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AIR INFILTRATION SITE MEASUREMENT TECHNIQUES

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Abstract

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

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1. INTRODUCTION

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

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

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

The tracer gas technique is the method most widely used for determining the actual air infiltration rate at a specific instant of time in the building. The use of a tracer gas, as the name implies, provides a method by which the air in the building can be tagged and thus identified so that an accounting can be made as to how much outdoor air replaces it. Only a small quantity of tracer gas is required, usually at concentrations in the parts per million, parts per billions and sometimes in the parts per trillion range. A wide choice of tracer gases is available today but based on the criteria of detectability, safety, simplicity, quantity and cost certain gases have proven to be preferable. Some common choices are sulphur hexafloride (SF_6), nitrous oxide (N_2O), carbon dioxide (CO_2), and ethane (C_2H_6). This paper discusses the various types of methods and equipments now in use in various parts of the world for the measurement of air infil^^tration by the tracer gas technique. Automated equipment for measuring the air infiltration rate by the decay (dilution) method, the continuous flow method and the constant concentration method developed by laboratories in the United States, Canada, the United Kingdom, Sweden, Denmark and Switzerland are described. Two simple and inexpensive techniques developed in the United States which do not require the deployment of on-site gas monitoring equipment are described. The first, called the air sample bag or container method, uses air grab samples collected after the injection of the tracer and which are analyzed in the laboratory for determination of the air infiltration rate by the dilution method. The second method, called an averaging infiltration monitor (AIM) by its developers at LBL, uses a constant injection/constant sample techinque to provide a measure of the average air infiltration rate experienced by the building over an extended period of time.

2. THEORETICAL BASIS FOR THE MEASUREMENT TECHNIQUES

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

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

where:

C_o, C are the outdoor and indoor concentrations of the tracer at time t

v(t) is the rate at which the air enters (or leaves) the building

f(t) is the rate per unit volume of production (or absorption) of the tracer gas inside the building

V is the volume of the building.

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

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

where:

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

and $C_1 = C(t_1)$.

Decay (Dilution) Method

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

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

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

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

where $DT = t-t_1$

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

Constant Flow Mode

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

$$C(t) = C_1 \exp\left(- \int_{t_1}^{t} \frac{v(s)}{V} ds \right) + F \int_{t_1}^{t} Q(t,s)\, ds \qquad (5)$$

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

$$C(t) = \frac{F}{Q} + \left(C_1 - \frac{F}{Q}\right) \exp\left[-\frac{Q}{V}(t-t_1)\right] \qquad (6)$$

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

$$Q(t) \simeq F/C(t) \qquad (7)$$

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

Constant Concentration Mode

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

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

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

$$v_i/V = f_i(t)/C_0 \quad (9)$$

where C_0 is the constant level of tracer concentration. Thus the air infiltration rate is determined by measuring the amount of tracer injected into each chamber required to maintain a constant level. The major criticism of this mode of using a tracer gas is that there is no stable control scheme which will do this [3] and therefore the level of tracer is never really constant.

3. AUTOMATED TRACER DECAY EQUIPMENT

Automated air infiltration measuring equipment using the tracer decay method has been developed by researchers at the National Bureau of Standards (NBS) and Princeton University and have been in use since 1974 in the United States. These systems use an electron capture gas chromatograph which can measure SF_6 in the ppb range. The earlier versions of these systems used mechanical sequencing timers to control the sampling and injection and recorded the output on a strip chart recorder [5,6]. Later electronic control circuits replaced the mechanical timers and an electronic peak detector was incorporated into the unit and thedata were recorded on a magnetic cassette in ASCII code [7]. Figure 1 shows a sample of data collected by this equipment in a seven storey administration building at Princeton University. The latest version of this series of equipment consists of a S-100 Buss microcomputer with two 5 1/4 inch dual-sided floppy disc drives, a real-time clock, a CRT terminal, an electron capture detector gas chromatograph, a ten port sampling manifold, five injection units and interfaces for both analogue and digital data [8]. This system has been used in air infiltration studies in large buildings. Figure 2 shows a schematic of a twenty-six storey, 450,000 m^3 office building in which air infiltration measurements are being made. Two such systems are deployed in this building. One measures the air infiltration rates in the tower (floors 3 to 26) portion of the building and is located in the mechanical equipment room of the 26th floor. The sampling network for this sytem is shown in figures 3 and 4. This system also measures the outdoor environment from a local weather station on the roof and the interior temperatures on each of the sampled floors. An exterior pressure measuring system will be added to this instrumentation. The second system is located in the lower mechanical equipment room and monitors the four lower zones of the building and the adjacent four storey Plaza Building. A typical trace of data from the tower is shown in figure 5. Injection occurrs 10 minutes before each hour. Note that the tracer is fairly well mixed after twenty minutes. Figure 6 shows the average daily air infiltration rates for the months of April and May of 1981. Days on which there are no data are usually weekends or holidays when the HVAC systems in the building are not operating. These air infiltration measuring systems have operated 18 days without human attention and 30 days without loss of data.

