j \leqq N: K_j = -\sqrt{2g\gamma_i|\Delta P_j|}.$$

To obtain unknowns $(\alpha A)_G$, $(\alpha A)_T$, and $(\alpha A)_R$ in Eq 1, only two more equations are required. In ordinary testing, this state is changed by pressurizing using a fan, but such use of a fan is substituted here by opening doors. For instance, Fig. 3 shows the state of keeping doors open at the ground floor. If the air inflow rate Q_G' from the opening and pressure differentials of the typical floors ΔP_j and ΔP_R are known by measuring the flow-velocity distribution with a multipoints anemometer having six sensors and the area of the opening and pressure difference measured with a high-accuracy capacitance manometer, Eq 2 becomes valid

$$Q_G' \fallingdotseq -\sum_{j=2}^{N} K_j' (\alpha A)_{T\cdot j} + K_R (\alpha A)_R \tag{2}$$

Next, when the top-floor doors are kept open as shown in Fig. 4, and air out-flow rate Q_R and the pressure differentials ΔP_G and ΔP_j of the typical floors are known as mentioned above, Eq 3 similarly becomes valid

$$Q_R'' \fallingdotseq K_G''(\alpha A)_G + \sum_{j=2}^{N} K_j'' (\alpha A)_{T\cdot j} \tag{3}$$

With the above equations, it is possible to obtain the respective values of αA. Further, the "$\fallingdotseq$" sign in Eqs 2 and 3 means that the air inflow and outflow rates through cracks of the door-opened floor have been neglected. However, when this method was applied to existing buildings, the sign of $\fallingdotseq$ was regarded as the sign of equal. The values of Q_G and Q_R can be estimated from the calculated value of the pressure differential ΔP, if αA of opened windows and doors can be estimated. If the position of the neutral zone is deviated to the upper or lower part, it is advisable to change αA of opened doors by about three stages at the ground floor or top floor where the pressure differential is great to obtain plural numbers of Eq 2 or Eq 3.

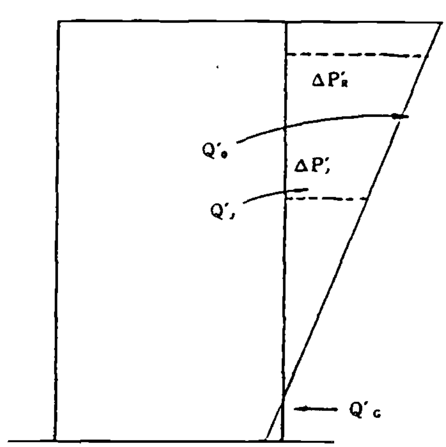

FIG. 3—*Door is kept open at ground floor.*

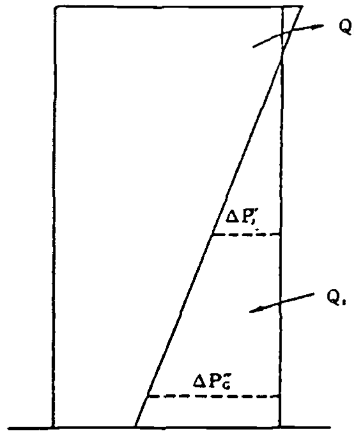

FIG. 4—*Door is kept open at top floor.*

Provided that the opening area is small, the error becomes greater. Namely, if the opening area is sufficiently larger than the areas of other cracks in the floor concerned, pressure difference across exterior walls becomes smaller, resulting in a state in which air leakage from other cracks becomes negligible.

Application Examples

Results of applying the simplified measuring method to three buildings are described below.

Nine-Story Building (Building A). This building, which was constructed in Sendai City (northern part of Japan), is a cast-in-place reinforced concrete building consisting of two basement floors (not facing outside air), nine floors above ground, and two top floors. Windows are fitted with steel sashes with fixed glazing. Each floor has a single swing window measuring 2.0 by 0.65 m at four locations. At every floor except the second and seventh floors, precision differential pressure gages (MKS, Baratron, etc.) are installed to measure the pressure difference between the outside and inside of the building, and their outputs are recorded by pen-recorders. To measure the outside pressure of the building, a hole is opened at a part of the seal of the sash of the openable window and a vinyl tube with inside and outside diameters of 2 and 4 mm, respectively, is passed through the hole and led to the pressure gage. Figure 5 shows the building's external appearance; the plan of the typical floor and measuring results are shown in Figs. 6 and 7, respectively.

Eq 4 was obtained from pressure distribution ⓐ at the normal state in the figure and Eq 1; Eq 5 was obtained from pressure distribution ⓑ with 1F porch door open and air inflow rate measuring result Q_G; Eq 6 was obtained from pressure distribution ⓒ, when 2F windows are kept open, and Eq 2.

A process of forming Eq 4 from Eq 1 is shown in Table 1. Equations 5 and 6 are formed by similar processes.

$$6.37\,(\alpha A)_G + 20.20\,(\alpha A)_T - 3.66\,(\alpha A)_R = 0 \tag{4}$$

$$32.30\,(\alpha A)_T - 6.53\,(\alpha A)_R = 2.33 \tag{5}$$

$$3.26\,(\alpha A)_G + 21.64\,(\alpha A)_T - 6.09\,(\alpha A)_R = -1.83 \tag{6}$$

FIG. 5—*External appearance (Building A).*

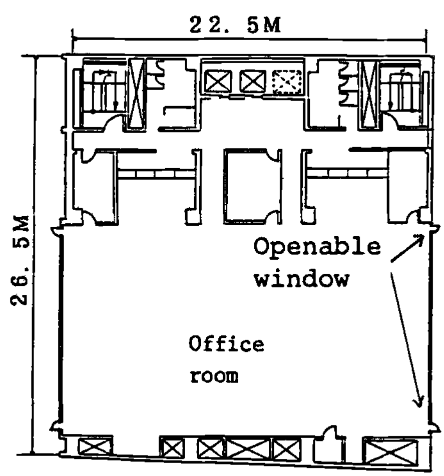

FIG. 6—*Plan of typical floor.*

Solution of the above three equations gives $(\alpha A)_G = 0.03$ m^2, $(\alpha A)_T = 0.03$ m^2, and $(\alpha A)_R = 0.21$ m^2. The crack at the top floor is too large.

This is due to the fact that all the opened ends of ducts are located at the top floor, and dampers in ducts are sometimes missing. The crack at 1F was $(\alpha A)_G = 0.04$ m^2 according to the measurement of crack dimensions around the door and was $(\alpha A)_G = 0.061$ m^2 in the circuit network simulation. Even when $(\alpha A)_T$ and $(\alpha A)_R$ are obtained by using the circuit network simulation, the results are 0.024 and 0.238 m^2, respectively, which are near the aforementioned values. When expressed in the unit exterior-wall area, $(\alpha A)_T$ comes to 0.8 cm^2/m^2.

Seventeen-Story Tall Building (Building B). This steel-frame building in the downtown

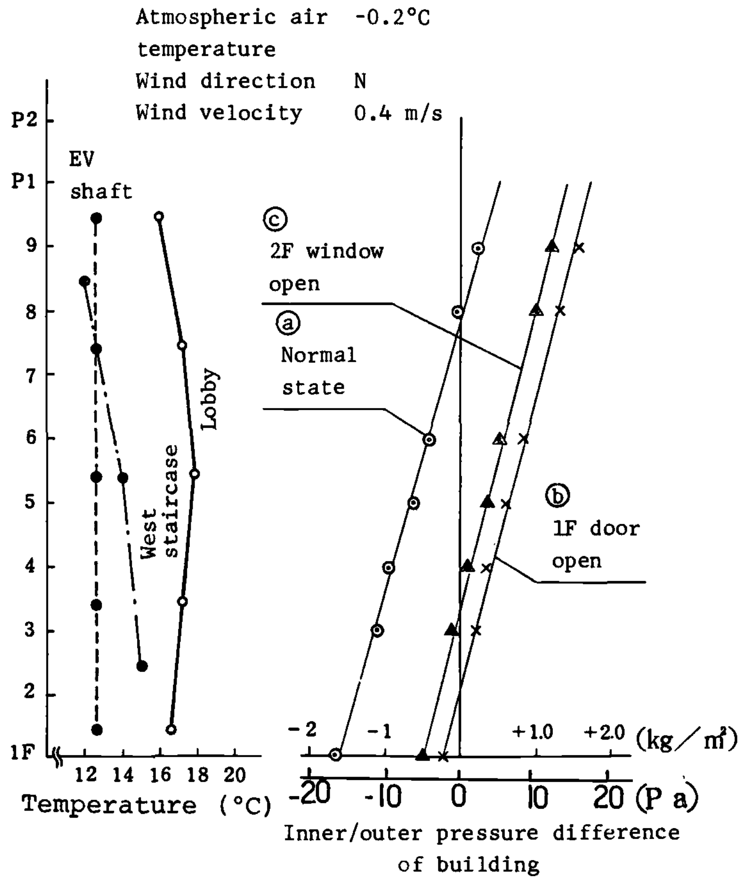

FIG. 7—*Measured results.*

area of Tokyo has exterior walls made of precast concrete panels, windows made of steel sashes with fixed glazing, and a single sliding window (1.8 by 0.65 m) at a single location for each floor above 9F, which is normally kept closed. Figure 8 shows its external appearance, Fig. 9 shows the plan of its reference floor, and Fig. 10 shows the measurement result. Outside air pressure is led to the indoor pressure difference gage by way of a vinyl tube penetrating a sealing part of the openable window sash. Since this building has a main air-conditioning machine room, parking area, and connecting passage to another building at the basement floor, its $(\alpha A)_G$ is very large compared with that of the top floor. This state is shown in pressure distribution ⓐ at normal times. As a result, the opening test of doors has been conducted using the entrance/exit (1.74 by 0.86 m) at the top floor. Symbols ⓑ, ⓒ, and ⓓ represent the values when fully open, at a width of 0.6 and 0.4 m, respectively. From the pressure distribution at this time and the air-leakage-rate measured values from open doors, Eqs 7 to 9 concerning $(\alpha A)_G$ and $(\alpha A)_T$ can be obtained as follows:

$$5.27\ (\alpha A)_G - 12.24\ (\alpha A)_T = 4.00 \tag{7}$$

$$5.07\ (\alpha A)_G - 19.66\ (\alpha A)_T = 2.82 \tag{8}$$

$$4.69\,(\alpha A)_G - 28.26\,(\alpha A)_T = 1.85 \tag{9}$$

Whichever two of the above equations are selected, $(\alpha A)_T = 0.1$ m² and $(\alpha A)_G = 1.0$ m² are obtained. The value of $(\alpha A)_T$ expressed in the unit exterior-wall area comes to about 2.8 cm²/m².

Here, if the exterior-wall airtightness at the typical floor is calculated by expressing it in $q = aA_w\Delta_P{}^{1/1.5}$ instead of calculating it in units of simple openings, Eqs 7 and 8 will become Eqs 10 and 11, respectively, as follows

$$5.27(\alpha A)_G - 2.68aA_w = 4.00 \tag{10}$$

$$5.07\,(\alpha A)_G - 4.30\,aA_w = 2.82 \tag{11}$$

where

2.68 and 4.30 are got by $\sum_{i=1}^{17} \Delta P_i^{1/1.5}$.

Symbol A_w is an exterior-wall area (354 m²) and a is a constant. From the above two equations, $aA_w = 0.6$ and $(\alpha A)_G = 1.06$ (m²) are obtained. Here, if aA_w is converted into an equivalent effective area when the ΔP is 1.0 kg/m², $(\alpha A)_T \fallingdotseq 0.12$ (m²) and 3.5 (cm²/m²) will be obtained, which is about 20% larger than when measured in units of simple openings mentioned earlier. If it is required to treat the exponent of ΔP as an unknown, this can be done by obtaining many equations by changing the open area in many ways, but it is somewhat difficult to maintain good accuracy.

Fifty-Five Story High-Rise Building (Building C). This 55-story high-rise building in downtown Tokyo has exterior walls made of aluminum curtain wall with fixed glazing. The outline of its typical floor and the layout of measuring equipment are shown in Figs. 11 and 12, respectively. This building was tested by keeping open the entrance exit at two locations on the top floor as shown in Table 2. The center between both gable sides of the building

TABLE 1—*Process of calculating coefficient* K *of Eq 4.*

Floor No.	Height*1 (m)	ΔP*2 (kg/m²)	γ*3 (kg/m³)	$\mathrm{Sign}(\Delta P)\sqrt{2g\gamma\lvert\Delta P\rvert}$*4	K
R	31.6	(0.56)*5		3.662	K_R=3.66
9	28.2	0.32	1.222	2.771	K_T=−20.20
8	24.8	0.05		1.097	
7	21.4	(−0.14)	1.293	−1.884	
6	18.0	−0.33		−2.891	
5	14.6	−0.53		−3.667	
4	11.2	−0.88		−4.725	
3	7.8	−1.03		−5.113	
2	4.4	(−1.32)		−5.788	
1	1.0	−1.6		−6.368	K_G=−6.37

*1 Height from the ground level to 1 m above the floor
*2 External wall pressure difference (inside vs. outside)
*3 Specific weight of air When ΔP>0: Indoor air (15.7°C)
When ΔP<0: Outside air (0.1°C)
*4 Sign (ΔP) = (1, ΔP>0)
(−1, ΔP<0)
*5 Figure in parentheses shows estimated value and others are measured values.

FIG. 8—*External appearance (the building on the right).*

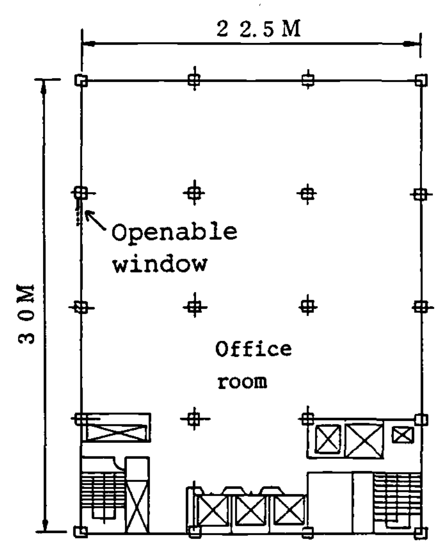

FIG. 9—*Typical floor of Building B.*

is the machine room (a stairwell through 5F to 6F), which is partitioned from the office room by precast concrete panels and also has an exterior wall of aluminum curtain wall. There were two louvres (about 0.6 m by 1 m) for outdoor-air intake which was used as one of the paths for vinyl tube wiring for measuring the building inner/outer pressure difference ΔP_{LO}.

The test was conducted in the early morning from 4:50 to 5:30. The mean wind velocity for 10 min was as calm as 1.0 m/s on the top roof, and the atmospheric air temperature was

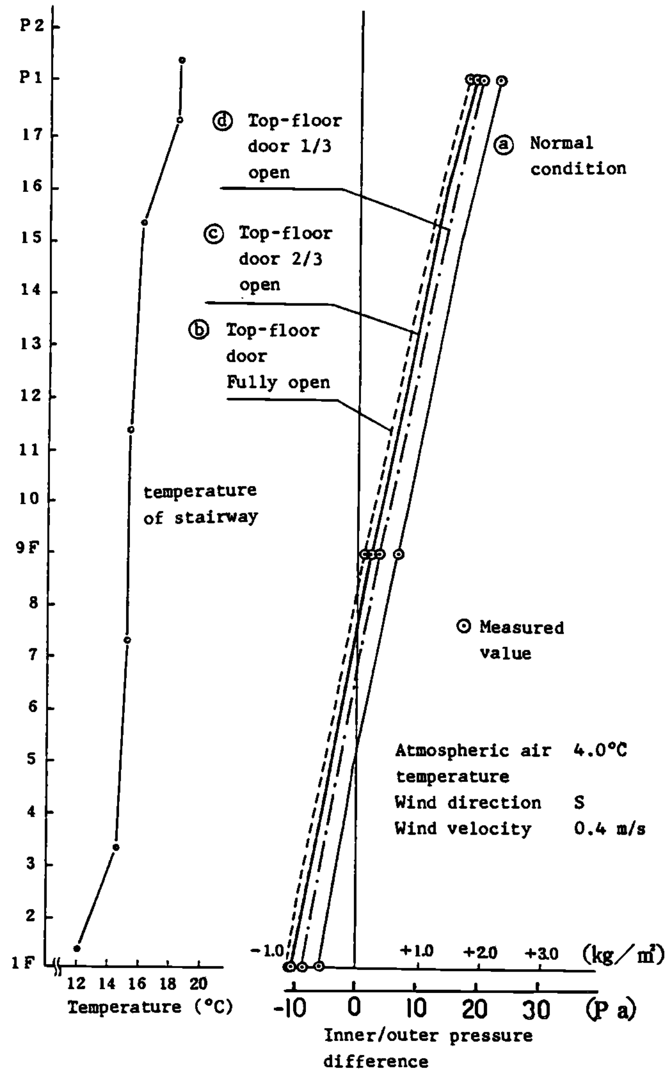

FIG. 10—*Measured result of Building B.*

stabilized at 10.5°C. Pressure distributions in Case 2 to Case 4 of Fig. 13, formulated in the same way as previously, will become as follows:

From Case 2:

$$14.55\ (\alpha A)_G - 127.16\ (\alpha A)_T - 9.75\ (\alpha A)_R = 13.22 \tag{12}$$

From Case 3:

$$14.57\ (\alpha A)_G - 118.91\ (\alpha A)_T - 9.36\ (\alpha A)_R = 15.63 \tag{13}$$

From Case 4:

$$14.77\ (\alpha A)_G - 107.59\ (\alpha A)_T - 9.16\ (\alpha A)_R = 18.54 \tag{14}$$

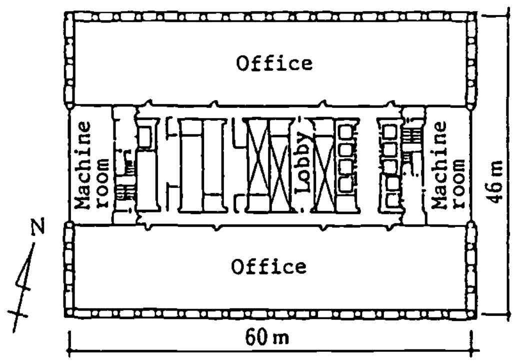

FIG. 11—*Plan of typical floor of Building C.*

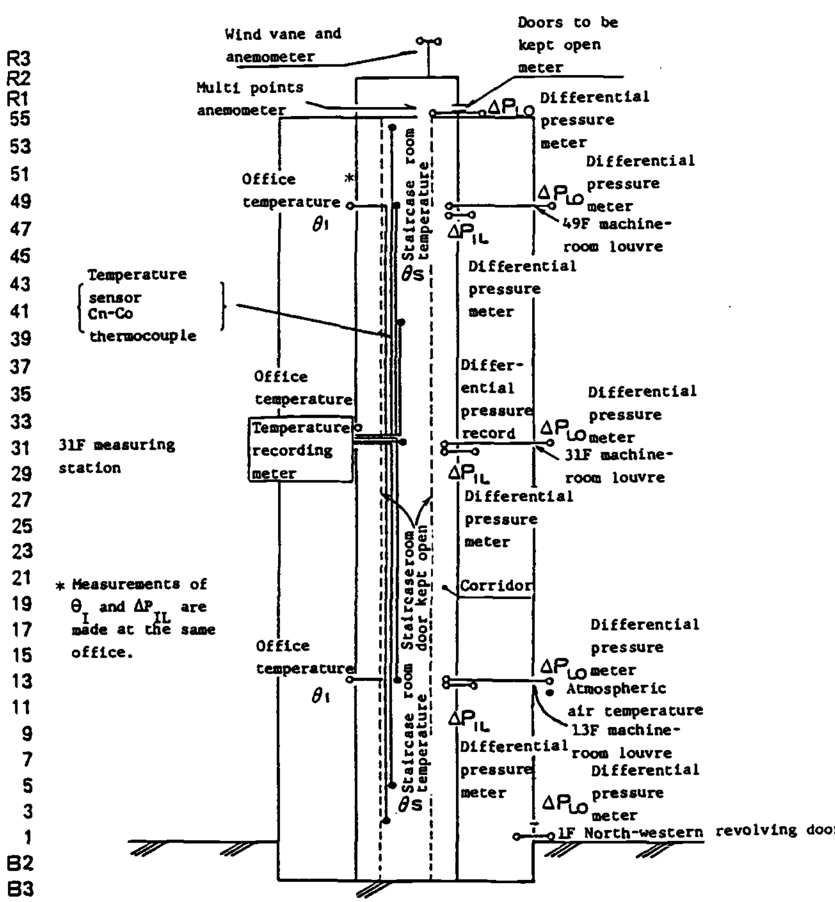

FIG. 12—*Measuring instrument layout diagram of Building C.*

TABLE 2—*Test cases.*

Case No.	State of Entrance/Exit door
1	Fully closed
2	East and west small doors kept open (2.54 m^2)
3	East and west large doors kept open (3.72 m^2)
4	East and west (large + small) doors kept open (6.26 m^2)

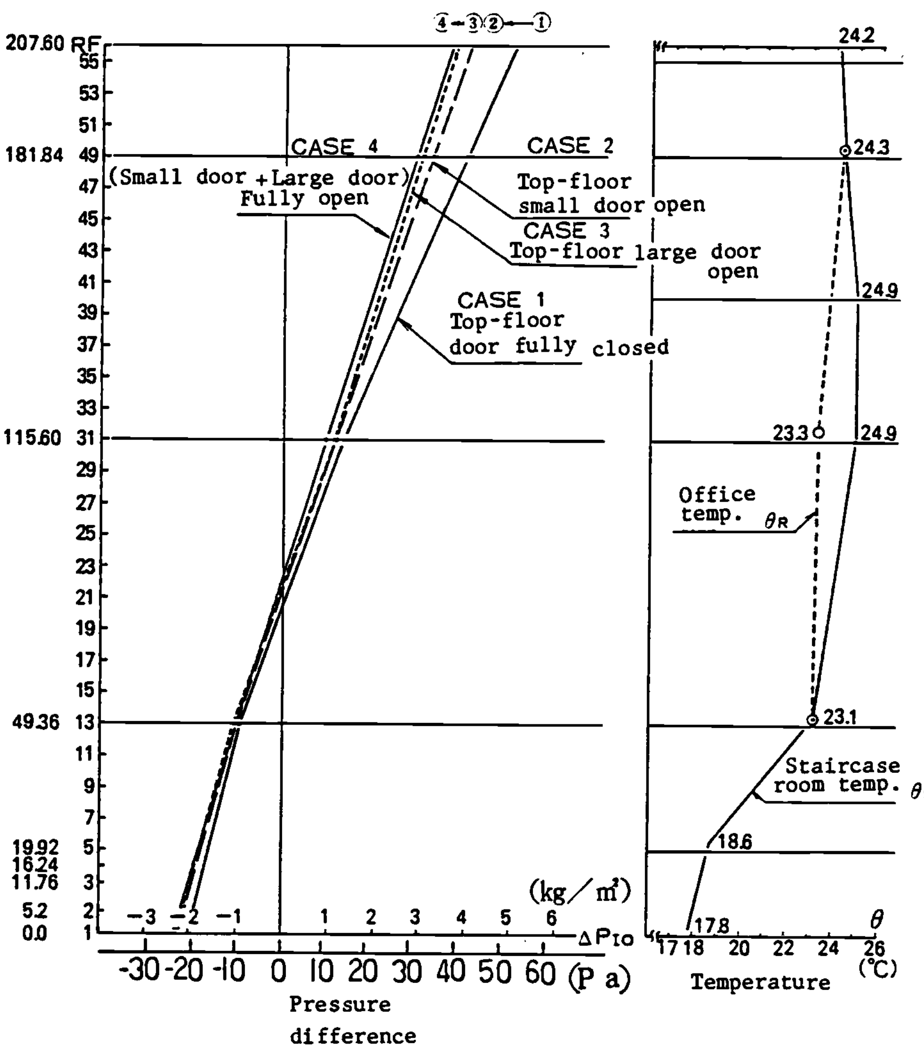

FIG. 13—*Pressure fluctuations due to top-floor entrance/exit door kept open.*

When the above equations are solved, $(\alpha A)_T = 0.12$, $(\alpha A)_G = 4.24$, and $(\alpha A)_R = 3.37$ (m^2).

