AUTOMATED AIR INFILTRATION MEASUREMENTS AND IMPLICATIONS FOR ENERGY CONSERVATION

David T. Harrje - Center for Environmental Studies
Princeton University, Princeton, New Jersey 08540

Richard A. Grot - Center for Building Technology
National Bureau of Standards, Washington, D. C. 20234

ABSTRACT

In the average home approximately one third of the energy for space heating is lost through air infiltration. The driving forces for air infiltration often become more severe in larger buildings. Correlation of air infiltration with parameters that are building-related (cracks, seals, porosity, etc.), occupant-related (door, vent, window openings, etc.) weather-related (wind direction, and intensity, outside temperature, etc.) and terrain-related (nearby structures, trees, fences, etc.) has required the development of specialized monitoring equipment. Using sulphur hexafluoride as a tracer gas, using automated procedures for seeding the gas into the building, and measuring the subsequent concentration decay, air infiltration has been measured for a wide range of circumstances. The details of the instrumentation presented here include: injection procedures, sampling methods, detection of the appropriate gas chromatograph concentration peak, and recording the data on magnetic tape for easy retrieval for computer calculations. The data resulting from such air infiltration instrumentation uses are providing the basis for improved energy modeling in buildings, evaluation of energy conserving retrofits, new and old building inspection, and a better evaluation of other air infiltration measurement techniques.

INTRODUCTION

In general the energy losses or gains of a building can be categorized into three groups: conduction through the walls, ceiling and floors of the building envelope, fenestration (the transmission of heat through the window systems), and air infiltration. The theoretical understanding, and prediction of the first two catagories is relatively straightforward in principle, though often quite complicated in practice. However, at present there is no theoretical method for confidently predicting the amount of air infiltration within a building. The variables, both physical and behavioral, that effect the phenomena of air infiltration and natural ventilation are not only numerous, but also dependant on quantities that are difficult to measure and predict. Air infiltration can be caused by door and window openings; the passage of air through cracks around windows, doors, foundation seals, wall corners, wall/ceiling, and wall/floor interfaces; by the porosity of the walls, floors, and ceiling; by the leakage in the air distribution system; by the need of the dwelling for combustion air for the heating system, etc. Each of these parameters can be influenced by the weather, the choice of building materials, the quality of the building construction, and the use of the building. By utilizing instrumentation that involves the direct measurement of air exchange rates, it is possible to bypass the estimation, and prediction difficulties. This paper deals with an automated approach to infiltration measurement using the tracer gas method. Various uses of this equipment are described as well as the principles governing the equipment operation.

THE TRACER GAS METHOD OF MEASURING AIR INFILTRATION

One method employed for the determination of air infiltration has been the introduction, and mixing of a small amount of a tracer gas into the building with subsequent measurement of the decay in concentration as a function of time. The theoretical justification of this method can be understood by considering the equation.

$$\frac{dC_i}{dt} = (C_o - C_i)\,\frac{\dot{v}(t)}{V} + \sigma(t) \qquad (1)$$

where C_o and C_i are outdoor, and indoor concentrations of the tracer gas at time t, $\dot{v}$ (t) is the rate at which air enters (or leaves) the building; σ(t) is the rate per unit volume of production (or absorption) of the tracer gas inside the building, and V is the volume of the building. The quantity $\dot{v}/V$ is the air exchange rate of the building usually expressed in air changes per hour. Equation (1) is nothing more than a global conservation of mass equation for the gas tracer; however, it is based on the important assumption that the building is a single chamber in which the tracer gas is uniform throughout; i.e., there is perfect mixing. A discussion of the errors in the determination of air infiltration using Equation 1 when mixing is not uniform can be found in Ref. (1a). A theroretical treatment of the application of the multi-chamber method of determining air infiltration rates has been given by F. Sinden in Ref. (2).