Hartman and Muhlebach [9] of the Swiss Federal Laboratories for Material Testing and Research have designed a tracer decay system controlled by a special controller. Data from this unit is analyzed off line on a central computer. This system uses N_2O as a tracer and an infrared analyser (MIRAN) operating in the 10 to 20 ppm range. This system can handle up to six rooms and also measures air temperature, humidity, wind velocity, wind direction and wind pressure.

4. CONSTANT CONCENTRATION TRACER GAS EQUIPMENT

Automated air infiltration measuring equipment using the constant concentration method has been developed in the United Kingdom, Denmark, Sweden and Canada. The U.K. automated air infiltration unit called Autovent [10] developed by Alexander, Gale and Ethridge of British Gas to acheive constant tracer gas concentration is based upon a microprocessor and a rapid analysis of the individual samples. The N_2O detector with a two second rise time allows that a room or zone may be analyzed every 6 seconds. The sampling is through tubes of equal length and the recorded concentration value (together with the previous reading) is used to vary the amount of N_2O injected prior to the next sampling. The nominal concentration is maintained at 50 $\pm$ 2 ppm. Injection takes place for durations up to half of the period (to a maximum of 30 seconds) between samples. Each of the injection lines is calibrated prior to the experiment so that the injection rate can meet local needs. The range of air infiltration that can be accomodated after calibration is from four or five to one. This equipment has been used over a period of almost two years with up to 12 rooms measured simultaneously. Overall accuracy of 10% is reported. Six houses have been carefully analyzed using this equipment. Futhermore, the analyzer has a second channel allowing CO_2 tracer gas analysis. Using two tracer gases simultaneously, exchange rates from the living area to the attic have been determined.

The Danish automated air infiltration system is microcomputer based and has been developed by Collet and McNally of the Institute of Technology in Taastrup. There are many similarities to the U.K. system in this new research effort focused on occupant activities such as opening and closing of windows and doors and their effect on air change rates in each of 10 rooms in a house south of Copenhagen. The injection of N_2O can take place essentially on a continuous basis, hence more than 10 to 1 variations in air change rates can be accommodated (from a few tenths to five or more air changes per hour with an accuracy varying from $\pm5\%$ to $\pm10\%$). Small (12 cm dia.) silent fans are spotted near the N_2O injection port in each room to promote rapid mixing of the tracer gas. Ten solenoid values are used to control injection, and another ten control sampling to the URAS-7N infrared detector. The experimental design also provides a tank of N_2O reference gas at 48 ppm to periodically check the design value of 50 ± 2 ppm N_2O concentrations within the home. Temperature and humidity sensors are being added to further increase reading accuracy. Since the study emphasizes occupancy effects, the tubing that runs throughtout the house has been kept as unobtrusive as possible (only 3-4 mm dia.). At the doorways metal tubes near the hinge are used to provide the tubing paths so that the door operation is unaffected. The N_2O injection orifices for each room were carefully designed to provide choked flow and were subsequently calibrated. The system can operate for up to six days unattended. Records are maintained on floppy disc, with a viewing screen provided to check on-site operation. Also a statistical package can be used on site to further provide system checks.