A crack at the motor damper of the duct penetration part at the point of contact between the occupied room (and corridor) and the machine room was less than 6% of $(\alpha A)_T$. The value of $(\alpha A)_T$ expressed in the unit exterior wall area comes to about 1.5 cm^2/m^2.

Also, $(\alpha A)_G$ was found, after measuring the door crack, to be about 1.0 m^2, and therefore the remainder was considered to be the crack mainly through and around ducts.

The authors have classified exterior wall airtightness as shown in Table 3 [*8*].

From the measurement examples, the airtightness of the exterior walls have been tentatively classified and sorted out as shown in Table 4.

Simplified Calculation of Air Infiltration Rate

Calculate the mean outdoor air infiltration of Building C during nighttime in winter, using the exterior-wall airtightness obtained by measurement. Airtightness of cracks on the typical floor can be obtained by

$$q = 1.5 \times 10^{-4} \sqrt{\frac{2g}{\gamma o} \Delta P} \times 3600 \ (m^3/h{\cdot}m^2)$$

or

$$q' = 2.16 \ \Delta P^{1/1.5} \ (\mathrm{m^3/h{\cdot}m^2})$$

Multiplication of each equation by exterior wall area $A_w = 783$ (m^2) gives the air infiltration rate from all exterior walls on each floor.

1. *Inner-outer temperature conditions*

The mean value of atmospheric air temperatures in Tokyo during 10 p.m. and 6 a.m. in January is 2.1°C. The air temperature inside the building is considered to be constant at 23°C. It is also assumed there is no wind.

TABLE 3—*Classification of exterior wall infiltration characteristics.*

Class	Equations	Equivalent Orifice Area Over αA at ΔP = 9.8 Pa (=1 kg/m^2)
Tight	0.72 $\Delta P^{1/1.5}$ ($m^3/h \cdot m^2$)	0.5 (cm^2/m^2)
Average	1.44 $\Delta P^{1/1.5}$	1.0
Loose	2.88 $\Delta P^{1/1.5}$	2.0

TABLE 4—*Tentative classification of exterior-wall airtightness.*

Cast-in-place reinforced concrete construction	Tight to average
Steel or steel and reinforced concrete construction	
Metallic curtain wall	Average to loose
Others	Loose

2. *Calculations*

First obtain the stack effect (= buoyancy) P (kg/m^2) which acts on this building. Denote the density (kg/m^3) of air at a temperature of t°C by γ_t, and the height of the roof by H, and we obtain

$$P = (\gamma_{2.1} - \gamma_{23}) \times H = (1.2833 - 1.1927) \times 207.6$$
$$= 18.81\ (\text{kg/m}^2) = 184.3\ (\text{Pa})$$

Next, from buoyancy P estimate pressure difference ΔP of the exterior walls of each floor. Since the neutral zone is the 21st floor (refer to Fig. 13), proportionally distribute the pressure difference ΔP_1 (= 18.81 × 21/55 = 7.18) of the ground floor and pressure difference ΔP_{21} = 0.0 to obtain the differential pressure ΔP_1 between the inside and outside of the building on each floor. When the pressure difference ΔP_w, which actually acts on the exterior wall, is to be obtained, assume that the exterior wall pressure load ratio [7][3] is about 80%.

Namely, ΔP_i is the differential pressure between the inside of the building shaft and outdoors and is a sum of the pressure difference of the shaft walls and that of exterior walls.

The result of obtaining the air infiltration rate of respective floors on the basis of the above concept is shown in Table 5. As a result of comparative studies of both cases of the simple orifice and the crack, it was found that the air infiltration from the typical floor was about 50 000 m^3/h or above, that on the floor including the entrance/exit to 3F to 2F was about 120 000 m^3/h, and that for the total building was 170 000 m^3/h.

The authors propose to call this method "exterior wall area method" by which infiltration rate is calculated on the basis of the area of the exterior wall [8].

Conclusion

In a tall building where the stack effect is operative, opening doors at the top or bottom floors gives the same effect as pressurizing or decompressing the entire building using blowers. We have introduced the method of obtaining the exterior wall airtightness using this principle. To apply this method, the following conditions must be taken into consideration:

1. The pressure difference on the floor where the doors and the window are opened should not remain at a large value. Airflow rate of infiltration or exfiltration through wall cracks except opened windows and doors must be ignored. For instance, the upper limit of the pressure difference will be about 30 Pa or below. Naturally, when the outside and inside pressure difference barely change, even with the doors open, it means that unknown cracks and openings larger than doors exist. Thus the experiment on that floor is meaningless. In general, it is difficult to apply this method when the building has a huge plane.

2. When the friction resistance of the airflow in the building is strong, while doors are opened, errors in the estimated values of the inside and outside pressure difference at the respective floors will become larger. Namely, the straight lines, which show the distributions in the height direction of pressure difference between the inside and outside of the building, must shift in parallel when doors are open. In this sense, Building C may have exceeded the application limit of this example.

Although this measuring method has the disadvantage of being governed by meteorological conditions, it is a simple measure not requiring fans. In addition, it is an effective method

[3](1) Pressure distribution in the region of typical floors caused by the stack effect can be easily explained with exterior wall pressure load ratio K', which is defined as $|\Delta P_w|/(|\Delta P_w| + |\Delta P_s|)$, where ΔP_w and ΔP_s are pressure differences across the exterior wall and elevator shaft. (2) K' is equal in principle to Tamura's actual/theoretical (= K), which was confirmed through measurements and computer simulation, Therefore, K has come to show more physical characteristics.

TABLE 5—ΔP_w *and infiltration rate.*

Fls	ΔP between shaft & Out-door ΔP_i (kg/m^2)	ΔP across exterior wall $\Delta P_w = 0.8 \times \Delta P_i$	Infiltration rate (m^3/H): $\alpha A\sqrt{\frac{2g\Delta P_w}{\gamma_0}} \times 3600$, $\alpha A=0.12$ (m^2)		Infiltration rate (m^3/H): $2.16\Delta P^{1/1.5} \times A_w$, $A_w=783$ (m^2)	
21	0.0	0.00	0		0	
20	0.36	0.29	909		740	
19	0.72	0.58	1286		1170	
18	1.08	0.86	1566		1530	
17	1.44	1.15	1810		1850	
16	1.80	1.44	2026	Sum of	2140	
15	2.15	1.72	2214	Typical	2420	
14	2.51	2.01	2394	floors	2680	Sum of Typical
13	2.87	2.30	2560		2940	floors
12	3.23	2.58	2712	47800	3170	56800
11	3.59	2.87	2860		3400	
10	3.95	3.16	3001		3630	
9	4.31	3.45	3136		3850	
8	4.67	3.74	3265		4060	
7	5.03	4.02	3385		4260	
6	5.39	4.31	3505		4460	
5	5.74	4.59	3617		4650	
4	6.10	4.88	3730		4840	
3	6.46	5.17	3839		5040	
2	6.82	7.00				
1	7.18	*				
B1 - B3		7.00x0.6=4.2				

* At the entrance floors exterior wall pressure load ratio is assumed to be 60%

for finding out not only the crack area αA_T of the typical floor but also cracks at the bottom and top.

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Comparison of Techniques

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Measurement of Airtightness, Air Infiltration, and Indoor Air Quality in Ten Detached Houses in Sendai, Japan

REFERENCE: Yoshino, H., Nagatomo, M., Yamamoto, Y., Matsumoto, H., and Utsumi, Y., **"Measurement of Airtightness, Air Infiltration, and Indoor Air Quality in Ten Detached Houses in Sendai, Japan,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 249–266.

ABSTRACT: Airtightness, indoor air quality, and air infiltration were measured in ten occupied, detached, two-story houses of wooden construction in the winter of 1986–87. The floor area of the houses was 120 to 160 m^2. The houses had various types of heating systems. Seven of the houses had exhaust fan units for ventilating living rooms with air-to-air heat exchangers. Airtightness was measured by the fan pressurization method. Equivalent leakage area per floor area was 1.9 to 5.7 cm^2/m^2. The concentrations of CO_2, NO_2, and suspended particles were measured. CO_2 and NO_2 concentrations in the houses where unvented oil heaters were used were higher than in the other houses. The airtightness and indoor air quality measured during this period were compared with measured results obtained for 13 detached houses during the winter of 1984–5. Air infiltration was measured by the concentration decay method using SF_6 as a tracer gas and was compared with the calculated value on the basis of equivalent leakage area.

KEY WORDS: airtightness, air infiltration, indoor air quality, detached houses, investigation

Nomenclature

- c_k Pressure coefficient for surface element k ($-$)
- g Acceleration of gravity (m/s^2)
- h_k Height of surface element k (m)
- n Exponent of the pressure difference ($-$), or air infiltration rate (1/h)
- p_i Inside pressure (Pa)
- Δp Pressure difference (Pa)
- Δp_r Pressure difference at reference condition (Pa)
- Δp_k Pressure difference for surface element k (Pa)
- v Wind velocity (m/s)
- A Effective leakage area (cm^2)
- A_r Effective leakage area at reference condition (cm^2)

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Ar^* Effective leakage area per floor area at the reference condition for Δp of 9.8 Pa (cm^2/m^2)
Q Air flow rate through a building component (m^3/h)
Q_r Air flow rate at reference conditions (m^3/h)
Q_k Air flow rate through surface element (m^3/h)
ρ_o Density of the outside air (kg/m^3)
ρ_i Density of the inside air (kg/m^3)

Newly constructed, detached houses in Japan, especially in the northern regions, are becoming more and more airtight and highly insulated due to the trend toward energy conservation and the demand for thermal comfort. In such houses, it is expected that the quality of the indoor thermal environment will be better than that of existing houses. On the other hand, there is the possibility of indoor air pollution due to poor air infiltration. Many existing reports reveal indoor air quality in residential houses. For example, Nakai et al. [1] reported the results of nitrogen dioxide (NO_2) concentration measurements in all-electric houses and houses using gas to prepare meals. However, there are few reports which investigate the relationship between the indoor air quality and the airtightness of a building envelope. Therefore, the authors investigated airtightness, indoor air quality, and air infiltration in ten occupied, detached wooden houses of a type common to middle class Japanese in the winter of 1986–87 and analyzed the relationship between these three factors. The authors [2] have already reported the results of indoor quality and airtightness as measured for 13 other detached houses in the winter in 1984–85. So, airtightness and indoor air quality measured during this period in 1986–87 were compared with measured results obtained in the winter of 1984–85. Air infiltration was measured by the concentration decay method, using sulfur hexafluoride (SF_6) as a tracer gas, and was compared with the value calculated on the basis of equivalent leakage area. The houses were situated in Sendai, which is located near the Pacific Coast and the main city in the Tohoku region. The latitude of Sendai is 38° 16′. The mean outdoor temperature in January is 0.9°C.

Description of Houses Studied

Table 1 describes the houses studied. All were constructed between 1985 and 1986. Houses 1 and 9 were built by conventional Japanese construction methods, which used columns and beams as structural materials. The other eight houses were built with wood-frame constructions. All of the houses had thermally insulated walls, ceilings, and floors. The walls had vapor barriers made of polyethylene sheets. The windows had double glazings or double sashes except for House 1, which had single glazings. The grade of thermal insulation used was higher than that in the existing houses, which had less than 5-cm fiberglass insulation in the wall. Houses 9 and 10 were experimentally constructed by a house builder and building material production companies working in cooperation.

The houses studied were heated by different types of heating systems: hot water floor heating, hot water heating with panel radiators or fan convectors, hot air central heating, and vented or unvented oil heaters. Houses 4, 5, 7, and 10 had concrete floors including hot water pipes with thermal insulation furnished under it. House 2 had a vented oil heater as well as an unvented oil heater in the living room. House 9 had a hot-air central heating system as well as an unvented oil heater in the child's room. All houses except for Houses 1, 3, and 9 had exhaust fan units situated in the outer walls, with air-to-air heat exchangers for ventilating the living rooms. House 9 had a central ventilation system with an air-to-air heat exchanger. House 3 had fans in the walls between rooms for circulating indoor air, as well as exhaust fans with air-to-air heat exchangers in the three rooms of the kitchen, the washroom, and the lavatory. But House 1 did not have an air-to-air heat exchanger.

TABLE 1—*Description of measured houses.*

House Number	Date of Completion	Floor area,[b] m^2	Depth of Insulation,[c] (cm)			Window[e]	Heating[f] Equipment	Ventilation in Living Room	Number of Family Members	House Builder
			Wall	Floor	Ceiling					
1	Dec. 1986	119	10	3	10	S.G.	CH. HW. Fan. con	Natural	3	A
2	Nov. 1986	120	10	5	10	D.S.	LH. V.&UV.	Mech.[g]	4	B
3	Dec. 1986	158	10	15	20	D.S.	CH. HW. Panel rad.	Mech.[h]	4	C
4	Dec. 1985	141	10	3F[d]	10	D.S.	CH. HW. Floor H.	Mech.[g]	3	B
5	Dec. 1986	144	10	3F	10	D.S.	CH. HW. Floor H.	Mech.[g]	4	B
6	Dec. 1986	142	10	5	10	D.S.	LH. V.	Mech.[g]	3	B
7	Sep. 1986	120	10	3F	10	D.S.	CH. HW. Floor H.	Mech.[g]	4	B
8	Dec. 1986	140	10	5	10	D.G.	LH. V.	Mech.[g]	4	B
9[a]	May 1986	124	10	7.5	20	D.G.	CH. HA.+ LH. V.&UV.	Central[i]	4	B
10[a]	Apr. 1986	121	15	5F	15	D.G.	CH. HW. Floor H.	Mech.[h]	7	B

[a] This house was experimentally constructed by a group of a house builder and building material productions companies.
[b] All houses have two stories.
[c] Glass wool is used for walls and ceilings except for House 1 with rock wool. Floors are insulated with foam polystyrene.
[d] F means that floor is made of concrete.
[e] D.S. = double sashes, D.G. = double glazing.
[f] CH. = central heating, LH. = local heating, HW. = hot water, HA. = hot air, V = vented oil heater, UV. = unvented oil heater, Floor H. = floor heating, Fan con. = fan convector, Panel rad. = panel radiator.
[g] Mech. = mechanical ventilation with an exhaust fan unit, which is situated in an outer wall, with an air-to-air heat exchanger.
[h] This house has fans in inner walls between rooms for circulating indoor air and exhaust fans with air-to-air heat exchanger in the kitchen, in the face washing room, and in the lavatory.
[i] Central mechanical ventilation with an air-to-air heat exchanger.

Airtightness

Method of Measurement

Airtightness measurements were made by the fan pressurization method [*3,4*]. Internal pressure was increased by a fan attached to a duct penetrating a thin board set in an open window. The pressure differences were measured by a capacitance manometer. Flow rate in the duct was measured by a thermistor anemometer. Measurements were carried out under conditions of such low wind speed that the indoor-outdoor pressure difference was stable. The inside and outside temperatures were not measured.

Results of Measurement

Figure 1 shows the relationship between the pressure difference across the building envelope and the volumetric flow rate. The pressure difference ranged from 4 to 30 Pa, where the capacity of the fan used gave the maximum pressure difference. The outside wind speed

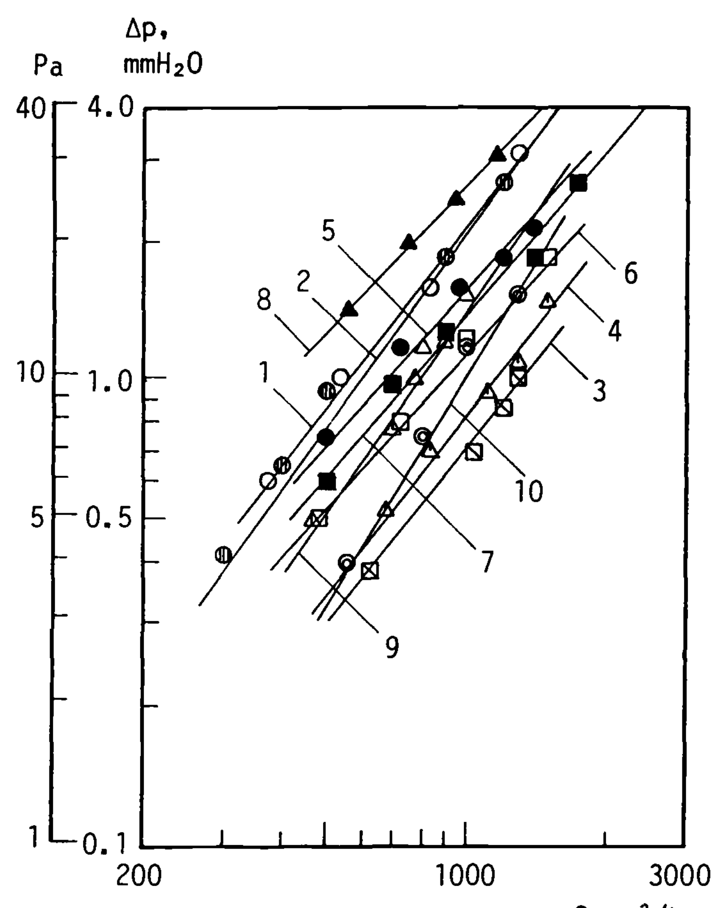


FIG. 1—*Pressure difference and volumetric flow rates.*

restricted the lower limit of the range. The relationship between the two factors is expressed by

$$Q = Q_r\left(\frac{\Delta p}{\Delta p_r}\right)^{1/n} \tag{1}$$

Table 2 shows Q_r and n for each house, which can be calculated by the linear curve fitting with each measurement data set. The Q_r is the value of Q when Δp is equal to the reference pressure, Δp_r. The reference pressure used is different between countries and between researchers. For example, in Norway and Sweden, the value used in the airtightness standard is 50 Pa. The 1985 ASHRAE handbook gives the value as 4 Pa. In Japan, the reference pressure of 1 mm H_2O (9.8 Pa) is usually used because it takes into consideration the pressure range exerted upon the building surface in a natural environment, the easy realization of the indoor-outdoor pressure difference by the pressurization method, and the easy handling of the figure of one in calculating formulas. The reference pressure is also given as 1 mm H_2O (9.8 Pa) in the draft of a Japanese industrial standard on airtightness measurement of buildings. The value of Q_r is distributed from 385 to 1290 m^3/h. The value of n ranges from 1.02 to 1.61. Table 2 also shows the effective leakage area [5], A_r, for each house, which can be calculated by the following equation (see Appendix A).

$$A_r = 2.78Q_r\left(\frac{2}{\rho_o}\Delta p_r\right)^{-0.5} \tag{2}$$

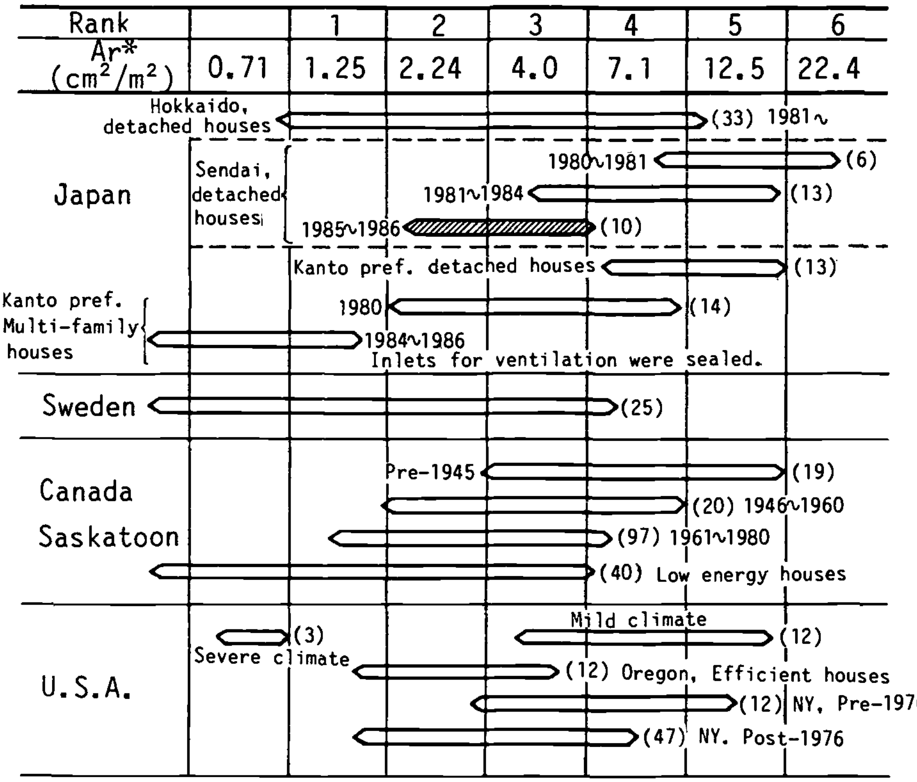
In Eq 2, ΔP_r is given as 9.8 Pa. The effective leakage area per floor area, Ar^*, is also included in Table 2. The value of Ar^* is widely distributed from 1.9 to 5.7 cm^2/m^2. House 8 was found to be the most airtight.

Comparison of Airtightness for Houses Using Effective Leakage Area Per Floor Area

Figure 2 shows the range of Ar^* for various houses in different countries. Where the original airtightness data were not shown as A_r for Δp_r = 9.8 Pa, these data were converted, assuming $1/n = 0.6$. The original figure is presented in the paper by Murakami and Yoshino [6]. The houses measured in this test are located from Rank 2 to 5 and appear tighter than the houses measured in 1985 in Sendai. The description of the houses measured in 1985 is presented in Appendix B.

TABLE 2—*Airtightness of measured houses.*

House No.	Q_r, m^3/h	n	A_r, cm^2	Ar^*, cm^2/m^2
1	528	1.33	369	3.1
2	563	1.37	396	3.3
3	1290	1.25	901	5.7
4	1120	1.28	776	5.5
5	641	1.12	446	3.1
6	857	1.12	596	4.2
7	752	1.17	528	4.4
8	385	1.02	266	1.9
9	760	1.44	521	4.2
10	976	1.61	690	5.7



Note: Figures in parenthesis indicate the number of housing units measured.