For a suitable application of this method in the determination of air infiltration rates, it is usually necessary that the tracer be chosen such that both C_o and σ(t) can be neglected. In that case, Equation (1) reduces to

$$\frac{dC_i}{dt} = -C_i\,\frac{\dot{v}(t)}{V} \qquad (2)$$

Equation (2), and for that matter Equation (1) is directly intergrable to give

$$C_i(t_2) = C_i(t_1)\, e^{-\int_{t_1}^{t_2} \frac{\dot{v}(t)}{V}\,dt} \qquad (3)$$

The quantity $\dot{v}(t_2, t_1)$, defined by

$$\dot{v}(t_2, t_1) = \int_{t_1}^{t_2} \frac{\dot{v}(t)}{V}\,dt, \qquad (4)$$

is the number of air exchanges in the time period (t_2, t_1). Therefore, by measuring the concentration C_i of the tracer gas at times t_2, and t_1, it is possible to determine the total number of air exchanges in the building in the time period (t_2, t_1). Inverting Equation (3) gives

$$\dot{v}(t_2, t_1) = \ln[C_i(t_1)/C_i(t_2)] \qquad (5)$$

The average air exchange rate, AI, in the period (t_2, t_1) would then be determined by

$$AI \equiv \frac{\dot{v}(t_2, t_1)}{t_2 - t_1} = \frac{1}{t_2 - t_1} \ln[C_i(t_1)/C_i(t_2)] \qquad (6)$$

In practice one usually selects an initial time t_o, plots ln $[C_i(t)/C_i(t_o)]$ against time, and determines the air infiltration rate from the slope of the line. If changes in air infiltration rate are slow, this is an acceptable method. It should also be noted that it is not necessary to determine the absolute concentration in order to calculate the air infiltration rate provided the relative concentration $C_i(t)/C_i(t_o)$ can be determined accurately (1)(3).

CHOICE OF A TRACER GAS

The choice of tracer gas was made after considering candidate gas properties, the necessary gas volumes, and the concentrations required to conduct studies without occupant safety problems over a period of days. The development of the extremely sensitive electron capture detector by Lovelock (4,5), and the observation that sulfur hexafluoride, SF_6, can be measured to concentration levels of the order of one part per billion in air by this technique (6), answered the requirements. Because SF_6 can be measured in minute concentrations, this gas has come into increasing use as a tracer of air movements (7,8,9). Indoor use for ventilation studies is also common (10,11,12). Besides the high sensitivity with which SF_6 gas can be measured, it is stable, inert, and nonflammable. It is not a normal background constituent of air. The gas is non-toxic in the concentrations used in tracer measurements (normally 5-30 ppb) and not highly toxic even when present as a major constituent in air, thus inadvertent loss of a one weeks supply of SF_6 would pose no danger to house occupants (factor of safety ~1000).

However, even though generally satisfactory, there are certain problems which must be considered using SF_6 as a tracer. The detector unit may require frequent calibrations to maintain the desired accuracy. Also, because of the high sensitivity of the measurement, minor leaks in regulators, valves, and connections which would go unnoticed in other gas measurement systems are completely unacceptable when SF_6 is used as an indoor tracer. In order to obtain the necessary high sensitivity, a gas chromatograph is used. This means that measurements are in the form of chromatographic peaks which may require more effort to automate, and data process than a continuous output. Although SF_6 is not normally present in air, the detector responds to other halogenated compounds such as certain refrigerants, and propellants used in aerosol spray cans. These compounds occasionally appear in the indoor background. Also, certain insecticides, and herbicides are halogenated compounds and can be present in the outside air at certain times of the year. In general, it is possible to detect the presence of these substances if care is taken in the analysis of the data.

