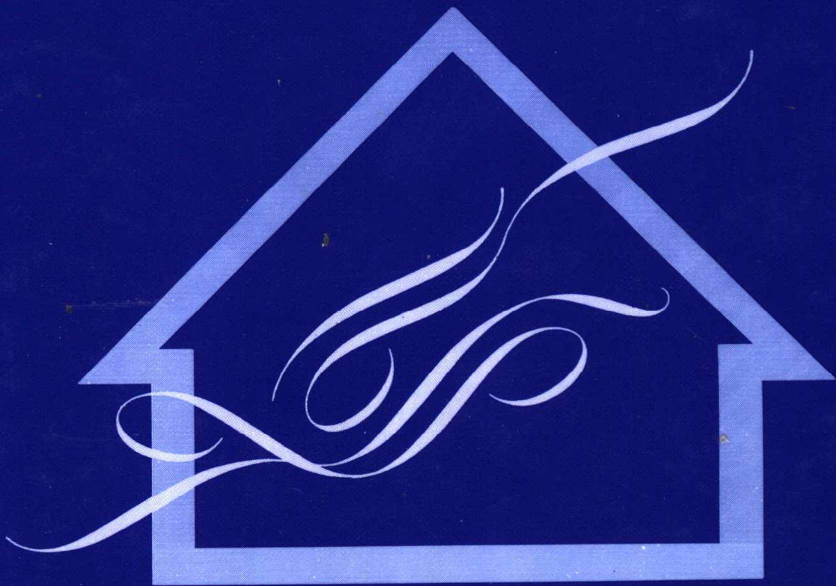
Air Change Rate and Airtightness in Buildings



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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.

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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.

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Tracer Gas Techniques

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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 m^3/h range, followed by a window opening at 17:10 hours, and then rapidly increased air infiltration to the ~150 to 300 m^3/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

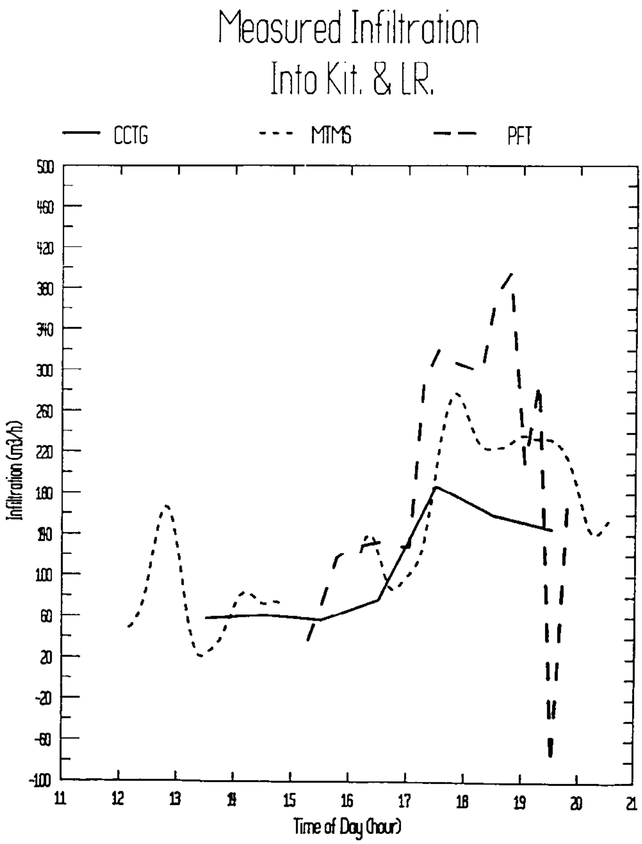

FIG. 2—*Three airflow measurement systems evaluating the air infiltration into Zone 3, kitchen and living room. Airflow changes have been introduced at several time intervals.*

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).*

Period Start Time	Action[a]	Infiltration Rate ± Standard Deviation, m^3/h: 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.*

Hour	Infiltration Rate, m^3/h: Zone 2 CCTG	Zone 2 MTMS	Zone 2 PFT	Zone 3 CCTG	Zone 3 MTMS	Zone 3 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).