FIG. 2—*Airtightness for various houses in different countries using* Ar*.

Indoor Air Quality

Method of Measurement

The concentration of carbon dioxide (CO_2) was measured by an infrared analyzer in the living room of each house. The concentration of NO_2 was measured by bare detector badges exposed for the measurement period in the living rooms and kitchens. This measurement follows the method utilized by Yanagisawa and Nishimura [7]. The concentration of suspended particles was measured by a dust meter of the light diffusion type. The measurement period differed from two to five days due to the occupant's availability to participate in the study.

Results of Measurement

Figure 3 shows variations of CO_2 concentration measured in each house during a single weekday of different measuring periods. In many houses, the CO_2 concentration increased in the morning between 7 a.m. and 9 a.m. and at night after 9 p.m. Figure 4 shows the cumulative frequency distribution of CO_2 concentration throughout the measuring period. The Building Standards Code of Japan prescribes that the limit of CO_2 for indoor air in air-conditioned space of office buildings be less than 1000 ppm. In Houses 2 and 9, the CO_2

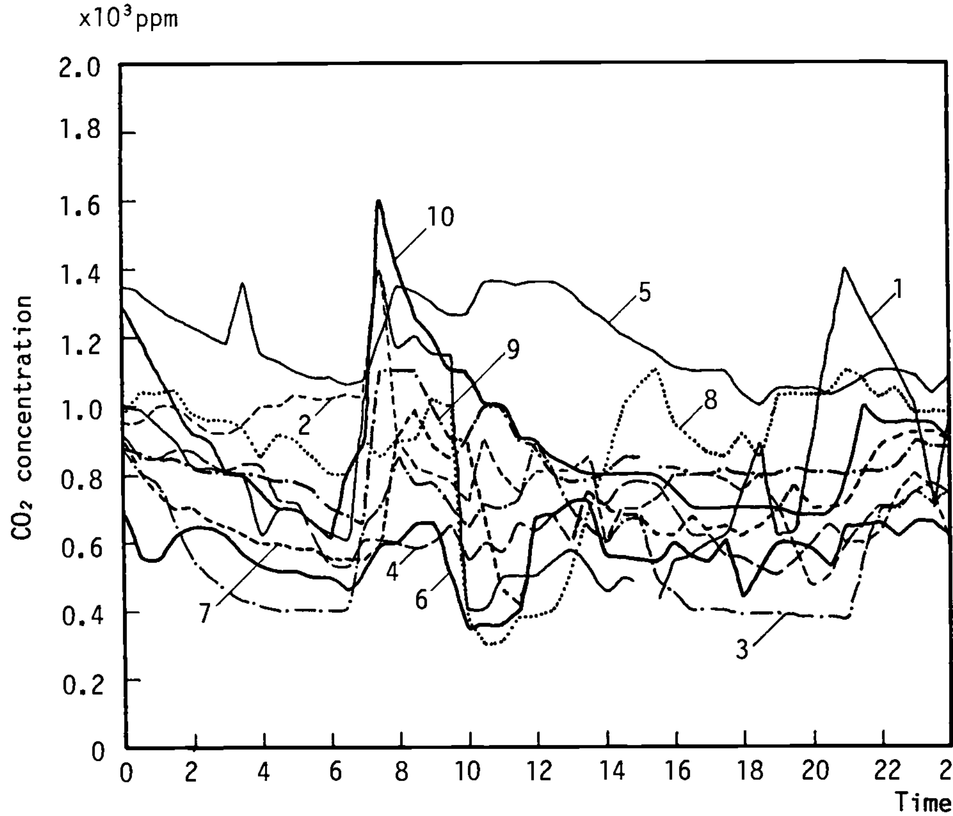


FIG. 3.—*Variations of CO_2 concentration during a single weekday.*

concentration was over 2000 ppm when the cumulative frequency was more than 95% because unvented oil heaters were sometimes used in the child's bedroom in House 9 and in the living room in House 2. In House 5, the CO_2 concentration was over 1000 ppm when the cumulative frequency was more than 27%. The occupant in House 5 reported that the exhaust fan unit with an air-to-air heat exchanger installed in the living room was scarcely used. Table 3 shows the mean concentration of CO_2, the value of which ranged from 560 to 1100 ppm. In Houses 2, 5, and 9, the mean CO_2 concentration was over 1000 ppm. The mean CO_2 concentration was lowest in House 6, where the occupant reported that the exhaust fan unit was always used in the evenings. These results show that the indoor CO_2 concentration was affected by the use of an unvented heater and an air-to-air heat exchanger. In House 1, which had no exhaust fan unit, the mean CO_2 concentration intervened among the mean values of the investigated houses.

Table 3 also shows the mean concentration of NO_2 in living rooms and kitchens. The bare detector badges used to measure the NO_2 concentration gave us only the mean value during the measurement period. The mean NO_2 concentration measured in the living rooms and kitchens was 9 to 74 ppb and 11 to 72 ppb, respectively. There is no standard of the acceptable level of NO_2 in indoor air. But according to The Environmental Recommendation of Outdoor Air Quality in Japan, the limit of the daily mean NO_2 concentration is 20 ppb. The mean NO_2 concentration in Houses 2 and 9 was higher than that in the other houses, because, as mentioned above, these two houses used unvented portable oil heaters. In the other houses,

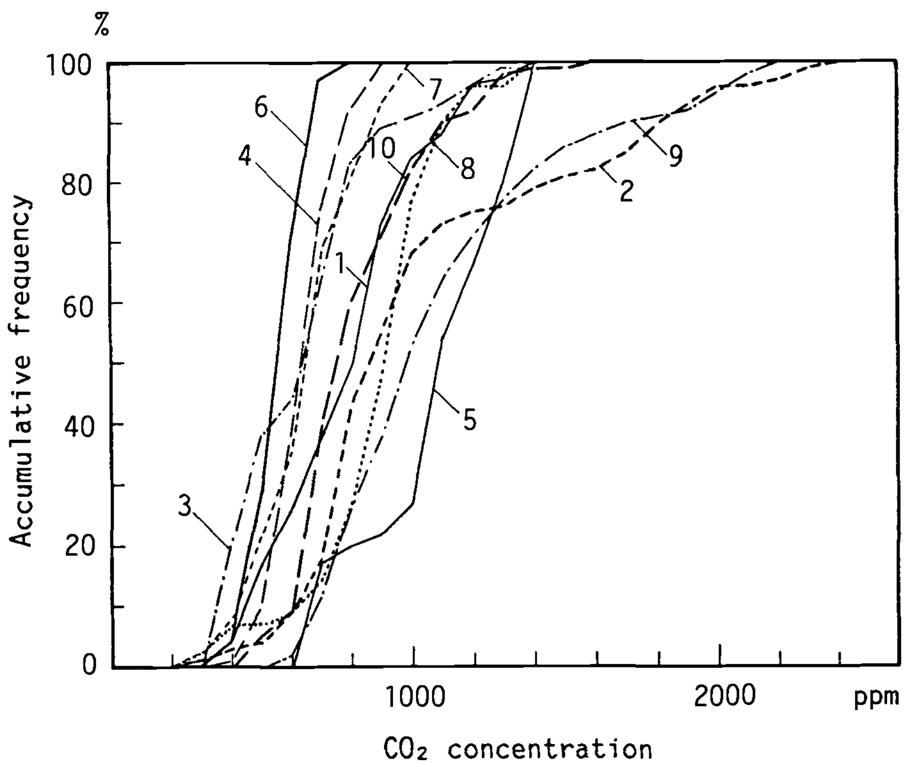


FIG. 4.—*Cumulative frequency distribution of CO_2 concentration for the measuring period.*

TABLE 3—*Mean concentration of CO_2, NO_2, and suspended particles.*

House Number	Measuring Period, 1987	CO_2 Concentration in Living Room, ppm	NO_2 Concentration, ppb		Suspended Particles, mg/m^3
			Living Room	Kitchen	
1	May 12, 13:00 to May 14, 9:30	800	11.5	14.6	0.030
2	May 14, 14:30 to May 17, 10:30	1044	42.9	39.8	0.011
3	May 17, 19:00 to May 19, 15:00	653	12.6	16.5	0.020
4	May 19, 19:00 to May 23, 9:00	642	9.0	10.6	0.017
5	May 23, 17:00 to May 25, 9:30	1078	8.5	13.1	0.012
6	May 25, 12:30 to May 27, 9:00	562	11.7	15.8	0.017
7	May 27, 12:00 to May 28, 17:00	656	9.2	12.0	0.011
8	May 30, 12:30 to Apr. 1, 10:00	892	14.5	16.5	0.029
9	Jan. 26, 12:30 to Jan. 28, 14:00	1111	74.1	72.2	0.035
10	Feb. 4, 14:00 to Feb. 6, 14:00	841	15.6	24.1	0.016

the mean NO_2 concentrations in the kitchens were higher than those in the living rooms due to the emmission of NO_2 from gas cooking stoves.

The relationship between mean CO_2 and NO_2 concentrations in the living room of each house is shown in Fig. 5, including the results measured in 1985. It is recognized again that the mean NO_2 and CO_2 concentrations in houses with unvented oil heaters are comparatively high.

The mean concentrations of suspended particles are also shown in Table 3. The Building Standards Code of Japan prescribes that the limit of suspended particles for indoor air in air-conditioned spaces of office buildings be less than 0.15 mg/m^3. The values are so low in all houses that no pollution problem for suspended particles was evident.

However, it is plain that unvented heaters should be used sparingly, and that exhaust fans with air-to-air heat exchangers should be used regularly in airtight houses such as those investigated in the present study.

The Relationship Between Airtightness and Indoor Air Quality

Figure 6 shows the relationship between the effective leakage area per floor area, Ar^*, and the mean concentrations of CO_2, including the data measured in 1985. The CO_2 concentration was averaged during the same day as shown in Fig. 3, which excluded the period when the unvented oil heater was used. The periods and the averaged values are shown in Table 4. The black marks in Fig. 6 during 1987 indicate a slightly negative correlation between the two factors. That is, the CO_2 concentration was higher in the more airtight houses. Compared

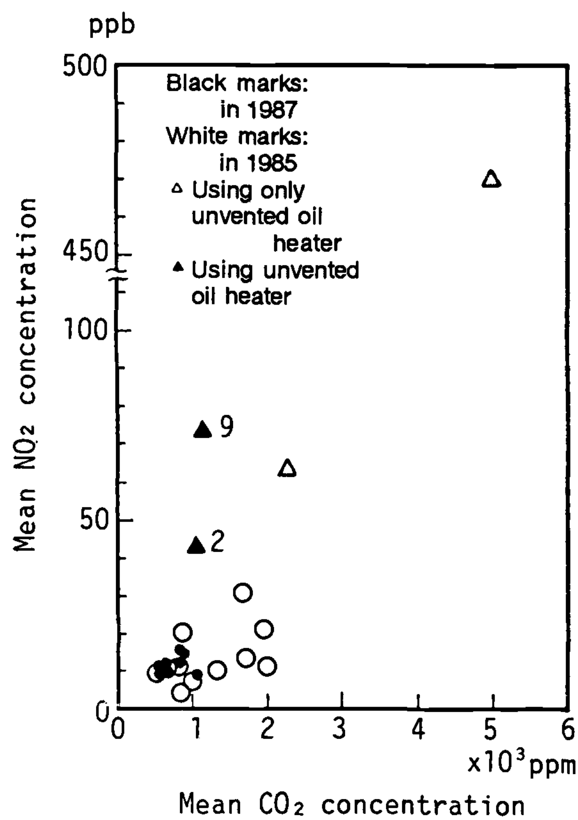


FIG. 5—*Relationship of mean concentration between NO_2 and CO_2 in living room.*

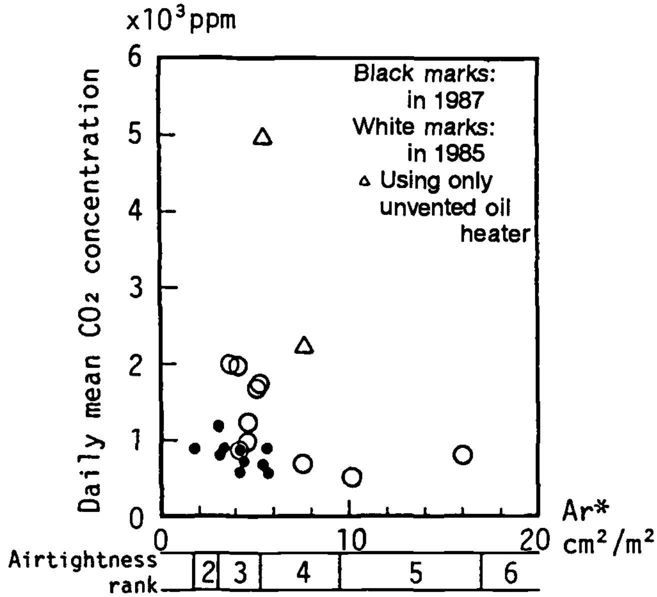


FIG. 6—*Mean CO_2 concentration during a single weekday and* Ar*.

TABLE 4—*Daily mean CO_2 concentration in a weekday.*

	Period, 1987	CO_2 Concentration
1	May 12, 15:30 to May 13, 15:00	789
2	May 16	828
3	May 18	583
4	May 20	678
5	May 24	1183
6	May 24	568
7	May 27, 12:00 to May 28, 11:30	714
8	May 31	873
9	Jan. 29, 15:30 to Jan. 30, 15:00	845
10	Feb. 5	893

to the results measured in 1985, the leakage areas of houses measured in 1987 were smaller and CO_2 concentrations were lower.

Figure 7 shows the relationship between effective leakage area per floor area, Ar^*, and the mean concentration of NO_2 in the living room during the measurement period. The value of NO_2 is the same as shown in Table 3. The results measured in 1985 are included in this figure. It is difficult to find the correlation between the two factors. In both Houses 2 and 9, having unvented oil heaters, NO_2 concentration was relatively high.

Air Infiltration

Method of Measurement

The air infiltration rate was measured by the SF_6 concentration decay technique [*8*]. Under the conditions that all windows and entrance doors were closed, all internal doors were

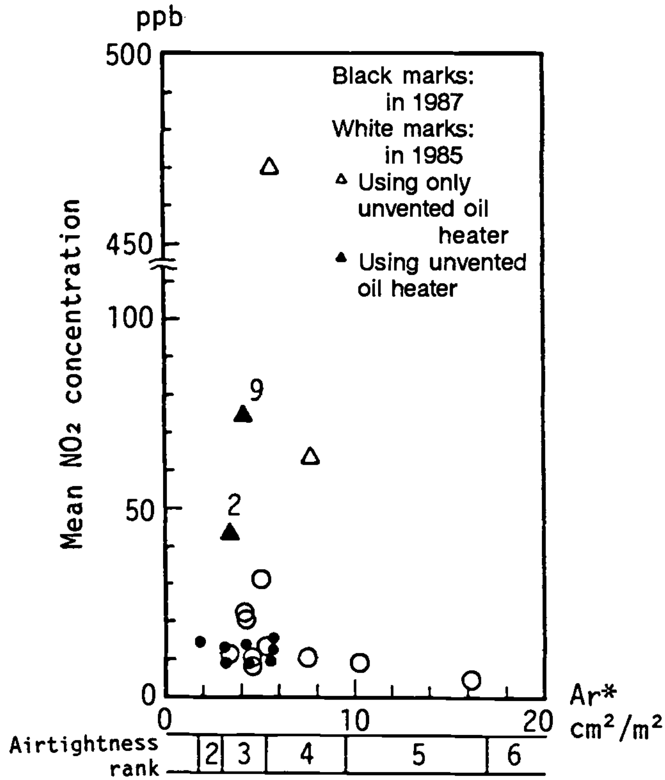


FIG. 7—*Mean* NO_2 *concentration during the measuring period and* Ar*.

open and exhaust fans were not operated, SF_6 gas, of a volume of about 50 cm^3, was released in the living room. After the indoor air and the SF_6 gas were mixed by electric fans for approximately 10 min, the indoor air in the living room was sucked into sampling bags by a pump to get a 0.5-L sample within 30s. This was repeated several times during the course of 1 h. In the rooms other than the living rooms, indoor air samples were taken a few times in order to check the mixing of SF_6 gas between the rooms. As the measurement was the first experience for the authors and was made when the house was occupied, the sampling interval and the kind of rooms in which SF_6 gas was sampled were different from house to house. The air samples were brought to our laboratory and analyzed a few days later by an electron capture detector. The air in each collected sampling bag was analyzed several times and averaged.

Results of Measurement

Figure 8 shows the decay of SF_6 concentrations plotted on a semilog chart in each house. The SF_6 concentration in the living room decreased in all houses except for House 8, where SF_6 concentration increased a half hour after the beginning of measurement due to incomplete mixing. In House 3, the SF_6 concentration in the second floor increased for 20 min following the beginning of measurement and finally reached the same level of concentration as in the living room. In House 4, the SF_6 concentration in the second floor at the beginning of measurement was higher than that in the living room. These results in Houses 3 and 4

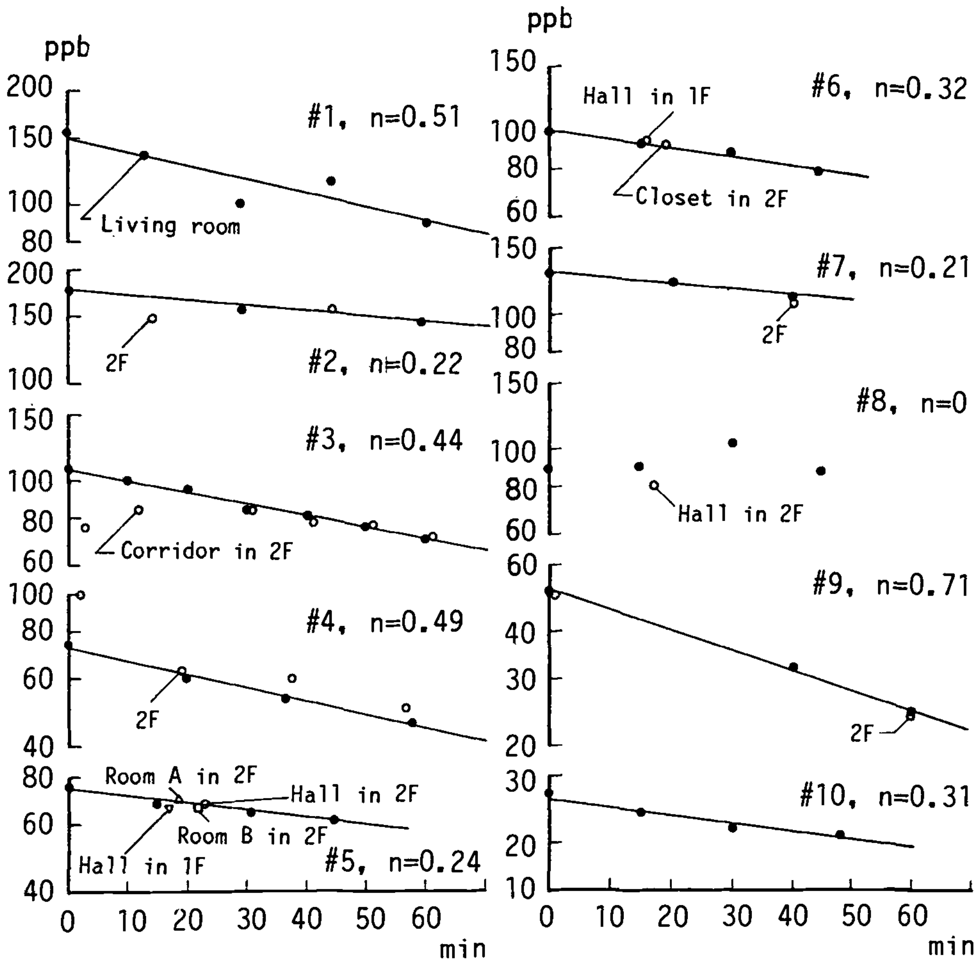


FIG. 8—*Concentration decay of* SF_6.

show that initial mixing between the rooms was incomplete. After about 20 min from the beginning of measurement, the SF_6 concentration in the other spaces was close to that in the living room. Therefore, it can be said that at least 30 min mixing by the fan was necessary for uniform distribution of tracer gas in the detached houses measured in this study.

The air infiltration rate in a whole house was estimated by a regression line on the basis of the SF_6 concentration measured in the living room. The results are shown in the column of "measurement" in Table 5. The air infiltration rate is widely distributed from 0 to 0.71. In the case of House 8, the SF_6 concentration did not decrease for 45 min. It was expected that the air infiltration rate would be significantly lower in spite of the problem of incomplete mixing. Therefore, the infiltration rate was interpreted as being zero for further analysis.

Air Infiltration Rate and Ar*

Figure 9 shows the relationship between the air infiltration rate and the equivalent leakage area per floor area. The air infiltration rate, of course, depends on both outdoor wind speed

TABLE 5—*Measured air infiltration rates using SF_6 and calculated values.*

House Number	Wind[a] Velocity, m/s	Indoor-Outdoor Temperature Difference, °C	Air Infiltration Rates, 1/h	
			Measurement	Calculation
1	1.5	7.7	0.51	0.11
2	3.4	9.0	0.22	0.15
3	3.5	16.1	0.44	0.33
4	0.6	8.5	0.49	0.19
5	12.6	9.5	0.24	0.35
6	13.6	12.1	0.32	0.55
7	3.5	20.0	0.21	0.27
8	4.9	17.1	0.0	0.09
9	6.4	12.0	0.71	0.29
10	7.7	13.0	0.31	0.55

[a]Wind velocity was measured at 52.1 m high at the meteorological station.

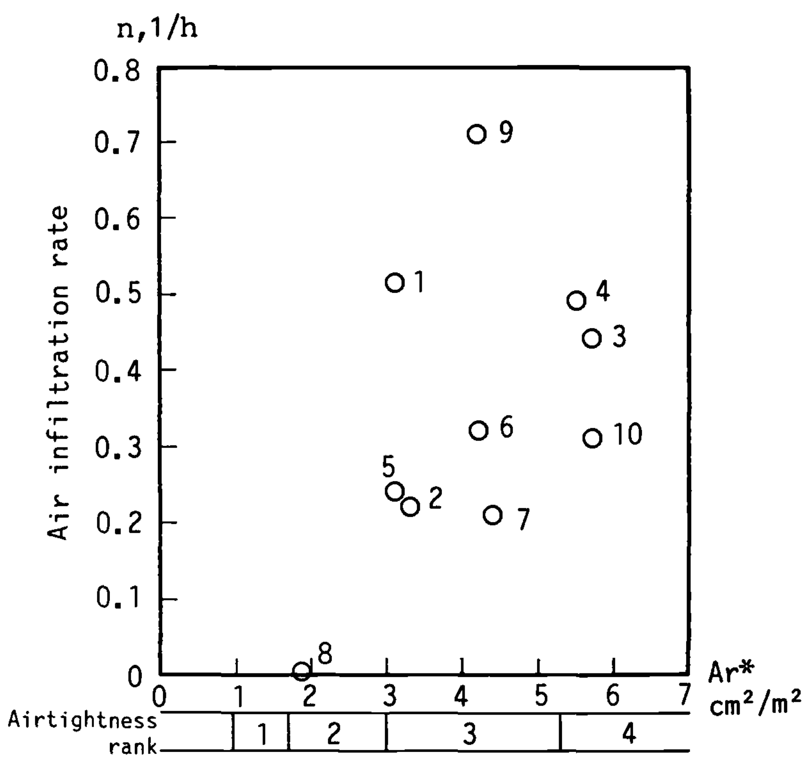


FIG. 9—*Relationship between airtightness and air infiltration.*

and indoor-outdoor temperature difference. Nevertheless, a positive correlation can be found between the two factors.