The use of similar concepts to measure air infiltration automatically have been used in the Swedish unit for tracer gas measurements reported by Pettersson of the Swedish National Testing Institute. The short response time of the N_2O analyzer has made it possible to collect a large number of samples per unit time. In the case of field measurements on a variety of buildings the problem of the two hour equipment warm-up time for the URAS-7N analyser has been solved by a 12V/220V transformer in the instrumentation van and warming up is accomplished in transit. An alternate MIRAN 101A analyzer requires 10 minutes or less to warm up. The arrangement of the 10 tubes to the analyzer allows 9 air samples and one fresh air purge. The fresh air must be raised to room temperature to avoid analysis problems. The pumping system moves the samples to the analyzer through 10 meter long, 6mm diameter plastic tubes within the house. When operated from the van, special 25 meter tubing is used to thermally insulate the enclosed 9 plastic tubes. The measurements are made at a certain definite frequency, treated by the microprocessor, and recorded as air changes per hour for the individual points.

Up to this point the emphasis in this section has been on the use of N_2O as the tracer gas. Dumont of the Natinal Research Council of Canada reports on a Canadian constant concentration air infiltration apparatus that is based on SF_6 as a tracer gas and used an electron capture gas chromatograph. The apparatus has been functioning for three years and is now available as a commercially packaged unit [1]. The unit has demonstrated the ability to hold SF_6 concentrations in a house constant to within ±4% over 15 minute intervals and ±2% over a one-hour interval. The controller feedback loop uses a proportional plus integral action. Unattended the unit has run 72 hours. Operating in the "sample" mode using the ITI detector, generally a level of 15 ppb of SF_6 is maintained. Consequently, the amount of tracer gas used during an experiment is very small. At the start of the experiment, it usually takes about 1 hour to reach the desired setpoint level of SF_6. To date more than 20 houses have been tested using this equipment.

The major weakness of the apparatus has been in the operation of the detector. With the very high usage that it is subject to, the column and the electron capture detector require considerable maintenance, cleaning and calibration. Zero drift of the detector is an ongoing problem. In addition, the switching valve, which uses a spool valve arrangement with O-rings, requires maintanence. Small leaks from the pressurized SF_6 supply have also been a source of difficulty. Normally the equipment is placed within the house being measured and consequently small SF_6 leaks will give a false indication of the air change rate. Comparing experience with other investigators, the maintanence problems sited here tend to favor a choice of infrared equipment if the higher concentrations (50 ppm range) are tolerable.

5. CONTINUOUS INJECTION TRACER GAS SYSTEM

Continuous infiltration monitoring system using the continuous injection mode has been developed at Lawrence Berkeley Laboratory in the United States to permit automated measurement of infiltration in a test space at half-hour intervals. This design decision was based upon stability considerations in the feedback loop of the controller. This unit originally used N_2O with an infrared analyser but later, due to environmental requirements in the U.S., was modified to use SF_6 with an infrared analyser. The system was designed to permit researchers to carefully examine the mechanisms that drive infiltration, i.e. the effects of weather and mechanical systems. The system is designed around a microcomputer that (1) controls the injection of tracer into the test space, (2) selects the sampling port used during an interval, (3) processes and records weather and system operation data, (4) calculates and records half-hour average infiltration values and (5) computes a new injection flow rate based upon the calculated infiltration to keep the concentration level in the test space within a particular target range. The calculation of infiltration is made using equation (6). In practice equation (6) is solved numerically by the microcomputer using a search algorithm that finds the set Q, C_1 and V having maximum likelihood consistent with the measured values of C and F for the time interval. The flow rate is then increased or decreased to a new value for the next half-hour interval to keep the concentration within a particular range.