AN AUTOMATED INSTRUMENTATION SYSTEM FOR MEASURING AIR INFILTRATION

For several years researchers at Princeton University, and the National Bureau of Standards have been working collaboratively on the development of a compact portable air infiltration measurement system. Descriptions of earlier versions of the equipment can be found in Refs. (1b), and (3). The present automated air infiltration unit consists of an electron capture detector, an automation unit (utilizing 12 printed circuit boards) an SF_6 storage and injection panel, a cassette recorder, and corresponding plumbing and tanks. The automation unit controls a series of valves which at periodic intervals sample air from one of two locations. The unit detects the first peak of the current after the zero crossing of the oxygen peak on the chromatograph and records on the cassette: the time in hours, minutes, and seconds; the standing current; and the peak current. The periodic intervals for sampling are selectable at either 2, 5, 10, or 15 minute intervals. The sampling from Port B (referred to as the standard) can be either 1 minute after each sample of Port A (switch position ALTERNATE) or once an hour. The injection of SF_6 into the dwelling can be set to occur either once every three hours or when the level of SF_6 is such that the peak current is above a selectable value.

The data are recorded on the magnetic tape cassette in ASCII, even parity at 1200 BAUD, and can be played back from the same recorder at 110 to 2400 BAUD into a computer or printed on a terminal with a RS232C interface. When used in conjunction with a terminal in a time sharing system employing ASCII code, the cassette acts as a paper tape reader (the instruction manual for both computer system, and cassette system provides the necessary details). A photograph of the automated air infiltration unit is shown in Fig. 1, and a schematic of the overall system is given in Fig. 2.