Comparison of Air Infiltration Rate Between Measurement and Calculation

Yoshino et al. [9] reported that, for estimating air infiltration from the results of an airtightness test, the assumption of uniform distribution of air leakage over the building envelope provided a good estimate, on the basis of a detailed field measurement of airtightness and air infiltration using three small test houses.

Then the authors calculated the air infiltration in the investigated houses utilizing the same method as one used by Yoshino et al. [9], taking into account some assumptions as shown in the following:

1. All the houses are of a simple rectangular shape with dimensions of 8 m in width, 8 m in depth, and 5 m in height. Also, it is assumed that each house was comprised of a single room.
2. Air leakage was uniformly distributed, that it, the effective leakage area of each house was distributed among the four walls, the ceiling and the floor, according to the area of each surface. Each wall was divided laterally into ten parts, and uniformly distributed cracks in each part were concentrated at the center of the surface.
3. The profile of the outdoor wind speed depends on the power law. The exponent is assumed to be 0.28 [10]. The wind speed at 5 m above the ground surface was used for a reference wind speed for calculating the surface pressures on the houses.
4. Wind pressure coefficients are assumed to be 0.12 for two of the walls, −0.08 for the other two walls, −0.06 for the attic, and 0.02 for the crawl space, taking into account that the houses measured were constructed close to one another [2]. The wind pressure coefficient depends on the shape of each house and obstacles surrounding the house; however, these coefficients are assumed to be constant for all houses.

The air infiltration rate was calculated using the network method [11], which is described below.

The pressure difference, Δp_k, across a concentrated crack k at height, h_k, from the floor level due to both wind and buoyancy effects is given as the following equation

$$\Delta p_k = C_k \left(\frac{\rho_o}{2}\right) v^2 - p_i + g h_k(\rho_i - \rho_o) \tag{3}$$

The air flow, Q_k, and the Δp_k for the crack k have the relationship

$$Q_k = Q_{r,k} \left(\frac{\Delta p_k}{\Delta p_{r,k}}\right)^{1/n_k} \tag{4}$$

The total volume of air flow into the interior through the cracks is zero, that is

$$\Sigma Q_k = 0 \tag{5}$$

Substituting Eq 3 into Eq 4, the inside pressure and the volumetric air flow through each crack are found iteratively by use of Eq 5. The air infiltration rate is obtained by dividing the total of volumetric air flow coming into the house by the interior volume of each house.

Indoor and outdoor air temperatures were measured simultaneously with the measurement of air infiltration. Data for outdoor wind speed were obtained from a meteorological station in Sendai, which was measured at a height of 52.1 m. The distance of the station from the houses studied ranged between 4 and 8 km, except for House 2 which was about 18 km from the station.

Table 5 shows the calculated results in the column of "calculation." Figure 10 indicates the comparison between measurements and calculations. This agreement is not good except for some houses. Especially, the calculation results of Houses 1, 4, and 9 are lower than the measurement results. The reasons for disagreement may be included in both the calculation method and the measurement method. That is, for the calculation, data of outdoor wind speed, which were obtained from a meteorological station far from the houses, were utilized, the wind pressure coefficients used were not adequate enough to model for all of the houses, and the uniform distribution of air leakage of a house was assumed. For the measurement, there was the possibility of incomplete mixing of SF_6 in a whole house. For obtaining better agreement in further study, it is necessary to take into account these factors.

Conclusions

Airtightness, indoor air quality, and air infiltration were measured in ten occupied, detached wooden houses in the winter of 1987–88 and the relationship between airtightness and indoor air quality was examined. Also, air infiltration was calculated on the basis of equivalent leakage area and compared with the measured value. The results are as follows:

1. The values of equivalent leakage area per floor area, Ar^*, were widely distributed from 1.9 to 5.7 cm^2/m^2. The houses measured for airtightness were located from Rank 2 to 5 and appeared to be more airtight than the houses measured in 1984–85.

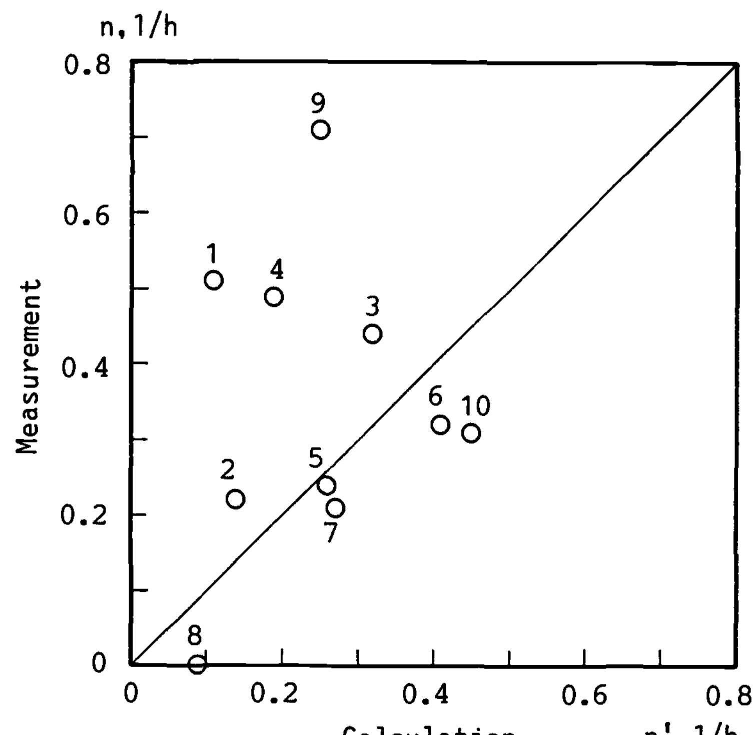


FIG.10—*Comparison of air infiltration rate between measurement and calculation.*

2. The mean concentration of CO_2 during the period of a few days was distributed from 500 to 1100 ppm. The CO_2 concentration was over 1000 ppm in Houses 2 and 9, where unvented oil heaters were used, and in House 5, where an exhaust fan with an air-to-air heat exchanger for ventilating the living room was scarcely used. On the other hand, the CO_2 concentration was lowest in House 6, where an exhaust fan was always used in the evenings. These results show that the indoor CO_2 concentration was affected by use of an unvented heater and an air-to-air heat exchanger. The NO_2 concentration measured in the living room and the kitchen ranged from 9 to 74 ppb and 11 to 72 ppb, respectively. The NO_2 concentration in Houses 2 and 9 was higher than that in the other houses.

3. The air infiltration rates measured using the SF_6 concentration decay technique were widely distributed from 0 to 0.71. The air infiltration rates, of course, depend on both outdoor wind speed and indoor-outdoor temperature differences. Nevertheless, a positive correlation was found between the two factors.

4. Air infiltration rates were calculated on the basis of equivalent leakage area. This agreement was not good except for some houses. The reasons for the disagreement were that data of outdoor wind speed, which was obtained from a meteorological station far from the houses, were utilized for calculation, the wind pressure coefficients used were not adequate enough to model for all of the houses, the uniform distribution of air leakage of a house was assumed, and, for the measurement, there was the possibility of incomplete mixing of SF_6 in a whole house. For obtaining better agreement in further study, it is necessary to take into account these factors.

Appendix A

In the case of orifice plate, the relationship between the pressure difference, Δp (Pa), across an orifice plate and the volumetric air flow, Q (m^3/h) is

$$\Delta p = \frac{\rho_o}{2}\left(\frac{Q}{A} \times \frac{10\,000}{3600}\right)^2 = \frac{\rho_o}{2}\left(\frac{2.78Q}{A}\right)^2 \qquad \text{(A1)}$$

where A is the effective orifice area (cm^2).

Therefore, the effective orifice area is obtained by

$$A_r = 2.78Q_r\left(\frac{2}{\rho_o}\Delta p_r\right)^{-0.5} \qquad \text{(A2)}$$

Substituting Eq 1 into Eq A2, the effective orifice area (effective leakage area) is given by

$$A = 2.78Q_r\left(\frac{\Delta p}{\Delta p_r}\right)^{1/n}\left(\frac{2}{\rho_o}\Delta p_r\right)^{-0.5} \qquad \text{(A3)}$$

If $\Delta p = \Delta p_r$, Eq A3 is rewritten simply as

$$A = 2.78Q_r\left(\frac{2}{\rho_o}\Delta p\right)^{-0.5} \qquad \text{(2)}$$

Appendix B

Description of houses measured in 1984–1985.

House Number	Date of Completion	Floor area, m^2	Depth of Insulation, cm			Window	Heating Equipment	Ventilation in Living Room	House Builder
			Wall	Floor	Ceiling				
1	Jan. 1983	109	5	5	7.5	D.S.	Vented oil heater	Natural	A
2	Jan. 1983	105	5	5	7.5	D.S.	Unvented oil heater and "Kotatsu"[b]	Natural	A
3	Jan. 1983	109	5	5	7.5	D.S.	Vented gas heater	Natural	A
4	Mar. 1983	110	5	5	7.5	D.S.	Unvented and vented oil heaters	Natural	A
5	Dec. 1984	109 F	10	2.5	10	D.S.	Floor heating and "Kotatsu"	Mechanical[a]	B
6	Sept. 1984	142 F	10	...	10	D.S.	Vented oil heater and "Kotatsu"	Mechanical	B
7	Sept. 1984	183 F	15	5	15	D.S.	Floor heating	Mechanical	B
8	Jan. 1982	110	5	5	7.5	D.G.	Vented oil heater and "Kotatsu"	Natural	A
9	Oct. 1984	152 F	5	5	10	D.S.	Floor heating	Mechanical	C
10	Mar. 1983	147 F	5	5	10	D.G.	Floor heating and "Kotatsu"	Natural	C
11	Aug. 1983	163 F	5	5	10	D.S.	Floor heating	Natural	C
12	June 1981	120 F	5	5	10	D.G.	Floor heating	Mechanical	C
13	Aug. 1981	109 F	5	5	10	D.G.	Floor heating and "Kotatsu"	Mechanical	C

NOTE: F = concrete floor is constructed. D.S. = double sashes, D.G. = double glazing. All houses have two stories except for House 13 with a flat.

[a]"Mechanical ventilation" means an exhaust fan unit, which is situated in an outer wall, with an air-to-air heat exchanger, except for House 13.

[b]"Kotatsu" means a traditional Japanese electric heater that is mounted under a low table.

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DISCUSSION

W. DeGids[1] *(written discussion)*—Were your Cp values based on measurements or taken from literature.

H. Yoshino (closure)—They were taken from Ref *2* in the literature.

[1]POB 217, 2600 AE Delft, Netherlands.

Marian B. Nantka[1]

Comparison of Different Methods for Airtightness and Air Change Rate Determination

REFERENCE: Nantka, M. B., **"Comparison of Different Methods for Airtightness and Air Change Rate Determination,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 267–282.

ABSTRACT: The problems of air change and airtightness in buildings are not sufficiently recognized in Poland, which results in the lack of precisely defined standards for building design. This paper discusses the correlation between airtightness and air change rates and presents measured and calculated air change rates with and without different sources of airflows in occupied houses. It discusses also the influence of pressure differences that were measured on the air change. The results of tests can be used to verify present standards in the field of airtightness and air change rates and give the basis for further testing of these processes.

KEY WORDS: airtightness, air infiltration and ventilation rates, small and large-scale pressurization tests, tracer gas method, calculating models

Description of the Houses and Methods of Analysis

This paper is the first part of an experimental study carried out by the author to estimate air change rate and the effect of these rates on energy consumption.

The work was done in four detached houses, occupied and located in the Silesia region of Poland. The houses are the same size and have the same floor plan. Localizations and the floor plans of these houses are presented in Fig. 1. All houses are built from hollow masonry units (walls) and prefabricated panels (floors and ceilings). Typical wood frame windows with double glazing were applied. Each house is heated by a boiler (located in the cellar) and a two-pipe heating system (without pumps) with cast iron heaters. The houses are ventilated by natural ventilation with ventilation shafts (without fans) situated in kitchens and bathrooms.

These identical two-story houses were built at the end of 1981. The floor area of the living space on each story is 89.7 m^2, the envelope area above the ground level is 289.7 m^2, and the indoor volume is 448.2 m^3. The ratio of the gross enclosure to this volume is 0.645/m. The local terrain consists of small lawns with trees and with shrubs around the lawns and trees.

Measurements were carried out in all the tested houses between September 1985 and April 1986 with the use of pressurization tests and a tracer gas method.

For individual house envelope components, such as doors, windows, and different joints, a small-scale pressurization technique was used. For these tests, airtight test chambers were

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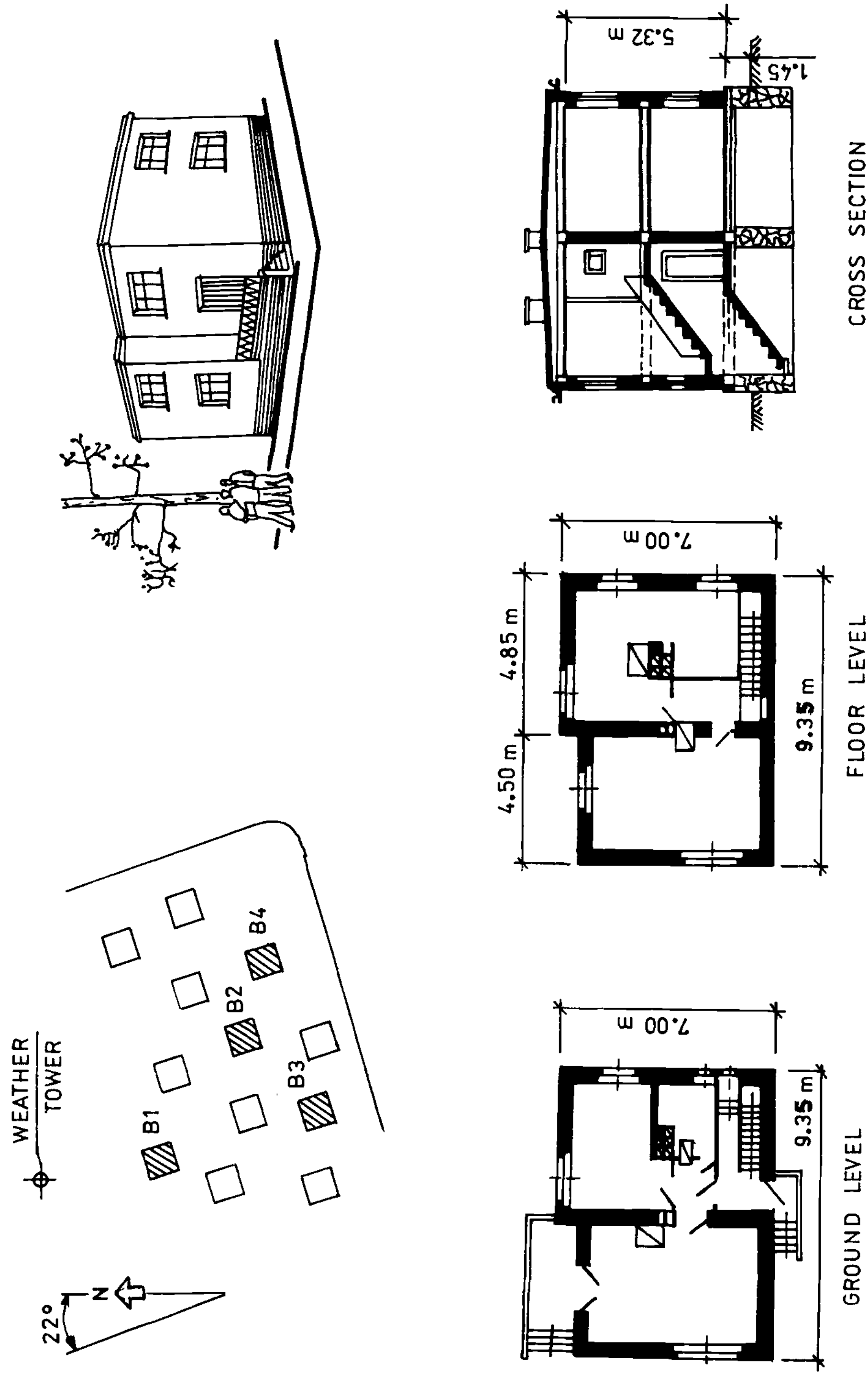


FIG. 1—*Location and floor plan of tested houses.*

used. The fan inlet was connected to this chamber by a duct of about 2.0 m in length and 0.2 m in diameter. This chamber was made of plywood panels covered with polyethylene sheets and was sealed around the perimeter of the test element with tape. The airflow rates of the fan were adjusted with a manual damper and measured with a laminar flow element. The pressure difference on selected points of the wall was measured with a diaphragm-type pressure transducer and a digital voltmeter. These measurements started in September 1985 and ended in November.

In September, the four houses were pressure tested using the large-scale pressurization technique. In this case, the fan used was of vane axial type with a variable-pitch blade that could be adjusted manually to obtain flow rates between 0 and 3 m^3/s. The fan inlet was connected by a duct, 0.4 m in diameter, to an entrance door replaced for the tests by a plywood panel. Each house was pressurized to the outdoor-indoor pressure differences from about 5 Pa to about 80 Pa in increments of about 10 Pa, and the airflow into the houses, required to maintain each pressure difference, was measured. These measurements make it possible to determine air leakages of all the surfaces (windows, ceilings, floors, etc.) of the tested houses.

Air change rates were measured simultaneously in all houses on 14 selected days (between February and April 1986) using the tracer gas method with methane as the tracer gas. For each test a large bottle containing about 3 m^3 of methane was placed in the cellar of each house. Methane was released from the injection samples in the center of the tested space. At each internal doorway, small mixing fans were installed. These fans were operated for 15 min to mix the tracer with the indoor air. Every 20 min after the tracer gas release, a sample of the indoor air was taken to the analyzer with a logger. The measurements lasted 3 or 4 h of each test day. The changes of methane concentration were recorded and then the air change rates were calculated. During these measurements, the outdoor and indoor air temperatures and wind velocities (with directions) were also recorded. At the same time, pressure differences in some selected points of the house walls were also measured.

All results of measurements were processed in accordance to the general flow theory. Airflow through a house envelope is a combination of viscous and turbulent flows. In practice, these flows can be characterized by the equation

$$\dot{V} = a\, A_z\, (\Delta p)^{\alpha} \tag{1}$$

where

$\dot{V}$ = air infiltration or natural ventilation rate, m^3/s (m^3/h),
a = average flow coefficient, $m^3/m^2s(Pa)^{\alpha}$ ($m^3/m^2h(Pa)^{\alpha}$),
A_z = area of a house envelope, m^2,
Δp = outdoor-indoor pressure difference, Pa, and
α = flow exponent between 0.5 to 1.0.

The above equation is a basic relationship for handling the data from the pressurization test. When $\dot{V}$ and Δp values are known (from measurements), both the average flow coefficient and flow exponent can be determined for each house element or for the house envelope [*1–4*]. For correct determination of the natural ventilation rate, the pressure differences and their changes must be defined. In general, these are the results of the simultaneous influence of stack and wind effect and also the underpressures which are generated by ventilation shafts, ducts (even if natural ventilation is employed), flue pipes, fireplaces, chimneys, etc. In the first case, i.e., if only the stack and wind effects are taken into account, the air change rate may be defined as the *air infiltration rate.* If all driving forces operate we are given the *total air change rate* (or ventilation rate). In both cases, the air change rate can be determined from the relation

$$n\ (IN \text{ or } T) = a\ (IN \text{ or } T)\ D(\Delta p)^{\alpha} \quad (2)$$

where D is the geometrical shape coefficient, i.e., the ratio of gross enclosure to volume of a house [*2,5,6*] and IN or T are indices for the air infiltration rate or the total air change rate, respectively.

One of the most important factors is the flow exponent, especially when the pressure difference is small or if the gaps have small dimensions [*3,7*].

The air change per hour is also related to the tracer gas concentration "c" according to the equation

$$c = c_o e^{-n\tau} \quad (3)$$

where c_o is the tracer gas concentration at time $\tau = 0$ and n is the air change rate per hour.

Hence, the air change rates obtained from the concentration decay method and the airtightness obtained from pressurization tests, substituted to Eq 1 and 2, allow us to determine pressure differences and flow exponents and also the relationship between them [*2,4,7*].

In addition to these measurements, the air infiltration rates and the total air change rates were calculated by using two models. At first, the Lawrence Berkeley Laboratory (LBL) model was used. After the determination of leakage values from the pressurization tests, the air change rate was measured by using the tracer decay technique averaging air exchange over 1-h and one-day periods. For measured data, the air change rate was calculated from the local weather variables and house parameters. For the same conditions, the author's model was used [*8*]. This model is based also on the results of pressurization tests and on the calculation of the average values (flow coefficients, pressure differences, etc). On the basis of tests, the average pressure differences and the average airflow coefficients must be calculated. These Δp and a values are determined as the mean values of the value characteristics of external walls, weighted by area [*9*]. Some results of measurements and their comparisons are presented below.

Results of the Measurements

The important results of small-scale pressurization tests and the scheme of the measuring stand are presented in Fig. 2. The figure shows that the air leakage rates for windows and window frame-wall joints are about $14 \cdot 10^{-5}$ to $41.7 \cdot 10^{-5}$ m^3/ms (0.5 to 1.5 m^3/mh); for window sills, about $4.17 \cdot 10^{-5}$ to $5.56 \cdot 10^{-5}$ m^3/ms (0.15 to 0.20 m^3/mh); for ceiling-wall joints lower than $0.28 \cdot 10^{-5}$ (0.01 m^3/mh) and for floor-wall joints, about $0.56 \cdot 10^{-5}$ (0.02 m^3/mh) at a pressure difference equal to 1 Pa. At the same pressure difference, the air leakage rate for entrance doors varies between $83 \cdot 10^{-5}$ and $167 \cdot 10^{-5}$ m^3/ms (3 and 6 m^3/mh). On the basis of the results and a simple author's method of calculation [*9*], average flow coefficients, e.g. a values, can be calculated. These a values per m^2 of exterior walls varied between $4.17 \cdot 10^{-5}$ and $11.7 \cdot 10^{-5}$ m^3/m^2s (0.15 and 0.42 m^3/m^2h) for the tested houses at a pressure difference of 1 Pa.