6. SIMPLE AND LOW-COST TRACER GAS TECHIQUES

In an effort to develop simple and inexpensive methods which can be used by inexperienced personnel, researchers in the U.S. have developed two techniques which can determine the natural air infiltration rates with a minimal effort. The main reasons that the tracer gas methods are complicated and expensive are: (1) the concentration monitoring equipment is costly, (2) its use requires highly trained technicians, and (3) the duration of the test is usually 2 to 4 hours. However, if one is not interested in a detailed history of the air infiltration rate, but wants only the total air exchange rate over a period of specified time, then it is possible to remove the tracer gas monitoring equipment form the field site and use air sample bags or containers to collect the concentration levels of the tracer at specific instants [7-11]. This method has been used by NBS to evaluate the air infiltration rates in a national sample of over 200 homes in the United States. The method is shown schematicallly in figure 7. The tracer gas (SF_6) is initially injected into the dwelling using syringes. After a mixing time of about 1/2 hour, an initial air sample is taken on each storey of the building. The tracer gas is allowed ot decay for a period of 1 to 2 hours and a second set of air samples is taken on each storey. The air samples are shipped to a laboratory and analyzed for their concentrations. The air infiltration rate is determined by equation (4). Figure 8 shows the results of these tests for the first heating season of the project [12].

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

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

7. CONCLUSIONS

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

ACKNOWLEDGMENTS

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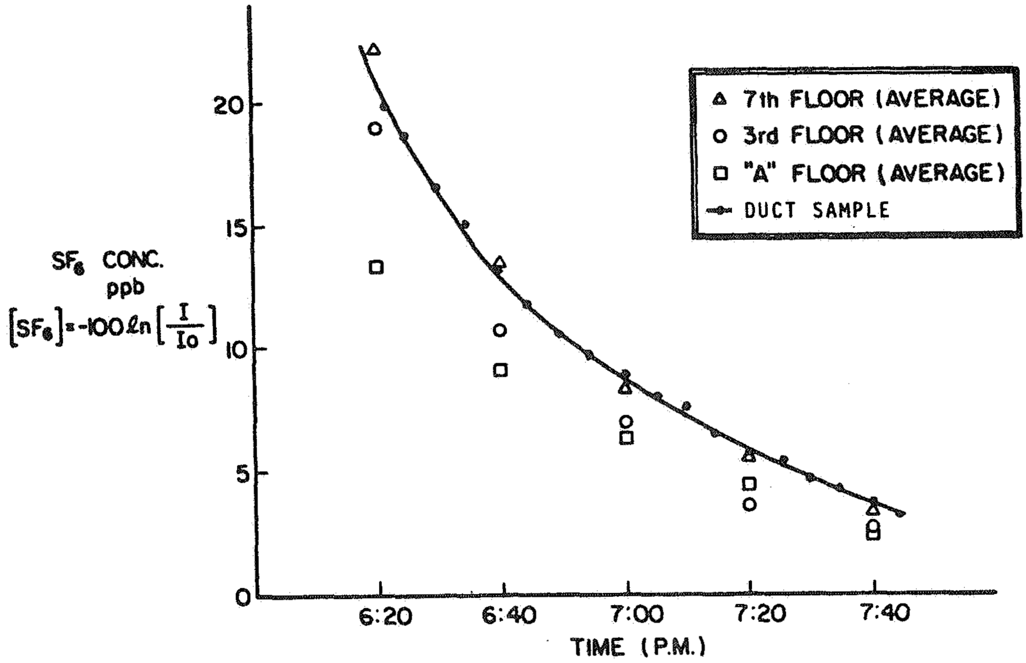

Figure 1. Decay Mode Tracer Concentrations in Test of Seven Storey Administration Building at Princeton, University

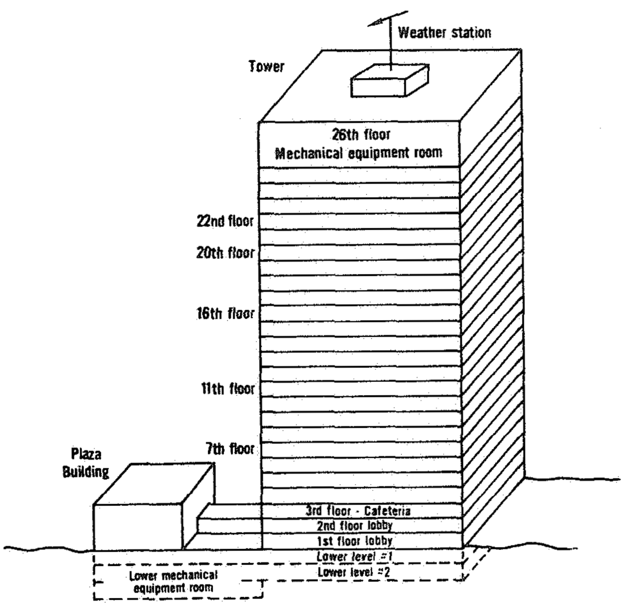

Figure 2. Schematic of 26 Storey Park Plaza Building in Newark, N.J.