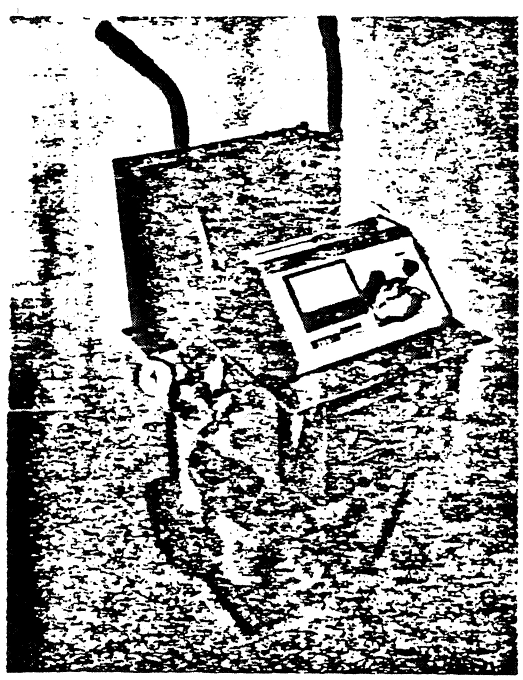

Fig. 1 AUTOMATED AIR INFILTRATION UNIT

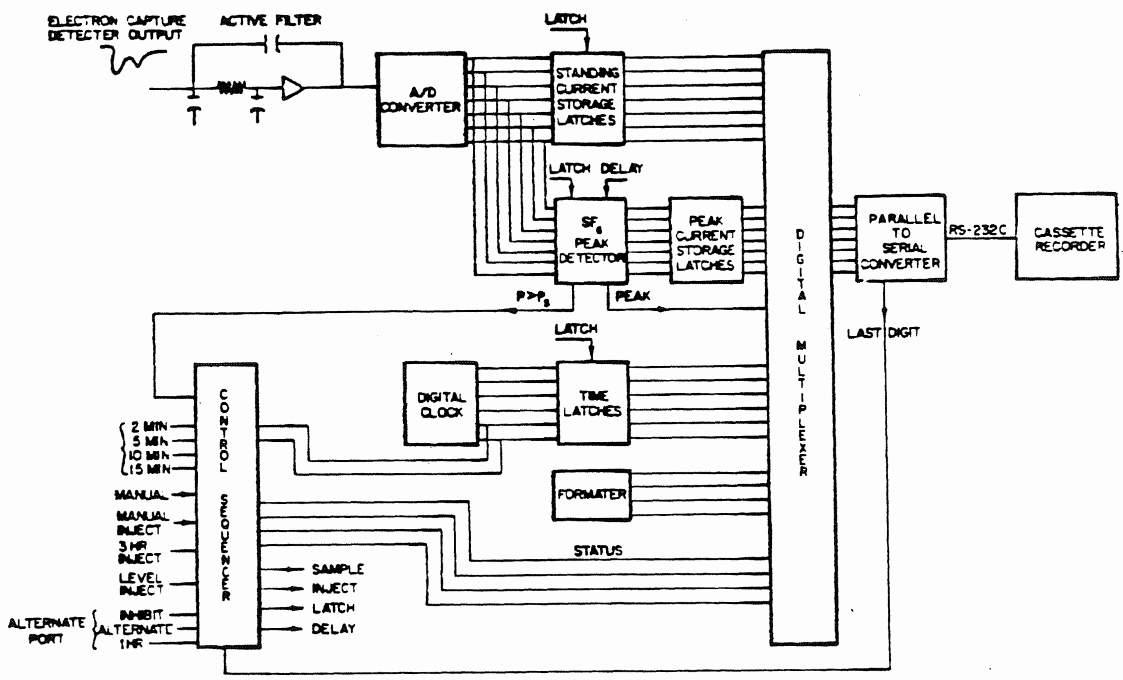

FIG. 2 SCHEMATIC OF AUTOMATION UNIT

EFFECT OF AIR INFILTRATION ON DWELLING ENERGY CONSUMPTION

As stated in the introduction, air infiltration is one of the major components of building energy losses. The automated air infiltration equipment, together with fuel consumption measurements and weather data, allows one to quantify the loss breakdown (1)(3). As an illustration of this procedure consider the set of data presented in Table 1 for a townhouse. The data in column 1 are the Julian date for the year 1975. The data in columns 2,3, and 4 are the average rate of gas consumption (cu.ft/hr.), the average temperature difference (degree F), and the average air infiltration rate for the time period 9 P.M. to midnight for each day. If one attempts to explain the observed gas consumption by a model of the form

$$G = K_1 + K_2\,\Delta T + K_3\,AI\cdot\Delta T \qquad (7)$$

then by using standard regression analysis techniques, 96% of the variation* in the gas consumption can be explain-

TABLE 1 Townhouse Energy Data for 26 Evenings

DAY	GAS Ft^3/H	ΔT °F	AI	$AI\cdot\Delta T$	RESIDUAL
31	25.3	45.0	.52	23.3	-.2
32	25.8	45.5	.55	25.0	-.7
33	30.5	45.8	.62	28.4	2.2
34	31.4	46.5	.60	27.9	2.8
44	44.2	54.8	.94	51.5	-1.4
45	36.6	50.0	.68	34.0	2.6
46	20.0	42.2	.54	22.8	-3.0
81	2.8	27.5	.41	11.3	-3.9
82	19.9	40.0	.58	23.2	-1.7
83	61.6	47.0	1.89	88.8	4.7
84	48.1	49.0	1.59	77.9	-5.3
85	36.6	42.6	1.36	57.9	-2.8
91	15.9	36.6	.59	21.6	-2.4
92	24.7	39.5	.65	25.7	2.4
93	29.6	39.9	.73	29.1	5.4
98	2.0	19.3	.49	9.5	2.2
99	17.6	31.7	.73	23.1	2.3
100	21.2	36.9	.69	25.5	.9
101	21.9	36.0	.86	31.0	-.2
102	6.5	24.0	.60	14.4	1.1
105	16.3	30.0	.82	24.6	1.6
106	9.0	30.8	.53	16.3	-2.5
107	5.5	23.8	.60	14.3	.1
108	11.5	29.5	.70	20.6	-1.0
118	.8	22.3	.47	10.5	-1.7
119	.8	15.5	.48	7.4	4.8

* The inclusion of only the temperature difference ΔT can explain only 77% of the variation.