Figure 2 shows also the contribution of various house components to the total air leakage rates for three values of pressure differences (see the lower part of Fig. 2). For example, if a pressure difference is about 30 Pa, windows including window frame-wall joints are the main contributing component, which may be high as 60% of the total leakage. Floor-wall joints and window sills can contribute 10 and 30% of the total leakage, respectively. For other pressure differences, these contributions do not vary significantly. For example, if the Δp-value is about 10 Pa, air leakages through windows, including window frame-wall joints, are decreased to about 50%; at the same time, window sills make up about 40% of the total air leakage. This is probably the result of the reverse effect.

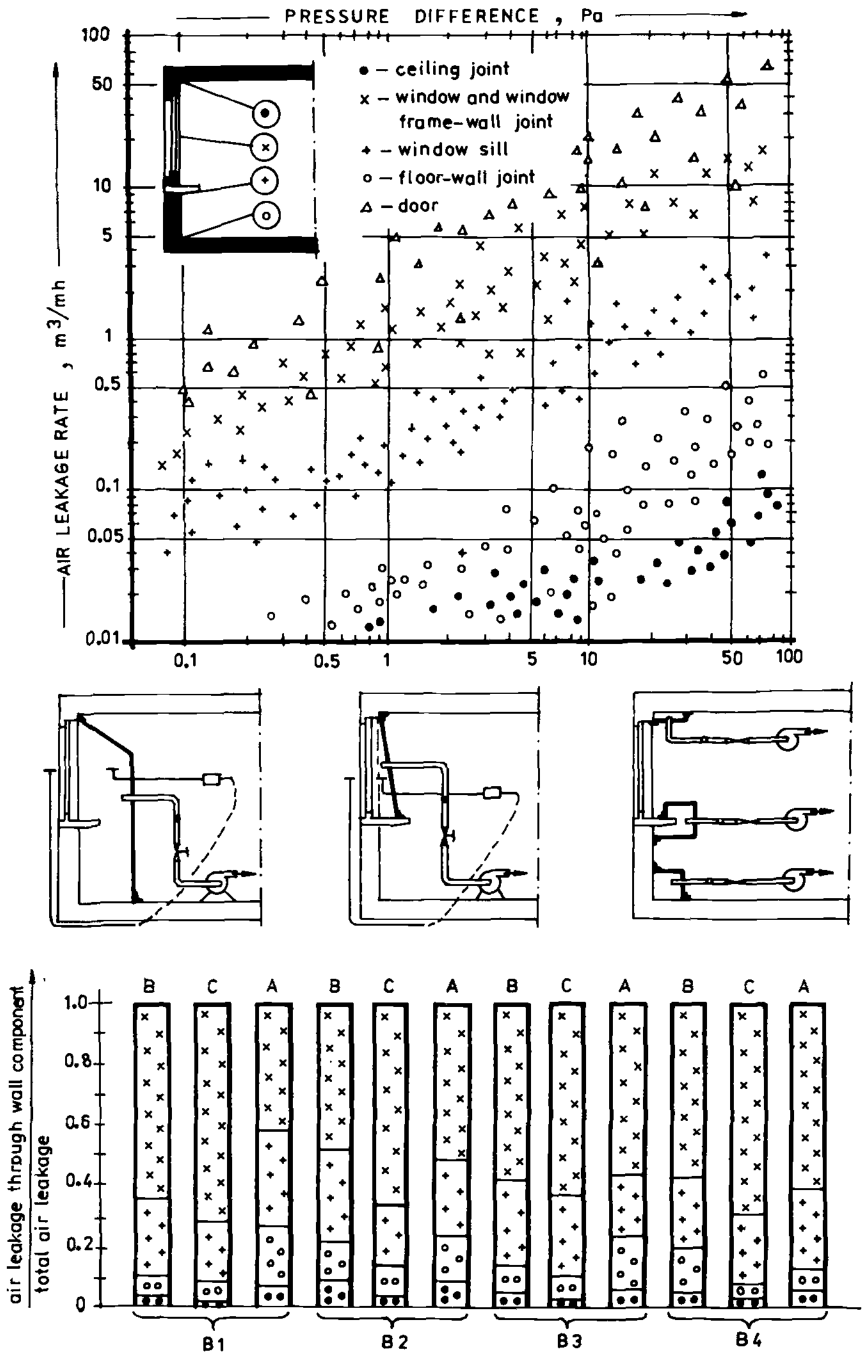


FIG. 2—*Results of small-scale pressurization tests (A for* Δp = *10 Pa; B for* Δp = *20 Pa; C for* Δp = *30 Pa).*

The basic pressurization tests were carried out in all the houses by using a blower door method. Some results of these tests are presented in Fig. 3. This figure shows the air leakage rates per unit area of the house envelope defined as the area of exterior walls plus the ceiling and the upper floor. The measured values of over-all air leakage rate and pressure differences were fitted to the flow equation (Eq 1), and both flow coefficients and flow exponents were determinated. The values of the flow coefficients were $3.9 \cdot 10^{-5}$, $2.8 \cdot 10^{-5}$, $2.5 \cdot 10^{-5}$, and $9.4 \cdot 10^{-5}$ m^3/m^2s (0.14, 0.10, 0.09, and 0.34 m^3/m^2h) at a pressure difference of 1 Pa for Houses B1, B2, B3, and B4. These *a* values correspond to flow exponents which are 0.78, 0.71, 0.68, and 0.68 for the tested houses, respectively. The data refer to the cases when all interior doors are closed. If these doors are open, the air leakage rates are lower or higher than the mentioned values for pressure differences about 10 to 15 or 50 to 55 Pa, respectively. These differences are about ±10% on the average.

Air infiltration [n (IN)] and total air change rates [n (T)] were measured in all the tested houses. Example results of the tracer gas method are presented in Fig. 4. These data are characteristic of houses when all exhaust orifices are closed but not sealed. Similar measurements were performed when these orifices were open (Fig. 5). When comparing a large number of the above results, it is possible to determine the increase of air change rates for both cases for measurements. Figures 4 and 5 show that, on the average, air infiltration rates are lower than total air change rates. The greatest increments of the air change rate were observed in House B1 (exposed) and House B2 (shielded and tight). In the latter case, i.e. for House B2, the increment is the result of high tightness both of the house envelope and the ventilation shafts and also of high air temperatures indoors (about 25 to 26°C, whereas in the other houses these temperatures varied between 18 and 21°C.)

In general, the overall tightness of the tested houses is excellent. The results of tests show that the air leakage is far less than that set by Polish standards and also than the maximum values obtained from a simple method of "tightening limitation" and optimum choice of ventilation system which has been worked out by the author and presented in detail in *BSER&T* [9]. Air infiltration and total air change rates in typical winter and spring periods are less than the recommended values or are similar to these values (except for House B3).

Results of Calculations and Discussion

The air infiltration rates and also the total air change rates were calculated by using some selected mathematical models or a method of air change rate estimation.

1. The air change rates for the tested houses were predicted with the use of two models, i.e., the LBL model and the author's model. These models are based on the pressurization data using Eq 1 or 2. The model developed at the Lawrence Berkeley Laboratory characterizes the leakage of the house by means of the effective leakage area, which is proportional to 4 Pa. In the author's model, the average flow coefficient and the mean pressure difference on the walls were determined also from Eq 1. But in this case, these *a* values are proportional to 10 Pa (the reference level according to Polish standards).

For the measured weather data, the air change rates from the measurements by means of the tracer gas method were used. Figure 6 shows the plots of the predicted (from calculations) versus the measured total air change rates for 14 measuring days. The average difference between the LBL model predicted air change rates and measured rates is ±20%. Similar errors were obtained from the author's model, but in this case, the sign of the $n(T)$ values is opposite, i.e., the difference is equal to about −20%. In both models, a discrepancy between a perfect agreement and the actual values increases for the houses in which air change rates are higher than 0.2 per hour for pressure differences from 4 to 10 Pa (especially in exposed or leaky houses). These differences probably result from the fact that the resistance of indoor airflows within the house was not taken into account in the author's model.

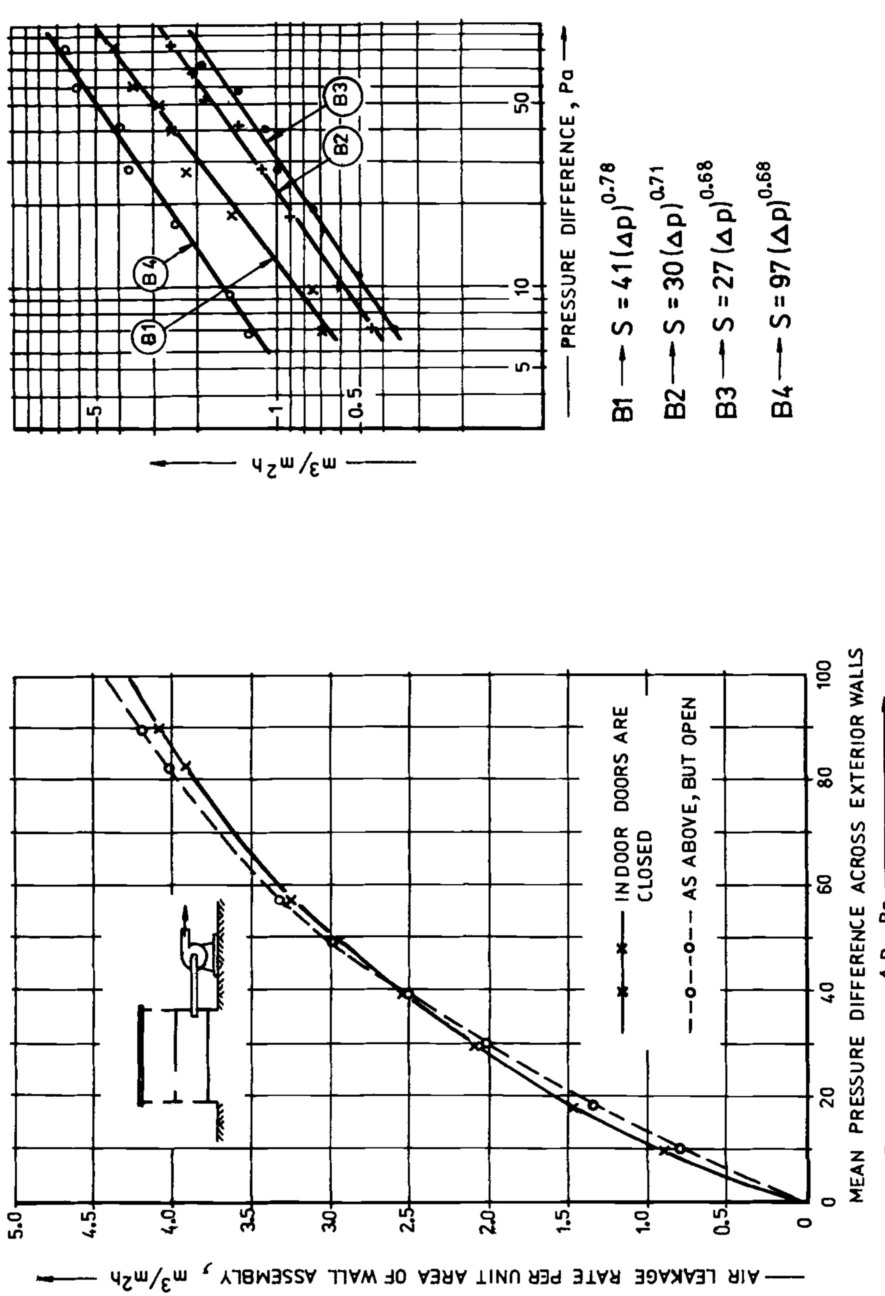


FIG. 3—*Relation between air leakage rates and pressure differences as the result of large-scale pressurization tests (the blower door method).*

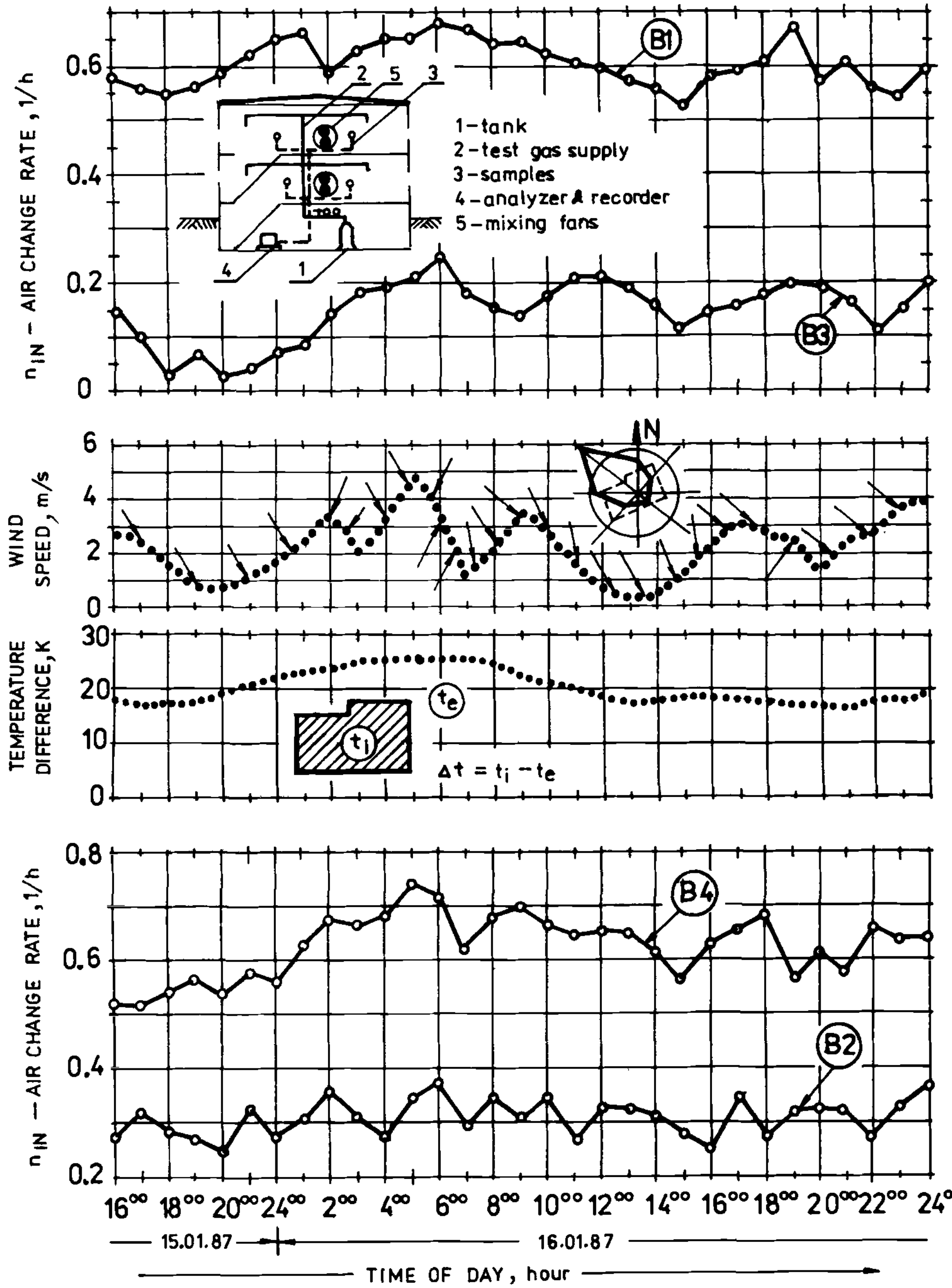


FIG. 4—*Example results of air infiltration rates for tested houses as the result of the tracer gas method (exhaust orifices are closed but not sealed).*

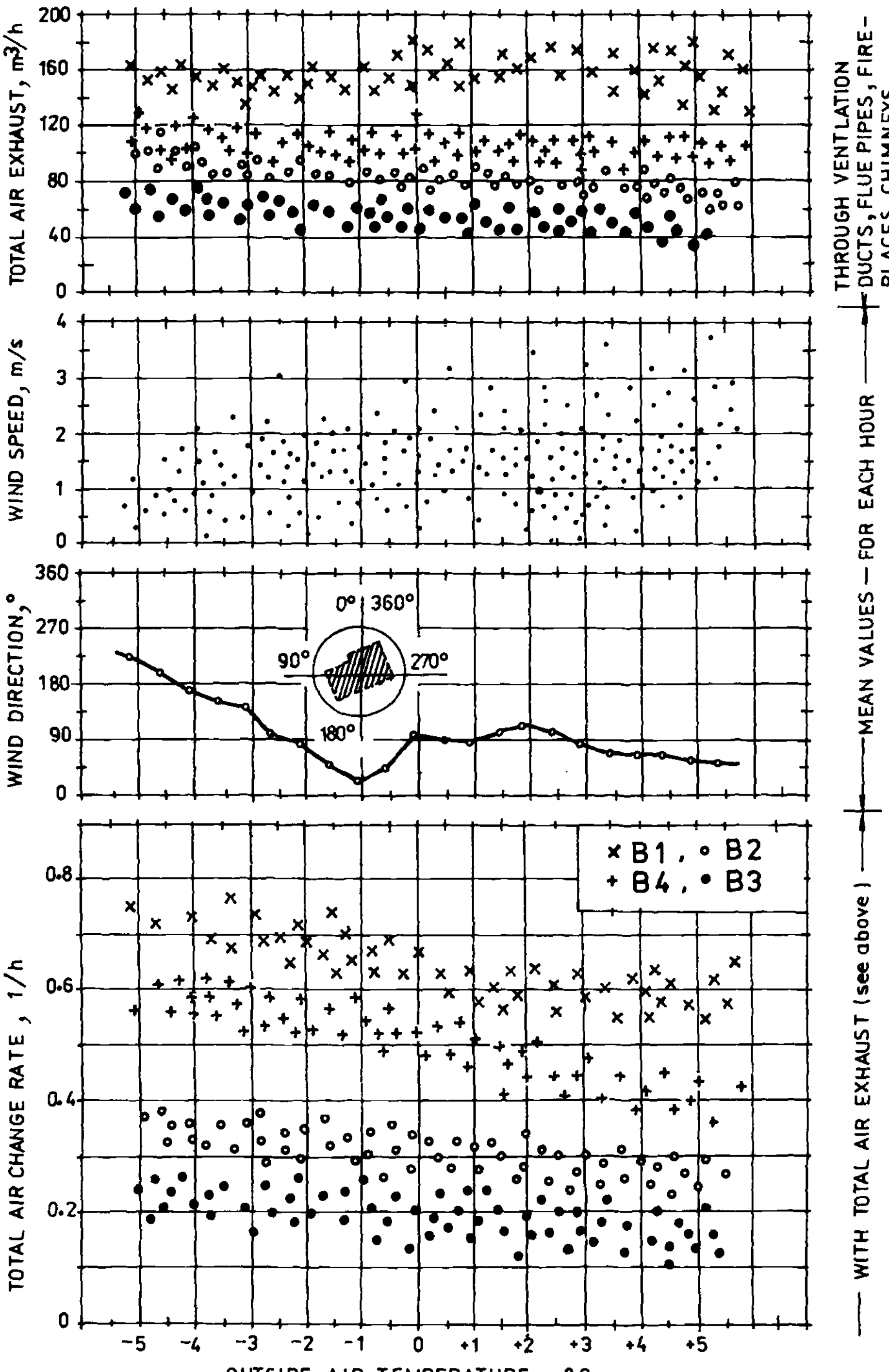


FIG. 5—*Relation between the total air change rates, the outdoor air temperatures, and the wind effects for tested houses as the result of the tracer gas method (cumulative and continuing data).*

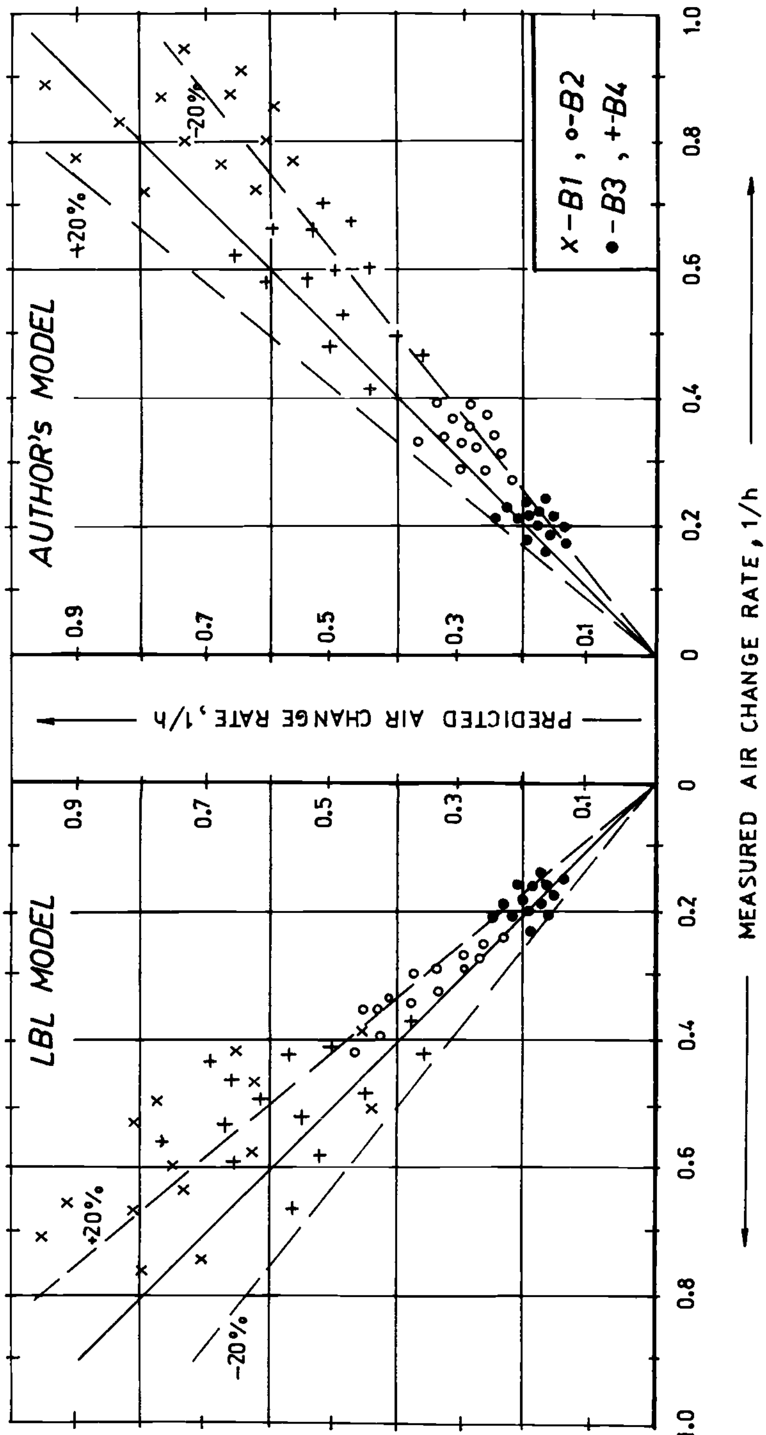


FIG. 6—*Comparisons of predicted and measured total air change rates.*

2. For the ranges of the weather data observed during the measurements, the results were fitted to the following general formula

$$n(T) = A + B\Delta T + Cw^2 \tag{4}$$

where

ΔT = indoor-outdoor temperature difference, K,
w = wind velocity, m/s, and
A, B, C = linear regression constants for a particular house.