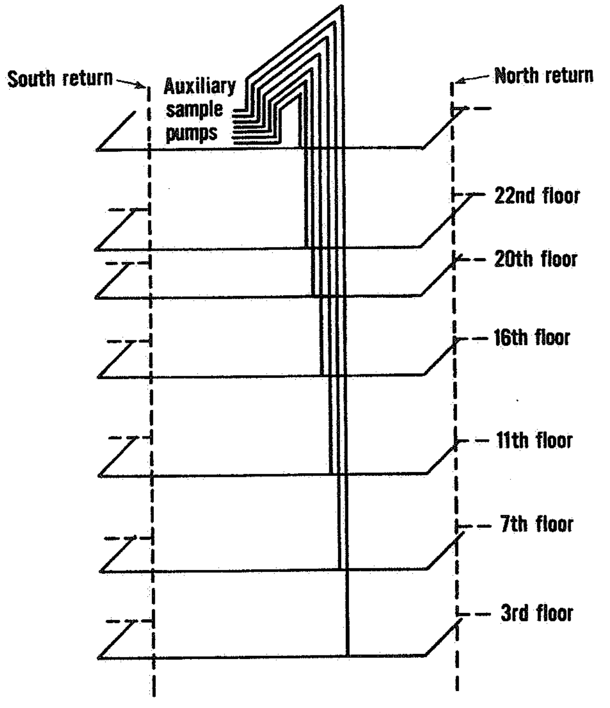

Figure 3. Schematic of Sampling Network for Tower of Park Plaza Building

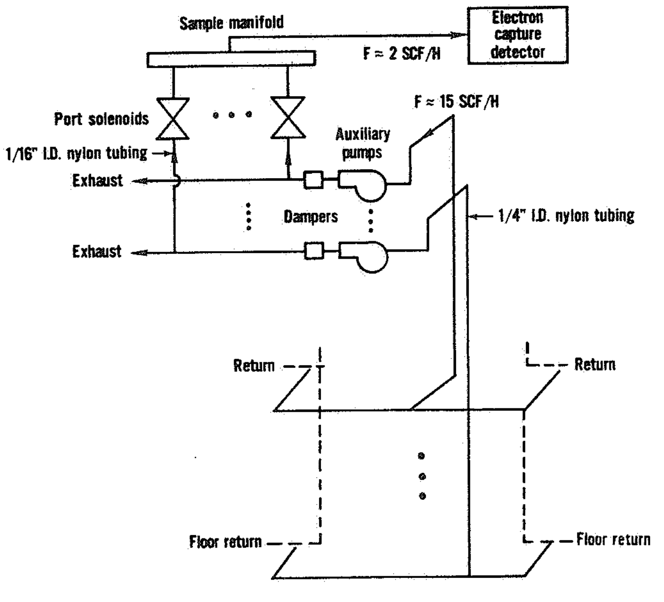

Figure 4. Detail of Sampling Network for Tower of Park Plaza Building