ed with the constants K_1, K_2, K_3 given by

K_1 = -19.0 (± 2.4)

K_2 = 0.75 (± .08)

K_3 = 0.45 (± .04)

with a standard error of 3.1 cu. ft. of gas per hour. If one considers the last two terms of Equation (7) as the heat losses to the dwelling, then for the period of time of the collected data, 32% of the dwelling heat loss was due to air infiltration. The first term can be interpreted as the internal heat gain to the dwelling. The size of this term can probably be attributed to the time of day the data was collected. The standard error of 3.1 cu.ft. of gas per hour can be attributed to the transient operation of the heating system. Normally one cycle of furnace operation consumes about 10 cu.ft. of gas, thus a difference of one cycle of furnace operation in the period of 3 hours from 9 P.M. to midnight can account for the standard error.

The last column in Table 1 is the difference between the actual measured value of the gas consumption, and the value predicted by Equation (7) (referred to as the residual).

FIELD USES

The automated air infiltration can be used in a number of ways to obtain the necessary field data. These applications include: detailed monitoring, event-triggered sampling, bag sampling and cross checking alternative techniques.

In the case of detailed monitoring in buildings using warm air heating/cooling, the air infiltration unit is placed near a central air return register, or the sampling probe is inserted into the return ducting at the furnace. Such placement uses constantly circulating duct air as a means of mixing the tracer gas throughout the building. This method of mixing has been found to be quite suitable in maintaining uniform tracer gas concentration, and thus providing data on the overall building performance (1) (3). Sampling is performed using one or two ports (e.g. living space and basement) and a choice of sampling interval. Concurrent weather, and fuel consumption data must be obtained for the detailed weather-energy-air infiltration correlations.

One also has the choice of event-triggered sampling using the same air infiltration equipment. This method may be preferred if prolonged operation of the furnace blower tends to increase air infiltration through living space pressurization or duct air losses in duct locations outside the living space. Timing for air infiltration sampling would rely on the natural furnace blower cycle, and occur at blower cut off so as to optimize prior mixing. Naturally, this technique restricts the number of individual concentration measurements obtained, but under normal heating system cycling this method will provide one or more data points per hour. Tracer gas injection under such operation must also be timed with the furnace cycle in mind, in that case initiated by the "fan on" condition, to promote mixing after injection.

Sampling a large number of buildings (or individual rooms in one building), even though the portability of the air infiltration equipment has been emphasized in the design*, can be more easily achieved through the bag sampling method. In this approach to air infiltration measurement, the building is seeded with tracer gas (SF_6 for this equipment, at initial concentrations of about 30 parts per billion). Using duct blower for mixing, the tracer gas is introduced into the building over several minutes to avoid local high concentrations, and thus speed the process of achieving concentration uniformity. Lacking a blower system, one depends upon portable fans to aid mixing. After approximately 20 minutes one is ready to take the first sample.** In the central duct system the sample is taken from the return duct. In the

* There are battery powered SF_6 detectors now available if one desires to take meter-read concentration data on site.

** Data from Ref. (3) indicates that the SF_6 concentration has become stable by that time.

non ducted building the sample bag may be filled by sampling each of the rooms in the building to obtain an average concentration. An hour or two later (so that sufficient time has elapsed for a noticeable concentration decay) a second bag sample is taken. Now the bags may be routinely analyzed with the SF_6 detection equipment operating under laboratory conditions, no SF_6 present. Using Equation (6), air exchanges per hour are calculated. Employed in this manner the automated unit with digital display can rapidly analyze a number of sample bags. One minute per sample, on the unit, plus the time to attach the bag, results in approximately 5 minutes total per sample even if a triple check of the concentration level of the bag contents is desired. As with any of the other infiltration measurement techniques a knowledge of the prevailing weather over the time of sampling is necessary to place the air infiltration level in proper perspective.