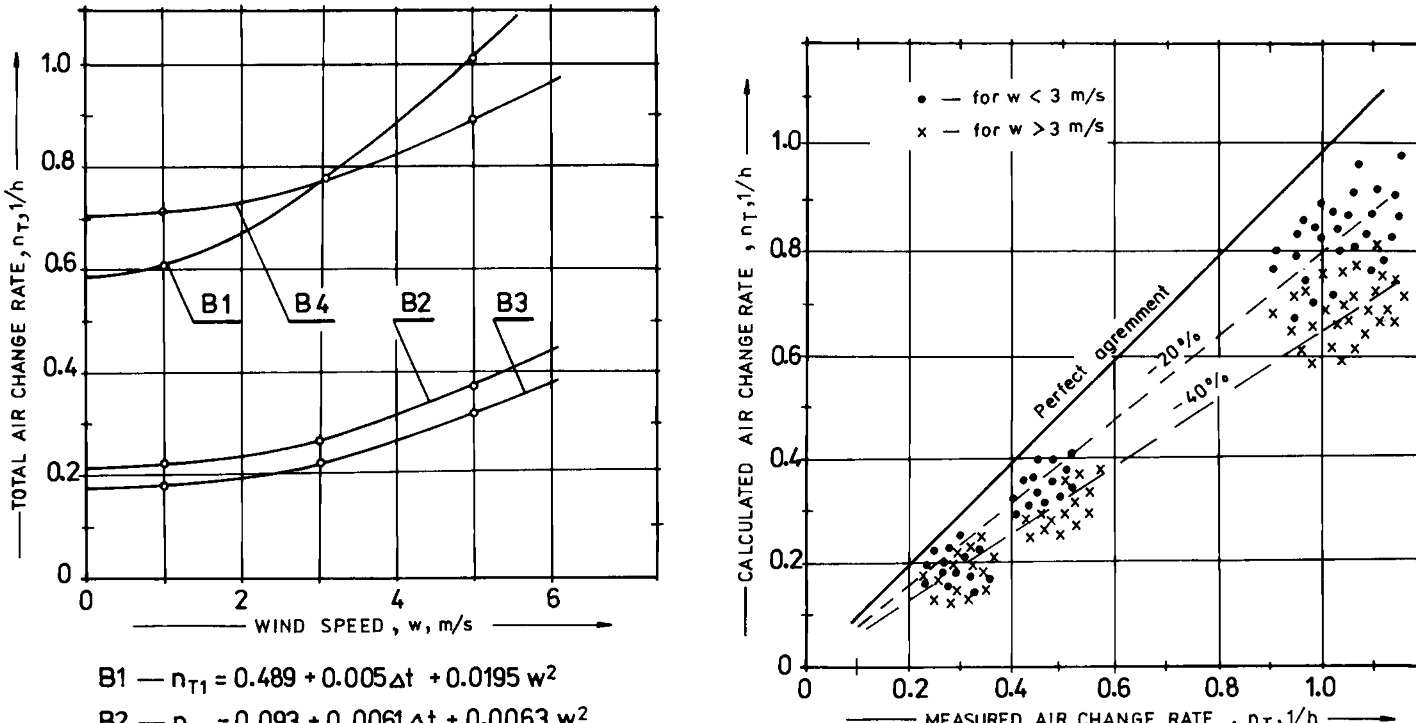
The analytical expressions which were obtained by means of the linear regression method are presented in Fig. 7. The same as for the comparisons presented above, daily air change rates that calculated the use of the relation (Eq 4) are similar to the measured $n(T)$ values, especially if the wind velocity is lower than 3 m/s. In these cases, the air change rates from Eq 4 are lower than the measured values by about 20 to 25%. When the wind velocity is higher than 3 m/s, the difference between the predicted and measured values is higher than described above and may be about 40%.

Special attention has been paid to the comparison of the measured and calculated pressure differences on the exterior walls of houses. These differences were measured in 16 points on the envelope of each house. On the basis of these measurements, the average pressure differences were calculated [9]. For the same conditions these pressure differences were calculated with the use of Eq 2. In this case, the values are based on the pressurization tests (a, α) and on the tracer gas method (n). Comparisons of measured and calculated Δp-values are presented in Fig. 8. As it shows, Δp-values from calculations are always lower than the same values from measurements. These differences average −20%. In general, this error is similar when air change rates are calculated by the author's model (see Fig. 6). Therefore, for the correctness of this model the pressure differences must be verified (e.g., by using a correction factor for Δp-values calculations). On the other hand, the above inaccuracy is related to wind effect. In practice, wind pressure depends not only on change of wind velocity and direction but on other factors such as the shape of houses, their location in terrain, or other terrain factors and is also a function of time. It is therefore necessary to work out a mathematical model for calculation of air change rates by means of the general equation $n(\tau) = f\{[\Delta p(\tau)]^\alpha\}$, where τ denotes time. This work will be continued by the author in the future.

In order to confirm the reliability of Honma's results [7], the relation between the total air change rate and the airtightness for the measured pressure differences has been considered. This relation is presented in Fig. 9 for all the tested houses. As is shown in this figure, the change of the flow exponent α is indeed proportional to the pressure difference and the flow coefficient, but the exponent varies irregularly. The primary cause of this irregularity may result from the fact that the exponent α is the function of not only the pressure difference but also of the air leakage value. Together with the increase of the pressure difference, both the flow coefficient and the flow exponent also change. These changes are characteristic, especially if the pressure differences vary between 1 and 5 Pa. When Δp becomes small, the flow exponent approaches unit (1), while at large Δp-values α approaches 0.5. At the same time, the change of the flow coefficient was observed. These changes are the biggest for low Δp-values and the smallest for high values of Δp. All the data are based only on the results of measurements (without mathematical verification). Apparently the present results can be the confirmation of the general study by Honma [7].

Further Research

Knowledge about airflows in houses and ways of testing this have been significantly increased in Poland over the last five years. The basic methods of measurements and cal-



B1 — $n_{T1} = 0.489 + 0.005\Delta t + 0.0195\ w^2$

B2 — $n_{T2} = 0.093 + 0.0061\Delta t + 0.0063\ w^2$

B3 — $n_{T3} = 0.069 + 0.0053\Delta t + 0.0059\ w^2$

B4 — $n_{T4} = 0.526 + 0.009\ \Delta t + 0.0071\ w^2$

FIG. 7—*Correlation of the total air change rates with the wind velocity for one temperature difference (ΔT = 20 K) and comparison of calculated and measured results.*

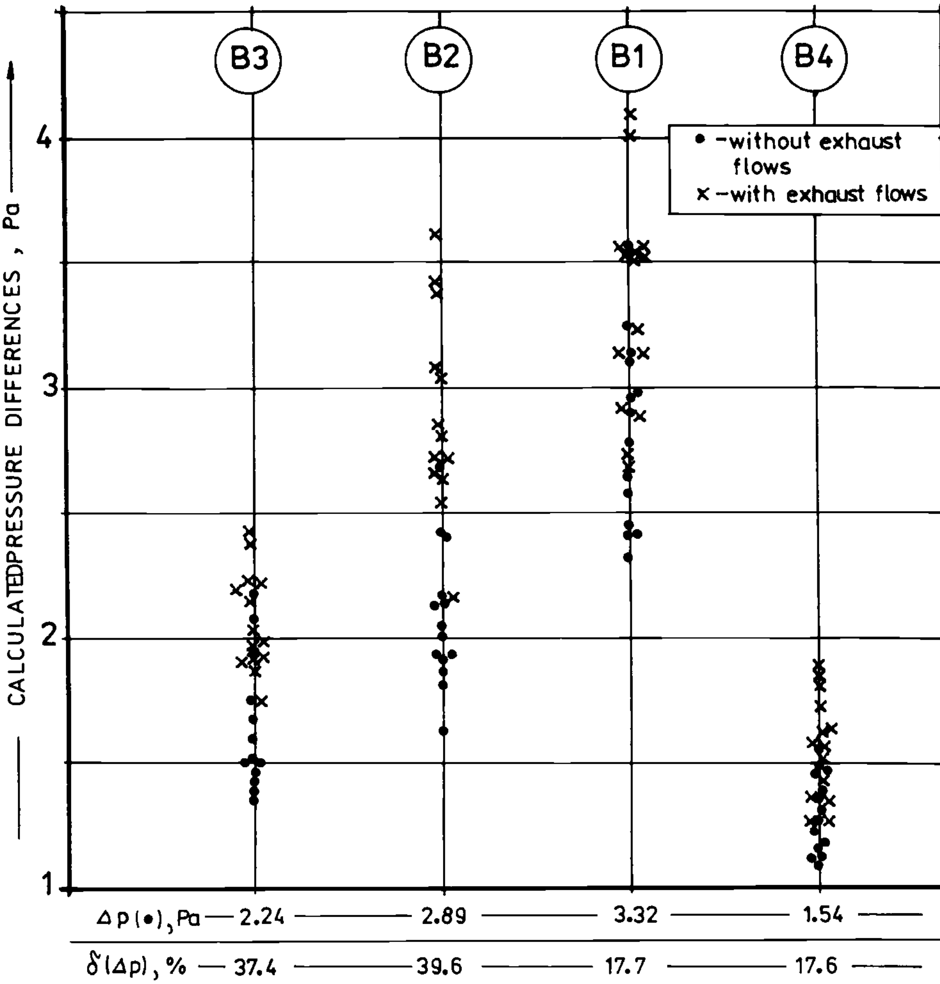


FIG. 8—*Comparison of calculated and measured average pressure differences for tested houses.*

culations of airtightness and air change rates have been adopted and used, and the principles of these methods have been determined. Further research will move three basic directions.

The first will be the continuation of research to improve the accuracy of the calculation models with particular consideration given to the flows related to the wind effect.

The second direction of future work will be in developing various tracer gas methods and various tracer gases (especially with sulphur hexafluoride).

The third stage of research will be the most important. In this stage, both the mathematical model and measurements in multizone structures will be used and analyzed. More consideration ought to be given to the problem of the relation between the separate zones in the mathematical simulation of airflow and measurements by means of various tracer gas methods.

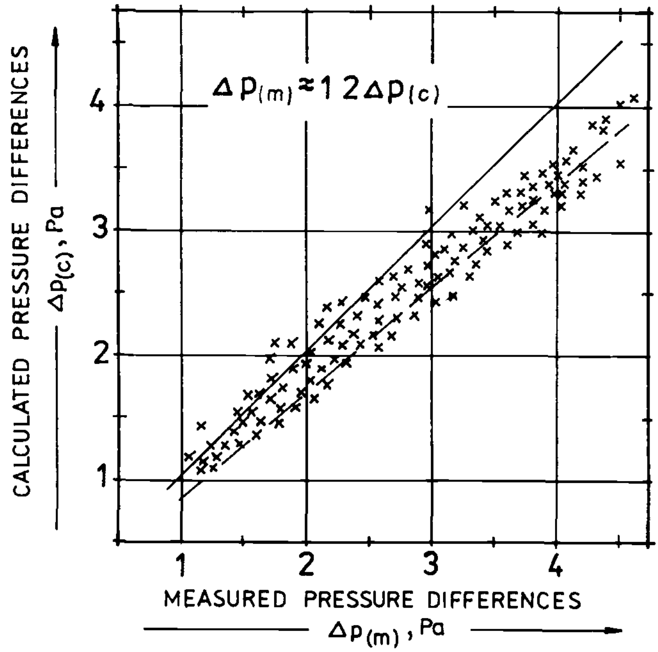


FIG. 8—*Continued.*

Conclusions

The present study was undertaken by the author to determine the general ways of measuring and calculating air change rates in selected houses. Airtightness and air change rates were measured in four houses in the Silesia region with pressurization techniques and the tracer gas method. For the same houses, the selected methods of air change rate prediction were used. On the basis of the analyses and comparisons of the present study, the results may be divided into two categories. The first one will comprise the characteristics of the tested houses. They are:

1. The average flow coefficient varies from $2.5 \cdot 10^{-5}$ to $9.4 \cdot 10^{-5}$ m^3/m^2s (0.09 to 0.34 m^3/m^2h) at Δp-value equal to 1 Pa; the flow exponents vary between 0.68 and 0.78. Airtightness for all the houses is satisfactory according to Polish standards.
2. The air change rate, taking into account infiltration and natural ventilation functioning, varies between 0.3 and about 1.0 per hour. These values are satisfactory only in two of the houses (B1 and B4). For Houses B2 and B3 the air change rate is lower than the minimum ventilation rate, i.e., 0.5 per hour (natural ventilation only).
3. The average air change rates (daily) correspond to the average pressure differences, which vary from 1.2 Pa (for Houses B3 and B4) to 3 to 4 Pa (for House B1).

The next category of results are general conclusions related to the methods of analyses used and the ways of air change rate predictions. They are as follows:

1. Airtightness characteristics of the envelopes of the houses can be obtained by conducting small-scale pressurization tests. In this case, a correct model should be applied for prediction of air change rates in which the relation between the weather data and the parameters of the houses would be determined more precisely.
2. A better method for airtightness determination is large-scale pressurization testing. In

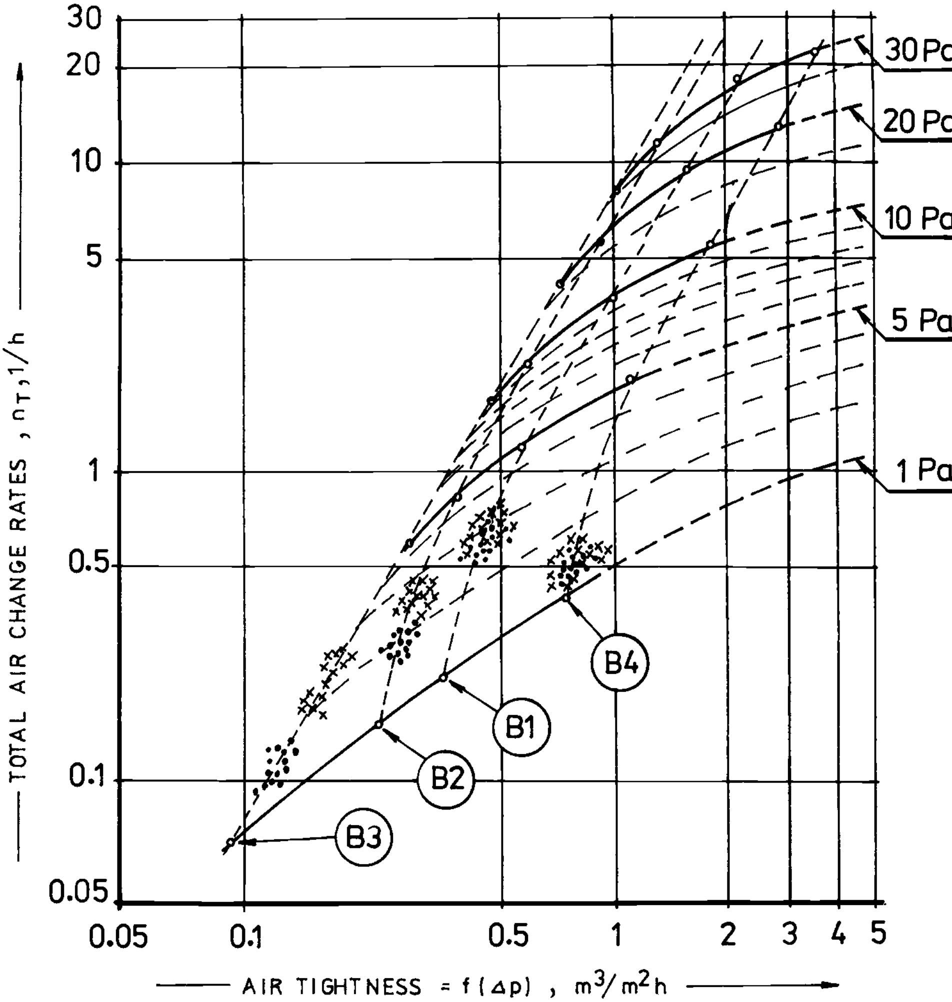


FIG. 9—*Correlation between total air change rate, air tightness, and the average pressure differences for tested houses.*

this case, the blower door method can be recommended as a correct technique. The method used in the research can be recognized as a correct technique. In this case it appears that the representative natural atmospheric pressure difference across an envelope must be maintained at 4 Pa (reference level). Thus, the pressure difference of 4 Pa instead of 1 Pa or 10 Pa recommended by Polish standards ought to be assumed as the reference level representative of natural ventilation.

3. The best method for air change rate determination is the tracer gas technique. However, this method does not take into consideration the difference between fresh air exchanges and intercellular airflows. Therefore, the measurements of air change rates should be complemented by the monitoring and recording of the pressure differences in selected points of external walls.

4. The air exchanges can be also determined by using the predictive models in which the basic assumption are the air leakage values from pressurization testing in specified houses.

The average percentage difference between the predictions and the results of the measurements are about ±20%. This difference can be increased to about −40% if the simplified methods are used. In this case, the percentage error can be about ±70% for an hourly air change rate (when hourly weather data were used).

5. The accuracy of air change rate predictions depends on mutual relations among airflow coefficients, flow exponents, and pressure differences. This relation is very important if the average pressure differences on the envelope of the house are lower than 5 Pa. This is characteristic of detached houses and of average winter conditions.

The above conclusions and the results of the author's previous research are the basis for further study which will be carried out in houses of various constructions by means of different measurement methods.

Acknowledgment

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Airtightness Characteristics of Electrically Heated Houses in the Residential Standards Demonstration Program

REFERENCE: Parker, D. S., **"Airtightness Characteristics of Electrically Heated Houses in the Residential Standards Demonstration Program,"** *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 283–293.

ABSTRACT: This paper examines airtightness data from 623 electrically heated residential buildings in the Pacific Northwest. The Residential Standards Demonstration Program (RSDP) was designed to demonstrate the merits of energy-efficient construction techniques. The control houses were intended to be representative of current construction practice in the four-state region (Idaho, Montana, Oregon, and Washington). The Model Conservation Standards (MCS) houses incorporated energy efficiency features including measures to reduce air infiltration and provide ventilation with heat recovery. The RSDP houses were primarily built in 1984 and monitored in the 1985–1986 heating season.

The airtightness of the tested homes was found to highly variable. Based on interpretation of blower door tests with the LBL infiltration model, we conclude that the typical MCS home had an average natural air change rate of about 0.25 air changes per hour (ACH) versus a rate of 0.49 ACH for the typical control house.

KEY WORDS: infiltration, residential, airtightness, fan pressurization tests, perfluorocarbon tracer gas measurements

With the Northwest Power Act of 1980, Congress stipulated that Model Conservation Standards (MCS) be created that would improve current building practice and help to preserve the inexpensive hydroelectricity resource indigenous to the Pacific Northwest region. The MCS standards were designed to be flexible to account for regional differences in climate severity and to allow different construction methods. One of the major elements of the proposed MCS was to save a large amount of heating electricity through the use of house-tightening measures followed by mechanical ventilation with heat recovery.

Implementation of the proposed efficiency levels has been demonstrated under the auspices of the Bonneville Power Administration in the Residential Standards Demonstration Program (RSDP). This program saw the construction of over 400 energy efficient houses in the four-state region. The program compared the monitored performance of the energy-efficient houses with an equal-sized group of new conventional houses. The primary heat source in all the houses was electricity. Included in this monitoring process were fan pressurization blower door tests of each house and perfluorocarbon tracer gas tests on a subset of the houses. These two tests were aimed at determining the relative level of air leakage in the two groups of buildings.

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Infiltration and Ventilation Assumptions in the MCS

Based on best available information, the developers of the MCS assumed that the air change rate in conventionally built houses averaged about 0.6 air changes per hour (ACH). This theoretically presented a large opportunity for energy savings. Thus, the MCS houses were designed to be airtight with sealed polyethylene vapor barriers and air-to-air heat exchangers. The planning assumption was that the as-built MCS houses would have a natural air change rate (induced by wind and temperature difference) of about 0.1 ACH with another 0.5 ACH of ventilation provided by air-to-air heat exchangers with 60% of the heat effectively being recovered. This results in a net reduction of 0.3 ACH over the conventional house. According to building energy simulations, overall space heat energy saving was estimated to be over 2000 kWh/year for an average new Northwest home.

Description of the Houses

All houses in the RSDP program were site built structures. Various physical characteristics of the houses are summarized in Table 1. Generally, the MCS houses are larger than the control homes. They also are more likely to have two stories, including a basement, and have fewer fireplaces than conventional structures. The number of occupants and temperatures maintained in the houses was similar in both groups. Due to the target levels of thermal integrity, the MCS houses typically had more insulation in walls, ceilings, and floors. Some of these features, such as the continuous polyethylene vapor barrier and the use of exterior wall insulation sheathing, could have significant effects on air leakage rates.

Fan Pressurization Infiltration Rate Estimates

All control and MCS structures had blower door fan pressurization tests performed according to ASTM Method for Determining Air Leakage Rate by Fan Pressurization Tests (E 779–81) standard to determine their relative airtightness. The data collected from these tests were then used with the LBL infiltration model to predict their seasonal natural air change rates [*1*]. The effective leakage area (ELA), normalized by the floor area, is a common measure of relative house tightness. Termed the specific leakage area (SLA), it is summarized

TABLE 1—*Selected physical characteristics of the RSDP homes.*[1]

Characteristic	Control Mean	Control Standard Deviation	MCS Mean	MCS Standard Deviation
Area, m^2	150.5	52.4	193.8	70.4
Volume, m^3	422.2	147.0	602.6	218.8
Height, m	3.11	1.40	3.28	1.21
Fireplace? (fraction)	0.30	0.45	0.19	0.39
Basement?[3] (fraction)	0.14	0.34	0.45	0.50
Occupants, number	3.18	1.31	3.28	1.41
Interior temp., °C	20.3	3.3	21.1	3.1
Ambient temp., °C	4.1	2.6	4.4	2.5
Terrain class (1–5)	2.91	0.66	2.97	0.67
Shielding class (1–5)	2.95	0.57	3.01	0.61
Specific leakage area[2]	2.54	2.53	1.55	1.01

[1] Sample size = 331 control houses, 292 MCS houses.
[2] cm^2/m^2.
[3] All houses without basements had ventilated crawlspaces.

for the two groups in Table 1. It shows that the MCS group had approximately 40% less leakage area than did the control group after normalizing for differing floor areas.

The ELA from the fan pressurization test is coupled to weather data, and a series of calculations are made to predict a seasonal air change rate. The LBL model has been widely used to estimate the relative air leakage of residential buildings, and comparisons to sulfur hexafluoride tracer gas test results have show reasonable agreement of predicted versus actual air exchange rates [*2*]. However, other research has found some evidence that wind-driven infiltration may be overestimated in the LBL model [*3*].

We used the fan pressurization results, audit data, and the correlation technique along with 30-year normal weather data for October through March to estimate the seasonal infiltration rates. The data for the overall sample of all buildings with complete data are summarized in Table 2. It will be noted that missing data led to a fairly strong attrition before the final sample was reached. There were many buildings that were missing vital pieces of information on which to make the air change rate estimates. These included floor space, volume, house height, and even results from the blower door test itself. Consequently the final sample size for the study of airtightness characteristics of houses in the RSDP project included 623 buildings: 331 control houses and 292 MCS houses.