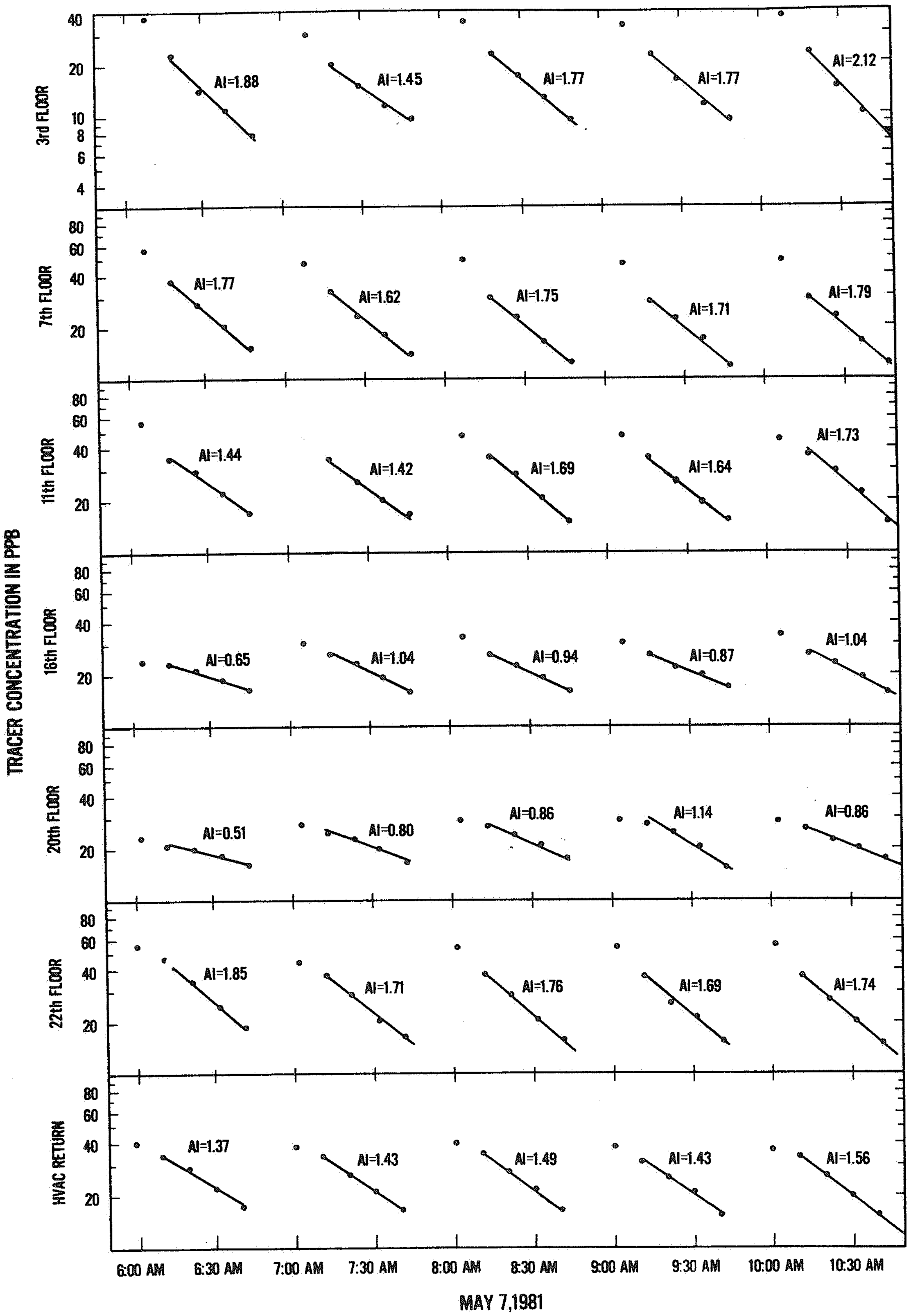

Figure 5. Typical Sequence of Test Data From Tower of Park Plaza Building.

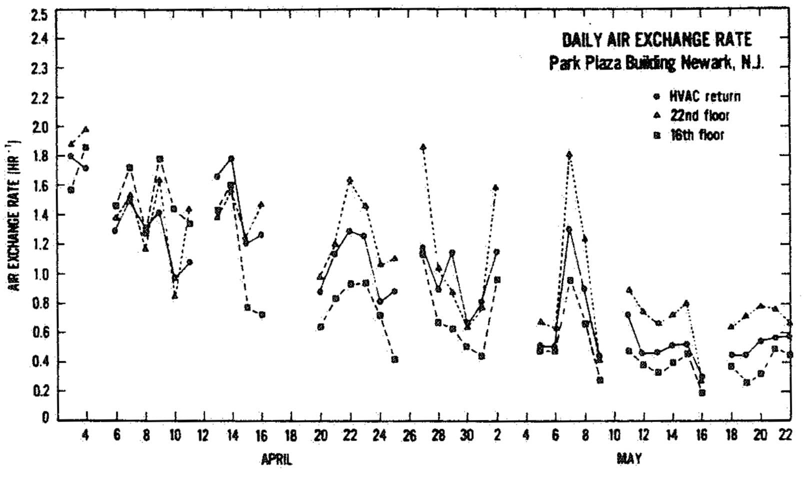

Figure 6. Daily Average Air Exchange Rates For Park Plaza Building.