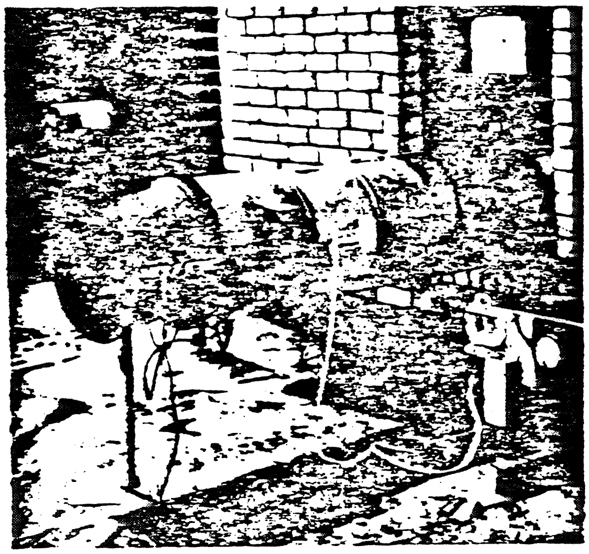

FIG. 3 WINDOW BLOWER UNIT

Another application of the automated air infiltration unit is to use it in conjunction with another method of air infiltration measurement as a cross check. One example is using the unit to establish the rate of air removal from a building that is being evacuated through use of a powerful window or door blower as shown in Fig. 3 (13)(14). Here the total test time rarely exceeds one half hour. Such a test series is shown in Table 2 where the air exchange rate per hour is shown to average 6.1.

This compares to a blower flow rate measured with a 16 pitot tube air flow calibration system, which taking into account house volume, resulted in 6 air exchanges per hour. Such tests serve the purpose of double checking air flow calibrations for both methods. The blower technique is a rapid method to establish origins of air infiltration. The tracer gas approach rates the dwelling as to actual infiltration rate under weather, building, and user events. The methods serve to compliment each other in the quest for cataloging, and understanding the air infiltration component of energy consumption.

TABLE 2 Tracer Gas with Blower Operating

Data				Calculated	
Date	Time	I_o	I	I_o/I	$\ln I_o/I$
*22	11:04:00	0.400	0.075	Injecting*	
22	11:06:00	0.399	0.099	4.030	1.394
22	11:08:00	0.400	0.131	3.053	1.116
22	11:10:00	0.400	0.164	2.439	0.892
22	11:12:00	0.400	0.187	2.139	0.760
22	11:14:00	0.400	0.212	1.887	0.635
22	11:16:00	0.400	0.247	1.619	0.482
22	11:18:00	0.400	0.269	1.486	0.397
22	11:20:00	0.400	0.291	1.375	0.318
22	11:22:00	0.401	0.313	1.281	0.248
22	11:24:00	0.400	0.329	1.216	0.195
22	11:26:00	0.400	0.343	1.166	0.154
22	11:28:00	0.401	0.354	1.133	0.125
22	11:30:00	0.401	0.361	1.111	0.105
22	11:32:00	0.401	0.370	1.084	0.080
22	11:34:00	0.401	0.376	1.066	0.064

6.10 air exchange based on unit calibration and 11:06 to 11:34 time interval

DATA INTERPRETATION

The digital data on the magnetic cassette contains all the necessary information as to time, date, sampling location and whether or not injection of new SF_6 is taking place. Often the data are plotted as air exchange rate versus time as shown in Fig.4 . Even without calibration refinements these data clearly represent the air infiltration history of the townhouse under study, where the variations indicate when SF_6 was injected. The test home was previously retrofitted, and infiltration rates are relatively low.