As expected, the MCS houses were more airtight than the control houses with an average air change rate of 0.25 ACH, although considerably leakier than the target natural air change rate of 0.1 ACH. Also, the blower door tests showed that the control houses were significantly tighter than the anticipated rate (0.6 ACH).

One significant bias was encountered in application of the LBL model. Assessment of the appropriate terrain and shielding class parameters to use with the fan pressurization data is somewhat subjective. In 90% of the sites, the technicians recorded shielding and terrain class III—the central values. A summary of the audited terrain and shielding values is given in Table 1. Subsequent reevaluation of site specific data has shown that most often the terrain classes were type IV—typical suburban surroundings in developed areas, rather than class III, which represents the rural terrain type.

Unfortunately, photographs or site plans were unavailable with which to properly readjust each of the houses on an individual basis. However, based on an analysis of the sensitivity of the LBL model to this input assumption and the possible bias in the method with regard to wind-driven infiltration, we estimate that the mean and median air change rates estimated in Table 2 are too high by 11 to 19%. Accordingly, we have added a case to Table 2 that includes the results decreased by 11% to account for this influence.

Perfluorocarbon Tracer Gas Measurements

A subset of 225 MCS and control houses had in situ air change rates measured with the perfluorocarbon tracer gas (PFT) technique developed at Brookhaven National Laboratory [*4*]. According to the PFT measurements, the average as-operated air change rate of the MCS houses was approximately 0.35 ACH. Of course, this figure includes the ventilation

TABLE 2—*Estimated seasonal air change rates for RSDP houses from fan pressurization tests.*

Group	Mean	Standard Deviation	Median	Min	Max	No.
Control	0.55	0.26	0.52	0.06	1.59	331
Adjusted	0.49	0.23	0.46	0.05	1.42	
MCS	0.28	0.21	0.23	0.02	1.83	292
Adjusted	0.25	0.19	0.20	0.02	1.63	

supplied by the air-to-air heat exchangers, so it is impossible to determine the natural rate of ventilation for the energy-efficient houses from the PFT measurements.

Using a single continuous PFT test, the estimated average air change rate in the control group was 0.31 ACH during the period December through March of 1985–1986. However, the developer of the PFT test procedures has estimated that, due to nonuniform mixing and closed-off rooms in the MCS and control homes, the results of the PFT test should be increased by an average of 34% [5]. This adjustment results in an average estimate air change rate of 0.42 ACH for the monitoring period for the control group of houses. A rudimentary comparison of the corrected and uncorrected PFT and fan pressurization estimates is given in Table 3.

It is important to note that the two tests measure two different characteristics. The fan pressurization test determines the relative leakage area of the structure, not including mechanical or occupant-induced ventilation. Conversely, the PFT test measures the average concentration of the tracer gas over time. Since ventilation and the concentration of pollutants are inversely related, tracer gas techniques measure the time-averaged reciprocal of infiltration—the rate of dilution. This has been termed the "effective" ventilation rate. The reciprocal of the PFT average tracer concentration is proportional to the harmonic average of the hourly air change rates. The actual air change rate, however, is the arithmetic average of the hourly rates. Since the harmonic average of any set of numbers is equal to or less than the arithmetic average, the PFT estimated rate will be biased low.

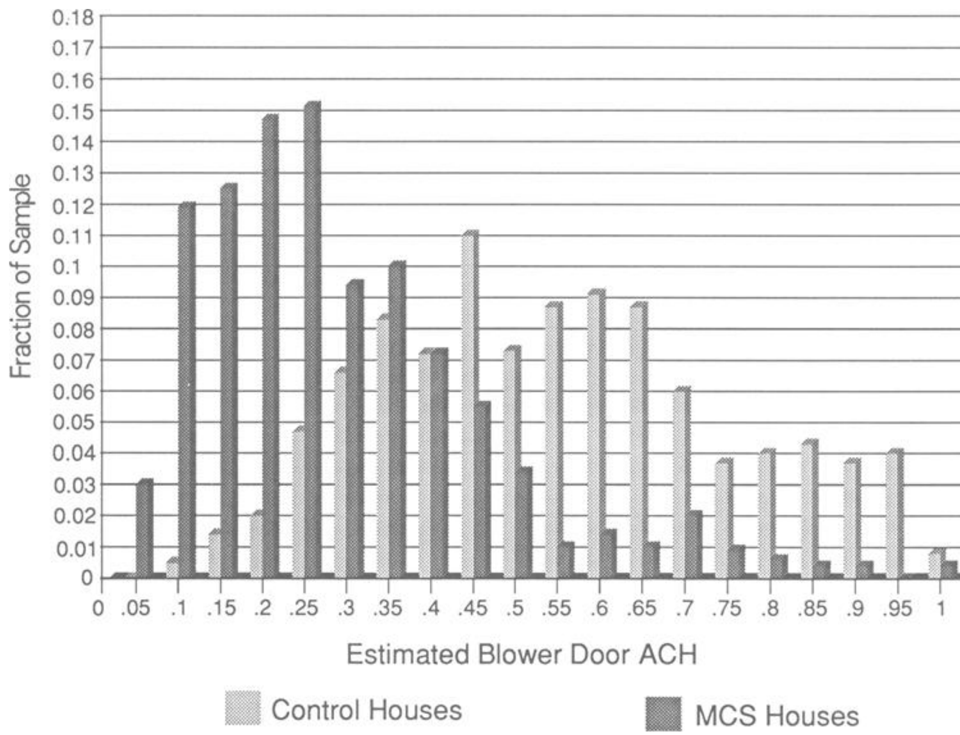
As a result, unless the ventilation rate does not vary during the test period, tracer techniques will tend to underestimate the average actual ventilation rate of the building [6]. The magnitude or this error depends on the fluctuation of the air change rate over the period of the test. We used the LBL model with average house characteristics to predict the underprediction resulting from variation in infiltration rate by comparing the difference in the estimated arithmetic average of the hourly air change rates to that of the harmonic mean. Using hourly Spokane, Washington typical meterological year data we found the underprediction to be only about 7%. However, since the concentration of pollutants are strongly related to the rate of dilution, the PFT estimates may be more appropriate with which to determine the impacts of house tightening on the indoor air quality.

Variation of Air Leakage in the Sample

Based on the data from both infiltration tests, we conclude that the typical RSDP control house will have an average air change rate of about 0.49 air changes per hour under normal weather conditions in the Northwest. This conclusion is generally consistent with another sample of residential buildings in the Hood River Conservation Project [7]. Both the LBL model and PFT test agree that the relative leakiness of Pacific Northwest houses varies tremendously. Figure 1 shows the blower door correlation estimated air change rates for the MCS and control houses. The shape of the two distributions are quite different. The MCS distribution is log-normal and reflects the fact that these houses were built to be tight

TABLE 3—*Comparison of fan pressurization and PFT air change estimates for the control group houses.*

Group	Mean ACH	Standard Deviation, ACH	Median ACH	No.
Fan pressurization	0.53	0.25	0.51	161
Adjusted	0.47	0.22	0.45	
PFT test	0.31	0.16	0.28	161
Adjusted	0.42	0.21	0.38	



FIF. 1—*Frequency distribution of estimated fan pressurization air change rates for control and MCS houses.*

and, more often than not, achieved that goal. However, as with the control group, there is a long tail of houses that did not achieve tight construction. The control group shows a more normal distribution. However, in either case, the air change rate of individual houses varies ten to one. Air leakage rates for the houses vary extraordinarily, even for the MCS houses that were designed to be tight.

The tremendous variation of air change rate, even on a seasonal basis, would seem to have implications for adequacy of infiltration air for ventilation in many homes. Many control houses that did not attempt tight construction still achieved very low levels of air leakage. Natural ventilation in these houses would not be sufficient for ventilation purposes on a seasonal level, much less on an hourly basis where the fresh air supply is dependent on varying weather conditions. Previous work has shown source strength to dominate indoor air pollutant concentrations, although analysis evidences a strong link to effective ventilation rates [*8*].

Variation of Airtightness with Heating System Type

We found the air change rates estimated by either test procedure to vary considerably depending on house heating system type. This is one of the most important results to be obtained from the RSDP data. Table 4 shows how the PFT air change rate varied with heating system.

This difference between the electric baseboard and electric forced air systems of 0.168

TABLE 4—*Average PFT air change rate*[1] *against primary heating system type control houses.*

Heating System	Mean ACH	Standard Deviation	Median	No.
Electric forced air	0.41	0.18	0.35	31
Baseboard electric	0.24	0.11	0.22	45
Radiant electric	0.22	0.11	0.24	10
Wood stove	0.18	0.20	0.17	4

[1]All rates are unadjusted.

($\pm$0.054)[2] ACH is statistically significant at better than a 99% confidence level. This represents an air leakage rate 70% greater in electrically heated houses with forced air heating systems than those without them. A previous study of infiltration rates in 31 East Tennessee homes found similar evidence of increased rates of air leakage in houses with forced air heating systems [*9*]. In that study, each time the duct fan operated the building infiltration rate nearly doubled (0.44 to 0.78 ACH).

The duct systems in RSDP houses with ventilated crawlspaces or unheated basements are located primarily outside the conditioned space. Only duct systems in houses with heated basement foundations had the air distribution system located primarily within the condition volume of the house. Since the blower door test will also pressurize the duct work in forced air houses, we would expect to see similar results for these structures. Evidence of this is seen in the values shown for the same sample for the blower door results in Table 5.

Although both estimating methods show that forced air heated houses are leakier than those with baseboard heat, the PFT test indicates a much greater level of magnitude in the differences. It is noteworthy that the LBL model has no way for accounting for the fact that leakage in the duct system is under considerably higher pressure differences that is leakage located in the building shell. The fraction of the leakage that is located outside the building shell effectively contributes to the air leakage rate. On the other hand, nonuniform mixing of interior air, a significant source of error with tracer gas measurements, is likely to be minimized in a forced air system.

A recent detailed study of residential duct leakage in the RSDP MCS and control houses found similar evidence of induced air infiltration [*10*]. The average air change rate, estimated by the LBL model, was 0.60 for ducted systems and 0.51 for nonducted ones.

Monitored consumption of space heat energy use in the RSDP houses follows the variation seen for air change rates. Houses with forced air heating systems showed normalized space heating budgets that were 15.9 ($\pm$7.3) kW/m^2 more than houses without forced air systems [*11*]. Furthermore, recent research in a hot-humid climate found similar evidence of induced ventilation from space conditioning systems [*12*]. Such results indicate that the interaction of air infiltration and space conditioning system operation in residential buildings is both significant and widespread.

Climatic Influences on the PFT Measurements

The period of December through March of 1985–1986 when most of the PFTs were in place was both warmer and less windy in the Pacific Northwest than the long-term average weather conditions. When the LBL model is used with average values for house volume, equivalent leakage area, and the actual Seattle weather data, the LBL algorithm predicts an average air change rate for the houses of 0.46 ACH. Thus, it appears that in the end the two tests can be shown to give average air change estimates within roughly 20% of each other provided that actual weather data are used and the PFT test procedures are carefully

[2]Uncertainty estimates are bounded by a 90% confidence interval.

TABLE 5—*Average estimated blower door ACH*[1] *against primary heating system type control houses.*

Heating System	Mean Value	Standard Deviation	Median	No.
Electric forced air	0.56	0.22	0.57	31
Baseboard electric	0.48	0.26	0.45	45
Radiant electric	0.56	0.36	0.53	10
Wood stove	0.65	0.22	0.61	4

[1] All rates are unadjusted.

executed. However, the disagreement on individual cases is very great and as yet unresolved. Figure 2 presents a scatterplot of PFT ACH versus that estimated by the fan pressurization tests. The data points are labeled by the heating system type. Visual inspection of the data shows similar values between the two tests on forced air systems, but substantial bias for zoned electric baseboard systems. An investigation is underway to examine some of the reasons for the rather extreme differences. This project, the Northwest Residential Infiltration Study (NORIS), is to be completed in 1989. Preliminary results from this study indicate that much of the differences may be explained by limitations in the procedure used to adjust airport windspeeds to site-specific windspeeds when applying the LBL model [*13*].

Influence of Physical Building Characteristics

Analysis of PFT and blower door test data showed significant differences around the four states. Specifically, results showed Oregon homes to be significantly less airtight than others. Idaho and Montana control houses appeared to be the most airtight. This is consistent with expectations since builders in colder climates are typically more familiar with tight construction techniques. The average blower door and PFT test results for the control houses in each state are compared in the boxplots in Fig. 3. The difference in Oregon homes from the rest of the sample is statistically significant in both blower door and PFT air change estimates at a 90% level.

The study also examined structural characteristics of the houses to see if physical features of the buildings could explain some of the variation in the air leakage data. Through the use of analysis of covariance techniques we were able to determine that houses with basements were less leaky than houses without basements. All nonbasement houses had ventilated crawlspaces in the sample. According to the LBL model, houses with basements for the control group had air change rates that were 0.100 ($\pm$0.078) ACH less than nonbasement structures. The same figure for the PFT test showed that the air change rates for basement houses were 0.072 ($\pm$0.065) less than nonbasement ones.

Building height showed the expected behavior in both samples. Due to the increased potential from the stack effect each additional meter of house height was associated with 0.0075 ($\pm$0.0054) additional air changes for the PFT tests. The coefficients for the LBL method were slightly higher due to the intrinsic use of the building height in that method's calculation of the air change rate.

We were also interested in whether the availability of bathroom fans might influence the PFT results. The analysis found no statistically significant difference at the 90% level between the PFT measured ACH of houses that did not have bathroom fans or did not use them and those who claimed to use the fans. This may indicate that bathroom fans, as installed, are largely ineffective.

We did find that houses with fireplaces were leakier than the rest of the group without this design feature. This was true both for the control and the more airtight MCS houses in both test procedures. Table 6 shows the blower door estimated air change rate for this

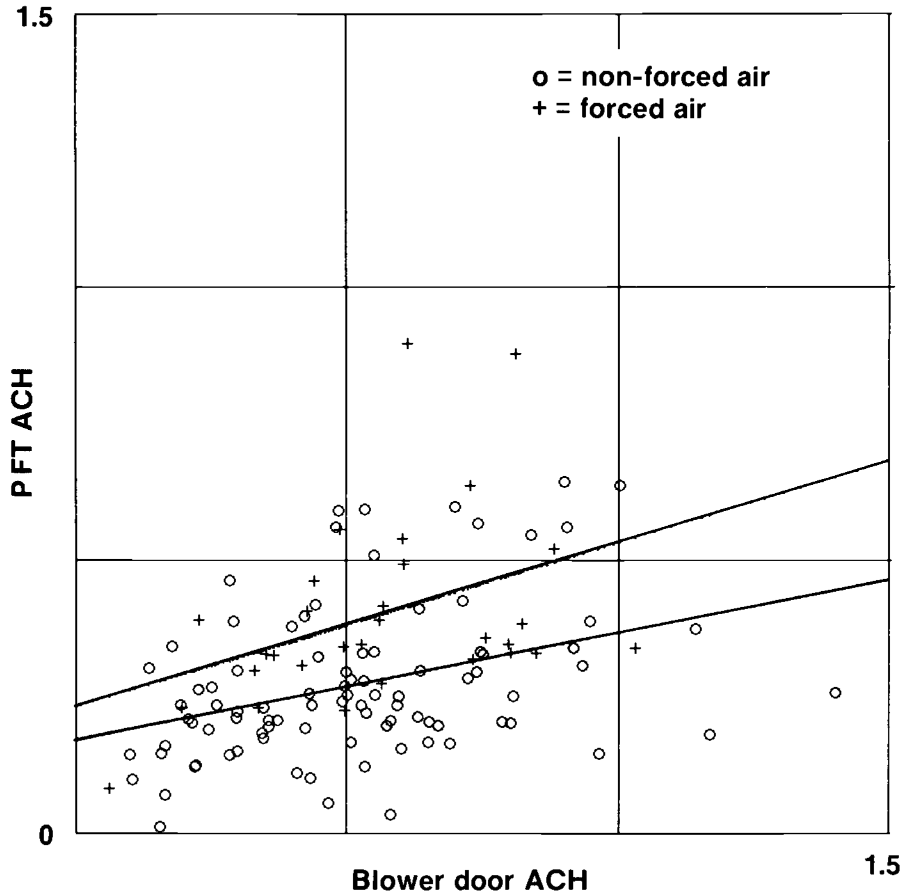


FIG. 2—*Comparison of fan pressurization and PFT air change estimates.*

analysis. According to the blower door estimates the houses with a fireplace will have a natural air change rate 0.064 (±0.043) ACH greater than those without one. The finding is significant at better than a 95% confidence level.

Adequacy of the Sample

The limitations of the data shown above should be understood when interpreting these results. An obvious limitation is the regional character of the data; it comes from the Pacific Northwest, which may be climatically dissimilar to other areas. Also, the RSDP project was not designed as a scientific experiment. The study group was not a probability sample; builders and occupants were self-selected, which may add bias to the estimates. Thus, we have no guarantee that the RSDP MCS demonstration homes actually represent what would be obtained for MCS houses from those more experienced with energy-efficient building techniques. Also, we know that a disproportionate number of builders of the control houses also built MCS houses in the RSDP program. This may have led to tighter construction for the control group than "current practice" dwellings since those builders were familiar with airtight construction practices. Consequently, we cannot be certain that the control houses actually represent current building practice in the Pacific Northwest.

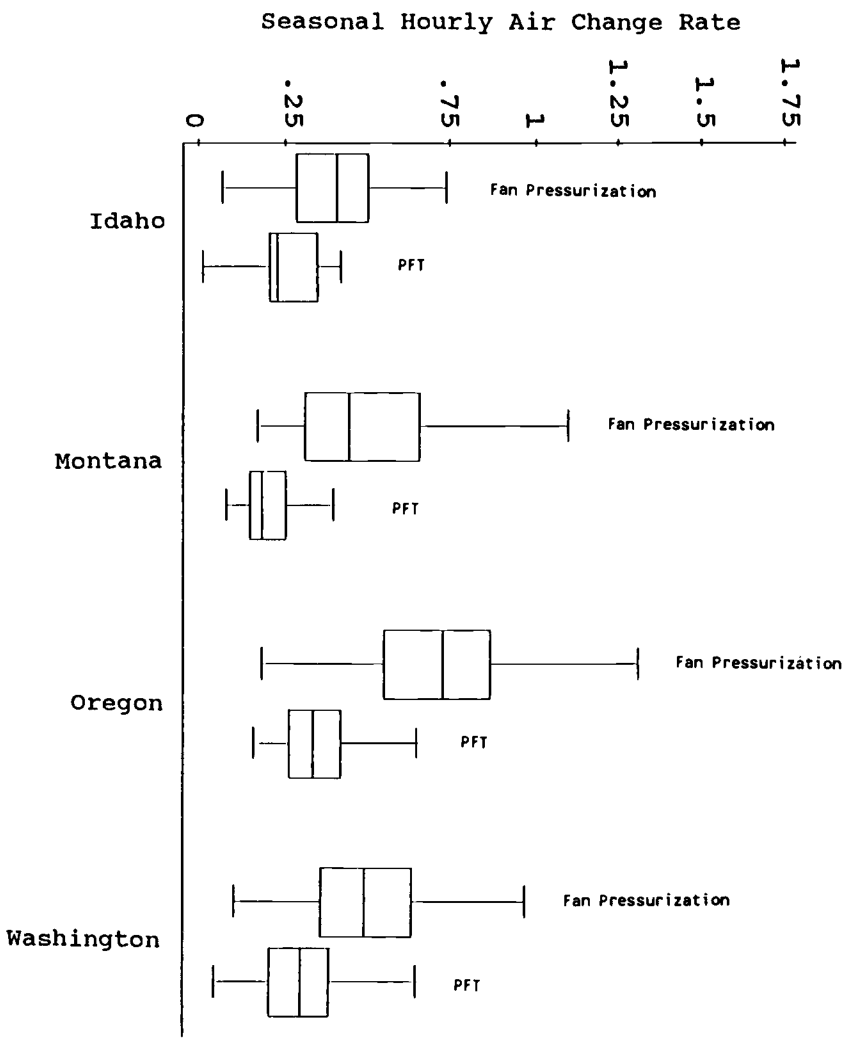


FIG. 3—*Fan pressurization and PFT air change rate estimates by state.*

TABLE 6—*Fan pressurization estimated ACH*[1] *against the presence of a fireplace control and MCS houses.*

Fireplace?	Mean	Standard Deviation	Min	Median	Max	No.
MCS						
Yes	0.31	0.24	0.05	0.26	1.83	69
No	0.27	0.20	0.03	0.22	1.26	223
Control						
Yes	0.60	0.26	0.21	0.56	1.44	97
No	0.53	0.26	0.06	0.50	1.59	234

[1]All rates are unadjusted.

Conclusions

Results from a large-scale monitoring project allow improved insight into the ventilation characteristics of energy-efficient houses in the Pacific Northwest. New current building practice houses may be more airtight than conventional wisdom might suggest. The RSDP control group of houses has an average air change rate of about 0.49 air changes per hour when using long-term normal weather data. The average for MCS houses using airtight construction techniques was approximately 0.25 ACH.

Air change rates in either group were extremely variable, with a range of nearly ten to one for either MCS or control houses. Housing characteristics identified as responsible for such variation included the presence of central forced air heating systems, basements, fireplaces, building height, and state-by-state differences in construction practices.

A central question raised by these findings is whether the level of airtightness in new housing being observed in this and other studies is acceptable from an indoor air quality perspective. Due to the observed variability in airtightness, we conclude that some mechanical form of ventilation may be necessary to insure recommended minimum levels of air change within residential buildings.

Acknowledgements

Special thanks to Alan Meier and Ed Vine of the Lawrence Berkeley Laboratory who prepared the database used in the analysis. Tom Eckman and Jeff Harris at the Northwest Power Planning Council provided additional assistance.

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DISCUSSION

P. Lagus (written discussion)—You ascribe the high air leakage rate determined by PFT technique in electric forced air houses as due to duct leakage. Why doesn't this enhanced duct leakage show up in the blower data determined for these houses? The blower door data didn't show significant differences between the four heating system types.

D. Parker (author's closure)—The major reason that the blower door technique does not show a greater difference between forced air and nonforced air systems is that the LBL model cannot account for the fact that leakage in the duct system is under considerably higher pressure than is leakage located in the building shell. To estimate air leakage rates, the LBL model assumes that all measured leakage is subjected to natural pressure differences arising from wind and thermal buoyancy effects. However, when operating, residential duct systems operate under pressures ranging from 25 to 75 Pa. Thus, leakage within the duct system is exposed to pressure differences that are an order of magnitude higher than commonly encountered weather-induced building shell pressures.

W. DeCups (written discussion)—Do you really think that the accuracy of your approach using the blower door and LBL model to produce air change rates can be compared with PFT results? In my opinion one uses much more detailed information on leakage distribution and pressured coefficient and a better model (than the LBL) to come to real comparisons.