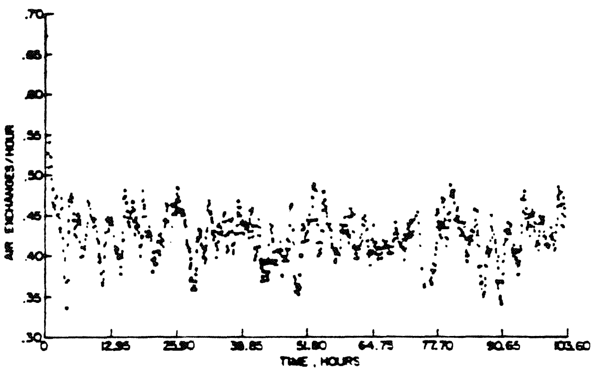

Fig. 4 TYPICAL CASSETTE PRINTOUT OF AI VERSUS TIME

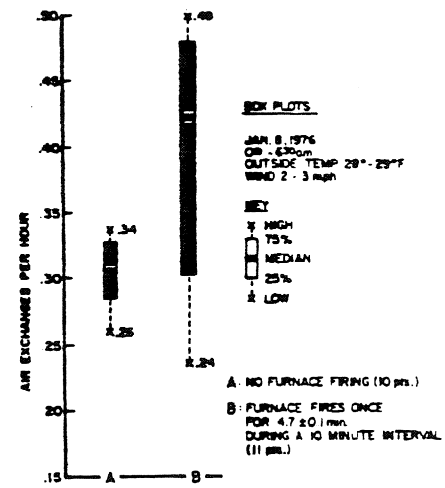

Fig. 5 AIR INFILTRATION & FURNACE FIRING

Air infiltration data may also be used to answer detailed questions that long have plagued energy estimates. Fig. 5 shows box plots of air infiltration rates with the furnace on and off in another retrofitted home. The automated data collection has served to pinpoint the additional >.1 air change per hour resulting from furnace operation that involves fuel combustion and induced air flow. Such data support the case for closed cycle furnace designs to conserve energy.

CONSERVATION IMPLICATIONS

Using the automated air infiltration equipment to monitor winter, and summer air infiltration in the Twin Rivers townhouses (15) it was shown that the average energy losses from air infiltration were between 30 and 40% during the heating season, but were less than 7% in the same townhouses in the summer. Thus weather influences on air exchange rates and hence energy were very evident. High wind conditions were shown to raise winter energy losses due to air infiltration to more than 60% of the total.

In the process of retrofitting those same townhouses, the use of air infiltration monitoring, and careful attention to the prevailing weather, has allowed quantitative measurements to be made of retrofit procedures. As energy supplies continue to become more critical the use of air infiltration measurements to document retrofits could become a vital part of the residential energy conservation program. In the future, building inspection, and load determination to establish the level of air infiltration energy losses, could use the automated equipment in either of two modes. One approach is monitoring air infiltration with or without external blower systems operating over a short time span. The second approach is the bag analysis method, previously described, where samples could be taken over a period of an hour or two from a number of building room locations. Building air infiltration inspection, automated or bag sample, has clear energy conservation significance.

Another aspect of infiltration measurement that cannot be over-looked is knowledge gained for future housing designs. Air infiltration standards must allow a certain minimum amount of air exchange in residential as well as commercial buildings and schools. Up to this point it has been a struggle to reduce the air infiltration losses in existing dwellings to levels that approach this lower limit. However, in new construction, using new materials, and improved vapor barriers, provision must be made to retain reasonable air exchange rates (16). The use of the monitoring equipment described in this paper will help document achievements in the reduction of air infiltration in new housing.

The analytical modeling of energy use

in buildings requires an accurate assessment of each component of energy loss. Air infiltration measurements play an important role in making the analytical modeling realistic (13). Not only does air infiltration influence, and at times dominate, the energy appetite of the building, but other portions of the structure, such as the attic, heavily rely on air exchange rates to establish local temperature conditions (17). Thus, analytical modeling of buildings also can be shown to be highly dependent upon quantitative measurement of air exchange rates, and infiltration.

ACKNOWLEDGMENT

The authors wish to thank ERDA, and NSF-RANN for support of this research effort. We also are indebted to Mr. Kenneth Gadsby for his devotion to the development, and deployment of the automated air infiltration units, and his field work in Texas. We also wish to thank Garry Caffey of Texas Power and Light for his cooperation in the blower-tracer gas studies.

REFERENCES

1.a C. M. Hunt, D. M. Burch, "Air Infiltration Measurements in a Four Bedroom Townhouse using Sulphur Hexafluoride as a Tracer Gas," ASHRAE Trans. 81 (1) pg. 1860291 (1975)

1.b C. M. Hunt, S. J. Treado "A Prototype Semi-Automatic System for Measuring Air Infiltration in Buildings using Sulphur Hexafluroide as a Tracer," NBS Tech. Note 898 (1976)

2. F.W. Sinden "Multi-Chamber Theory of Air Infiltration", accepted for publication in Building and Environment, Pergamon Press, London

3. D. T. Harrje, C. M. Hunt, S. J. Treado and N. J. Malik "Automated Instrumentation for Air Infiltration in Buildings", Princeton University, Center for Environmental Studies Rpt. No. 13 (April 1975)

4. J. E. Lovelock, Institute of Petroleum, Gas Chromatography Discussion Group, (May 1957).

5. J. E. Lovelock, "Electron Absorption Detectors and Technique for Use in Quantitative Analysis by Gas Chromatography", Anal. Chem. 35. 474-491 (1963).

6. N. L. Gregory, "Detection of Nanogram Quantities of Sulfur Hexafluoride by Electron Capture Methods", Nature Oct. 16, 1972.

7. B. E. Saltzman, A. I. Coleman, and C. A. Clemons, "Halogenated Compounds as Meteorological Tracers", Anal. Chem. 48 (6). 753-758 (1966).

8. A. Turk, S. M. Edmonds, H. C. Mark, and G. F. Collins, "Sulfur Hexafluoride as a Gas Tracer", Env. Sci. & Tech. 2 44-48 (1968).

9. R. N. Dietz, E. A. Cote, and G. J. Ferber, "Evaluation of an Airborne Gas Chromatograph for Long Distrance Meteorological Tracing", American Chemical Society, Division of Water Air and Waste Chemistry. Preprint of Papers Presented at 165th National Meeting, Dallas, Texas, April 1973 13 (1). 5-11 (1973).

10. "Natural Ventilation for Fallout Shelters", Dept. of Architectural Engineering and Institute for Building Research, Pennsylvania State University (1966) prepared for Office of Civil Defense, Dept. of Army, GSA Subcontract No. B-64201-U.S., Subtask 1231B.

11. L. Rubin and R. Gittins, "The Use of a Portable Gas Chromatograph and Tracer Gas for the Determination of Air Ventilation Rate", Panametrics Company Report.

12. P. J. Drivas, P. G. Simonds, and F. H. Shair, "Experimental Characterization of Ventilation Systems in Buildings", Env. Sci. & Tech. 6 (7), 577-666 (1972).

13. D. T. Harrje, C. Caffey and K. Gadsby "Tracer Gas and Blower Approaches To Air Infiltration Measurement - Field Stydy", Princeton University, Texas Power & Light (Report in preparation.)

14. S. Stricker, "Measurement of Air-Tightness of Houses", ASHRAE Trans. 81 (1) pg. 148-167 (1975).

15. D. T. Harrje, "Retrofitting, Plan Action and Early Results Using the Townhouses at Twin Rivers", Princeton University Center for Environmental Studies Rpt. No. 29 (June 1976).

16. W. Winkelstein Jr. "Air Quality Inside Bukldings Subject to Stringent Energy Conservation Measures", Lawence Berkeley Laboratory (April 1975).

17. G. S. Dutt, J. Beyea, "Attic Thermal Performance - A Study of Townhouses at Twin Rivers", Princeton University Center for Environmental Studies Rept. (June 1977).