D. Parker (author's closure)—The comparisons within the paper between the estimated air change rate using the PFT tests and that calculated from the LBL model are rudimentary and approximate. As previously described, the two tests measure different quantities. The PFT test measures the rate of dilution of a tracer gas over time in the building as it is operated. This includes occupant-related effects such as the opening of windows and doors, mechanical ventilation, and unintended infiltration increases from the operation of forced air distribution systems. On the other hand, the results from the blower door test are more indicative of relative building tightness. When coupled with weather data, however, the LBL model can be used to estimate natural air infiltration in an approximate manner. The LBL model does have some important drawbacks:

1. The algorithm represents a single zone model of building air infiltration and may not accurately account for multiple zone effects.
2. The model assumes that building air leakage is uniformly distributed about the building, only differentiating between horizontal and vertical leakage ratios.
3. Simplifying assumptions are made that relate the interaction of balanced and unbalanced flow components of overall building air leakage.
4. The model does not account for air exchange created by mechanical conditioning or ventilation systems.

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[2]POB 217, 2600 AE Delft, Netherlands.

5. No allowance is made for occupant-induced ventilation such as opening windows, doors, or fireplace dampers.
6. Use of the model with nonsite weather date requires a somewhat subjective assessment of applicable terrain and shielding classes.

Even so, previous comparison between tracer gas results and predictions from the LBL model show a reasonable level of agreement [2].

Peter S. Charlesworth[1]

Air Infiltration and Ventilation Centre's Guide to Air Exchange Rate and Airtightness Measurement Techniques

REFERENCE: Charlesworth, P. S., "**Air Infiltration and Ventilation Centre's Guide to Air Exchange Rate and Airtightness Measurement Techniques,**" *Air Change Rate and Airtightness in Buildings, ASTM STP 1067,* M. H. Sherman, Ed., American Society for Testing and Materials, Philadelphia, 1990, pp. 295–303.

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

Measurement techniques provide the fundamental means of acquiring a greater understanding of air infiltration and ventilation, in that they enable primary data to be obtained from existing structures. In recognition of the importance of measurement techniques, the Air Infiltration and Ventilation Centre (AIVC) has produced a document titled *Air Exchange Rate and Airtightness Measurement Techniques—An Applications Guide.*

The guide primarily examines the measurement of air change rate, interzonal airflow, and airtightness. The broad aims of this document are to indicate the variety of techniques which are available, to provide detailed information about several techniques, and to offer advice regarding the selection of techniques for particular applications. This paper describes the scope, structure, and content of this guide to air exchange rate and airtightness measurement techniques.

KEY WORDS: air change rate, interzonal airflow, airtightness, infiltration, measurement techniques, ventilation

The International Energy Agency (IEA) sponsors research and development in a number of areas related to energy. In the area of energy conservation in buildings, the IEA is funding various programs to predict more accurately the energy use of buildings. One such program is the IEA's Annex V, the Air Infiltration and Ventilation Centre (AIVC). This annex has particular responsibility for promoting a greater understanding of infiltration and ventilation in buildings.

Ventilation is the general term applied to the transport of air into, through, and out of a building. It is necessary to consider ventilation since it affects both the energy consumption and internal environment of a building. This may be promoted by natural or mechanical forces. Infiltration is the fortuitous leakage of air through cracks and gaps in the building fabric.

Infiltration is caused by pressure differences created by the dynamic action of the wind

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and differences in air density due to indoor-outdoor temperature differences. Therefore, infiltration can be viewed as uncontrolled ventilation.

Ventilation is a complex process which is influenced by a variety of constructional, behavioral, and environmental parameters. Because of these complexities, ventilation is often regarded as one of the least understood aspects of building physics. However, in recent years the development of several specialized measurement techniques has enabled the ventilation behavior of a large variety of buildings to be quantified.

Techniques are available which enable the flow rate of air into a building, under normal environmental conditions, to be evaluated. Methods also exist which allow the airflow rates between internal spaces to be measured. Evaluation of the overall airtightness of the building shell has become routine and, in some countries, mandatory. The location and distribution of air leakage sites can be determined, and the air leakage characteristics of specific building components or leakage paths can be evaluated.

Measurement techniques provide the fundamental means for acquiring a greater understanding of air infiltration and ventilation in that they enable primary data to be obtained from the evaluation of existing structures. In recognition of the important role practical methods play in air infiltration and ventilation studies, the AIVC has produced a guide to air exchange rate and airtightness measurement techniques. This paper describes the scope, structure, content, and use of the guide without presenting details of any specific measurement techniques.

General Scope And Structure Of The Guide

The information in the guide is presented in seven chapters:

1. Chapter 1: Selecting a Technique
2. Chapter 2: Measurement of Air Exchange Rates
3. Chapter 3: Measurement of Airtightness
4. Chapter 4: Equipment and Instrumentation
5. Chapter 5: Measurement Technique Standards
6. Chapter 6: Detailed Description of Measurement Techniques
7. Chapter 7: Detailed Description of Instrumentation

A glossary of terms relevant to air infiltration and ventilation measurements is also included.

The guide has been designed so that the material suited to any user's particular area of interest or current level of expertise is readily accessible. By examining the flow chart given in Fig. 1 (this figure appears at the beginning of the guide) readers can determine which parts of the document are appropriate to their requirements. For example, readers who are already familiar with measurement techniques may wish only to consult the detailed information presented in Chapters 6 and 7, whereas readers new to the field will find that the information presented in Chapters 2, 3, and 4 provides a basic introduction to the subject.

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

Selecting a Technique

Chapter 1 of the guide describes and discusses the parameters which are important in gaining a greater understanding of the ventilation behavior of buildings. These are:

Air Change Rate—This is a measure of the bulk movement of air into and out of a space and is defined as the volumetric rate at which air enters (or leaves) a space divided by the volume of the space. Measurements of air change rate enable a building to be assessed in terms of its ability to provide adequate ventilation for its occupants, and allows the energy

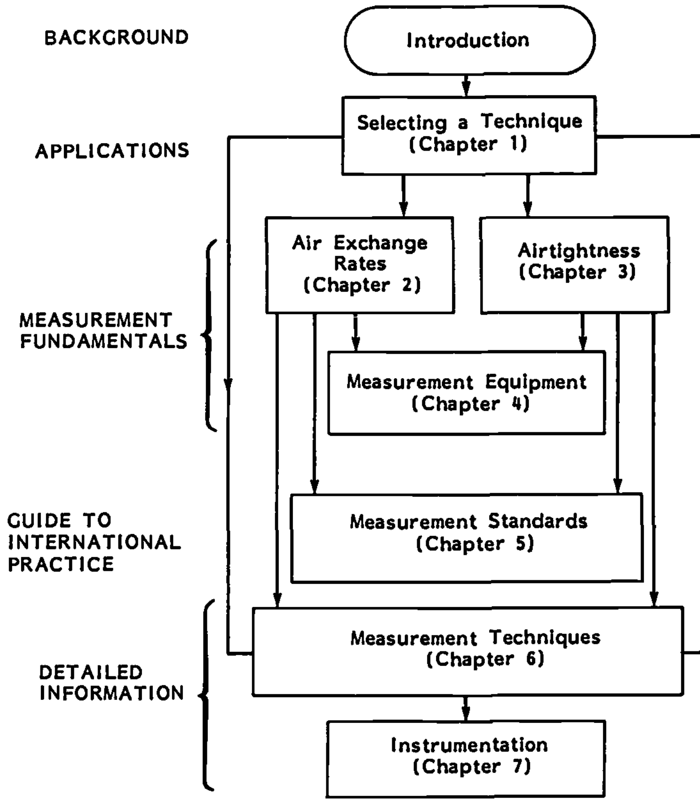

FIG. 1—*Scope and structure of the guide.*

loss due to infiltration and ventilation to be evaluated. The measurement of air change rate is examined in Chapter 2 of the guide.

Interzonal Airflows—The bulk movement of air into and out of a building causes air to flow between the various internal spaces of that building. This internal air movement plays a vital role in the distribution of pollutants throughout the ventilated space. Therefore, in order to gain a complete understanding of the ventilation behavior of a building it is desirable to know the rate of air exchange between the various internal spaces of the structure. The measurement of interzonal airflow is examined in Chapter 2 of the guide.

Air Leakage Characteristics—Air change rate and interzonal airflows are parameters which are themselves dependent upon a variety of factors. A basic approach in air infiltration and ventilation measurements is to negate the influence of many of these factors evaluating the air leakage characteristics of the building fabric only. In any building there are many potential leakage sites. These may be either adventitious or intentional. In order to assess the leakage performance of the building, it is necessary to determine quantitatively the relationship between the airflow through, and the pressure differential across, the leakage paths. The evaluation of air leakage characteristics is examined in Chapter 3 of the guide.

The main applications of infiltration and ventilation measurement techniques are also discussed in Chapter 1. The applications are presented in a series of flow charts that examine the following:

1. Fundamental data and research.
2. Standards.

3. Building diagnostics.
4. Indoor air pollution.
5. Ventilation efficiency.
6. Mathematical models—input and validation.

These flow charts provide the reader with a step-by-step guide to selecting the correct measurement technique for any given application. An example of this type of flow chart, taken from the guide, is shown in Fig. 2.

A series of tables provides summaries of the main measurement techniques examined by the guide. Techniques are grouped together according to the parameters which they evaluate, that is:

1. Air change rate methods.
2. Interzonal airflow methods.
3. Building envelope airtightness methods.
4. Building component airtightness methods.
5. Leakage location and qualitative methods.

These tables list the equipment required to perform the measurement, the actual quantities measured, and some of the factors affecting the selection of a particular technique. An example of this type of table is shown in Fig. 3. The tables and flow charts in Chapter 1 are all cross referenced with the main body of the guide.

Measurement of Air Exchange Rates

The fundamental theory and practice of measuring air exchange rates is presented in Chapter 2. Air exchange between a building and the external environment (air change rate) is examined as is the air exchange between the various internal spaces of a building (interzonal airflows). Air change rate is usually measured by injecting a single tracer gas into a building and measuring its concentration with time. There are three main variations of single tracer gas measurements:

Decay Rate Method—With this method, a one-time injection of tracer gas is made. The gas is allowed to mix with the internal air; this may be promoted by small electric fans or the building air handling system. The concentration of gas, over a given time interval, is then monitored with a suitable detector. The decay of the tracer gas in the building can be related to the air change rate.

Constant Emission Rate Method—With this method, tracer gas is injected at a constant rate into the building and its concentration with time monitored. The air change rate is inversely proportional to the measured concentration.

Constant Concentration Method—For this method, the concentration of tracer gas is held at a constant level within the building. This is achieved by providing a controllable variable flow rate of tracer into the building. The air change rate is proportional to the amount of tracer injected to maintain the concentration.

The detailed theory of each technique is presented and the practical solutions to the theory are discussed. For interzonal air flow measurements, multiple tracer gas methods are most often used. The multitracer gas versions of the three basic techniques shown above are examined.

Measurement of Airtightness

Chapter 3 presents the fundamental theory and practice of evaluating the air leakage characteristics of buildings and building components. There are two basic approaches to building envelope airtightness measurement:

D-C Pressurization—With this method, a uniform static under or over pressure is created within the building. The flow rate required to produce this pressure is measured, as is the pressure difference across the envelope. From a knowledge of these two parameters, the air leakage characteristics of the building can be evaluated.

A-C Pressurization—In this technique, a small varying pressure difference is created across the building envelope, using a piston-type blower door which can be distinguished from naturally occurring pressures. Because of this distinction the airflow through the envelope, due to the applied pressure differential, can be evaluated.

These two techniques are discussed in some detail. This chapter also contains a section describing the techniques used to located leakage sites in the building envelope.

Equipment and Instrumentation

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

Tracer Gases—Tracer gases are used in the measurement of air exchange rates. The guide discussed the desirable characteristics of tracer gas and provides information about gases which have been used in practice.

Tracer Gas Analyzers—The role of the gas analyzer is to determine, as accurately as possible, the concentration of tracer gas in a sample of air from the measured space. The guide provides information about commonly used analysis methods and offers advice regarding choosing an analyzer to make tracer gas measurements.

Commercial D-C Pressurization Equipment—Measurements of building envelope airtightness can be performed by using a fan which is temporarily installed in the building envelope. This type of equipment was developed initially as a research tool. Versions of this type of equipment are now available from several commercial organizations. This equipment is often known as a blower door. The guide discusses blower door design and provides detailed information about several commercially available blower door fans.

Instruments for Measuring Climatic Parameters—Many different climatic parameters can be measured. However, only those most relevant to infiltration and ventilation studies are considered by the guide. These parameters are wind speed wind direction and air temperature. This chapter is cross-referenced with Chapter 7, which contains detailed descriptions of several instruments.

Measurement Technique Standards

Several standards have been developed which relate to ventilation measurements. Chapter 5 discusses eleven selected standards from around the world. The criteria for selection is that they relate to site measurements of buildings or building components.

Two main groups of standards are examined:

Air Change Rate Measurement Technique Standards—The guide examines four standards in this category. Three deal with the decay rate method, and one standard covers the constant concentration method.

Airtightness Measurement Technique Standards—The guide examines seven standards in this category. Five deal with whole-envelope airtightness measurement, and two standards cover building component airtightness measurement. Brief summaries of the all the standards are presented and a comparison of similar standards is made (see, for example, Fig. 4).

Detailed Description of Measurement Techniques

Chapter 6 currently contains detailed descriptions of nine measurement techniques. Because the guide is presented in a loose-leaf format, updates of current techniques or infor-

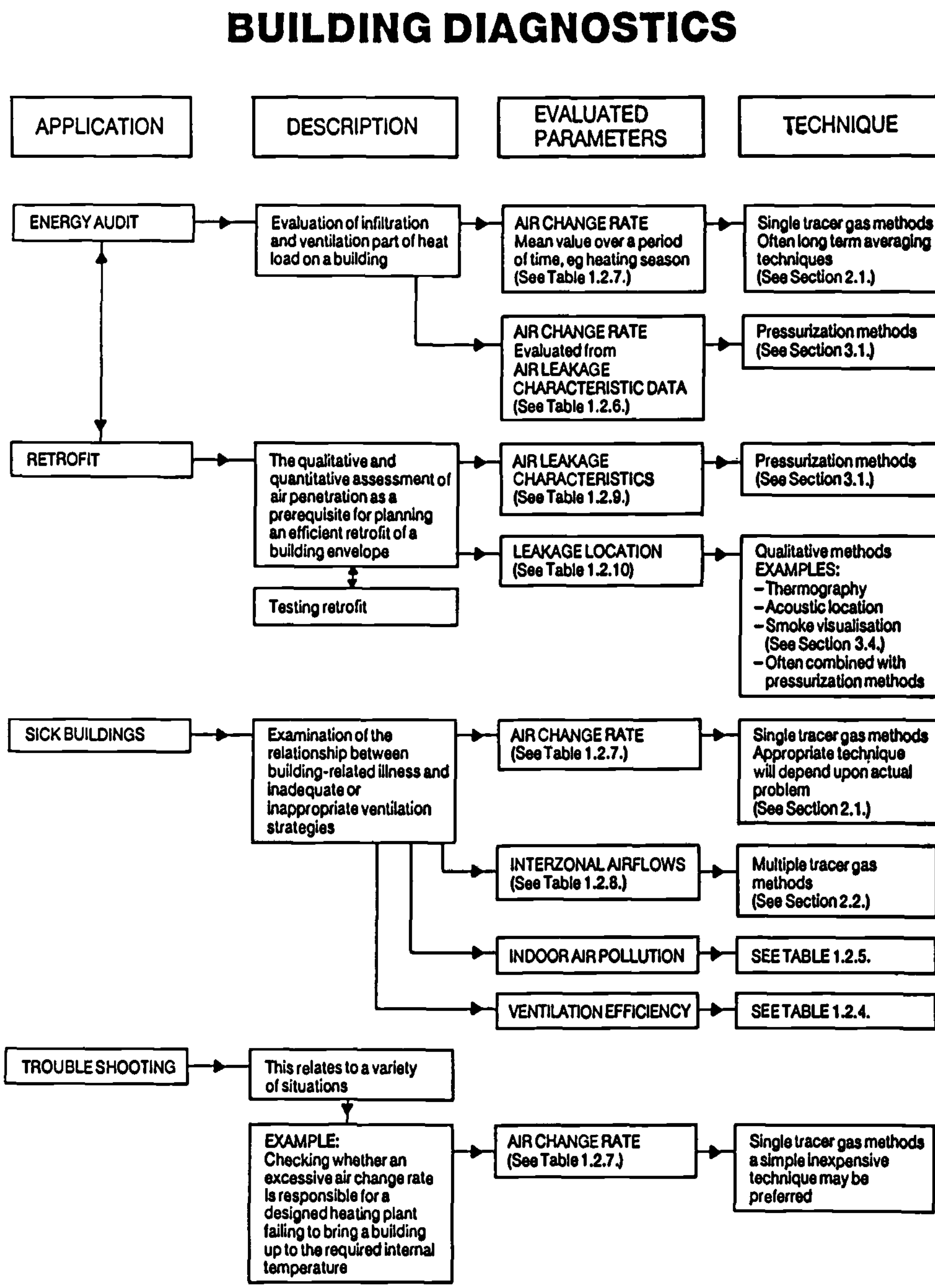

FIG. 2—*Example of an application and selection flow chart.*

BUILDING COMPONENT AIRTIGHTNESS METHODS

TECHNIQUE	EQUIPMENT	MEASURED QUANTITIES	FACTORS AFFECTING SELECTION
DC PRESSURIZATION COLLECTOR CHAMBER (Further details in Section 3.2.)	*ESSENTIAL* Collector chamber (Sealing box) Fan Flow rate measurement device Differential pressure measurement device *OPTIONAL* Second fan to balance pressure between collection chamber and room	Airflow rate through component Pressure difference across component Component dimensions	Relatively low cost method Ideal for examination of buildings which have a large number of replicated components Time and skill is required to adjust the collector chamber to a given component
DC PRESSURIZATION LABORATORY TESTING (Further details in Section 3.2.)	Test chamber Fan Flow rate measurement device Pressure differential measurement device	Airflow rate through component Pressure differential across component Component dimensions	High initial cost to build facility Good design allows many types of components to be tested Results may be 'better' than site measurements due to controlled workmanship
DC PRESSURIZATION REDUCTIVE SEALING (Further details in Section 3.1.1.)	Pressurization equipment (See Table 1.2.9.) Sealing products For example: plastic sheet Sticky tape	Air flow rate through envelope Pressure difference across envelope Building volume Degree of sealing (Type, number and location of sealed components)	Low cost method Patience and skill are required to seal components effectively Does not apply to components which cannot be isolated Similar work can be performed with AC pressurization
DC PRESSURIZATION Balanced fan (Further details in Section 3.2.)	Two or more sets of pressurization equipment (See Table 1.2.9.) Pressure differential measurement and control devices	Air flow rate through main test fan Pressure difference across test component Pressure difference across other partitions (Should be maintained at zero) Building volume	Increase cost due to more equipment Skill required to balance pressure differentials In complex buildings several sets of equipment (more than three) may be required or several sets of measurements must be made More susceptible to wind effect errors than single fan method
FLOW RATE METER (Further details in Section 3.2.)	*ESSENTIAL* Pressure compensating flow rate meter Flow collection chamber *OPTIONAL* DC pressurization equipment (See Table 1.2.9.)	Airflow rate through measured component Component dimensions	Can measure natural air flow rate through facade components Flow collection chamber does not have to provide an air tight seal Limited flow rate range Large leaks in facade cannot be evaluated Large internal leaks make pressure compensation difficult

FIG. 3—*Example of a measurement techniques summary table.*

mation about new techniques can be added easily. Information about each technique is presented in a standard format, thus aiding comparison and selection. The information in the standard format is presented in the following main sections:

1. Type of Technique
2. Range of Application
3. Equipment and Instrumentation
4. Setting Up and Operating Details
5. Presentation of Results
6. Measurement Accuracy
7. Availability of Measurement System

The guide currently contains detailed descriptions of the following techniques:

1. Tracer gas decay rate—site analysis.
2. Tracer gas decay rate—grab sampling (bottles).
3. Tracer gas decay rate—grab sampling (detector tubes).
4. Tracer gas constant emission rate—passive sampling.
5. Tracer gas constant concentration.
6. Multiple tracer gas decay rate.
7. D-C pressurization—external fan.

COMPARISON OF AIRTIGHTNESS MEASUREMENT STANDARDS

Standard	Recommended Fan Flow Capacity	Pressure Tap Location	Differential Pressure Range	Limiting Conditions	Expression of Results	Accuracy
CAN/CGSB -149.10-M86	Maximum 1.5–2.5 m^3s^{-1}	At least four taps around building leading to an averaging container	0–50 Pa underpressure	Windspeed < 5.6 ms^{-1}	Equivalent leakage area	Airflow ± 5% Δ P ± 2 Pa
NEN 2686	Maximum 1.2 m^3s^{-1}	One tap at building facade	15–100 Pa overpressure or underpressure	Natural Δ P across envelope < 5 Pa usually windspeed < 6 ms^{-1}	Flow coefficients Flow rate at 1 and 10 Pa in m^3s^{-1}	Airflow ± 5% Δ P ± 5%
SS 02 15 51	Sufficient to produce Δ P of 55 Pa	One tap 10 m from building ending in a T-piece	0–55 Pa over pressure and underpressure	Windspeed < 6 ms^{-1} 10 m from building	Air change rate at 50 Pa	Airflow ± 6% Δ P ± 3 Pa overall ± 10%
E779-87	Not stated	One tap location not stated	12.5–75 Pa overpressure or underpressure	Ideal windspeed < 2 ms^{-1} temperature 5–35°C	Plot of flow against Δ P Equivalent leakage area	Airflow ± 6% Δ P ± 2.5 Pa
DP9972	Sufficient to produce Δ P of 60 Pa	Ideally near neutral plane	10–60 Pa overpressure or underpressure	Natural Δ P across envelope < 3 Pa	Flow coefficients	Airflow ± 5% Δ P ± 5%

FIG. 4—*Example of comparison of measurement standards.*

8. D-C pressurization—internal fan.
9. A-C pressurization.

Detailed Description of Instrumentation

Chapter 7 contains descriptions of instruments which have been used in making some types of air exchange rate or airtightness measurements. The descriptions are presented in a standard format, and issues such as measurement method, precision, response time, input requirements, and possible applications are addressed. Information about three instruments is currently presented in this chapter: the infrared gas analyzer, the electron capture gas detector, and the electronic micromanometer.

Role of the Measurement Techniques Guide

The role of this guide is to increase general awareness of air exchange rate measurement techniques and their application. By providing the fundamental theory and practice of making measurements, and detailed information about several techniques, it is hoped to meet the needs of a wide range of readers. However, the following groups of people are specifically targeted by the guide:

Research and Academic—The guide will act as a directory of current techniques and will promote discussion about measurement techniques by research workers.

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

Nonspecialist Consultants—The guide will introduce measurement techniques to nonspecialist consultants, indicate the variety of methods available, and give advice as to where further information may be obtained.

The guide to air exchange rates and airtightness measurement techniques is available from the Air Infiltration and Ventilation Centre (AIVC) at: Barclays Venture Centre, University of Warwick Science Park, Sir William Lyons Road, Coventry, CV4 7EZ, United Kingdom.

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