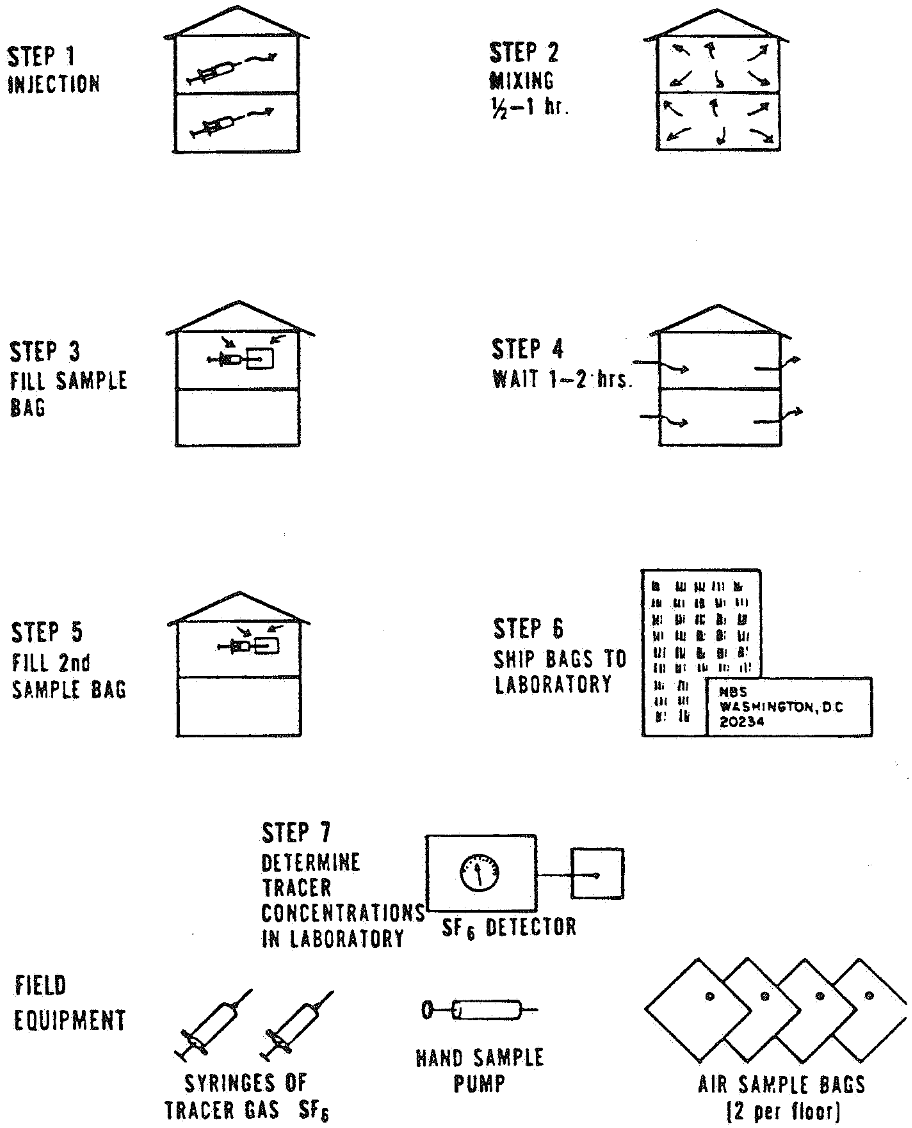

Figure 7. Schematic of Air Infiltration Measuring Technique Using Air Sample Containers.

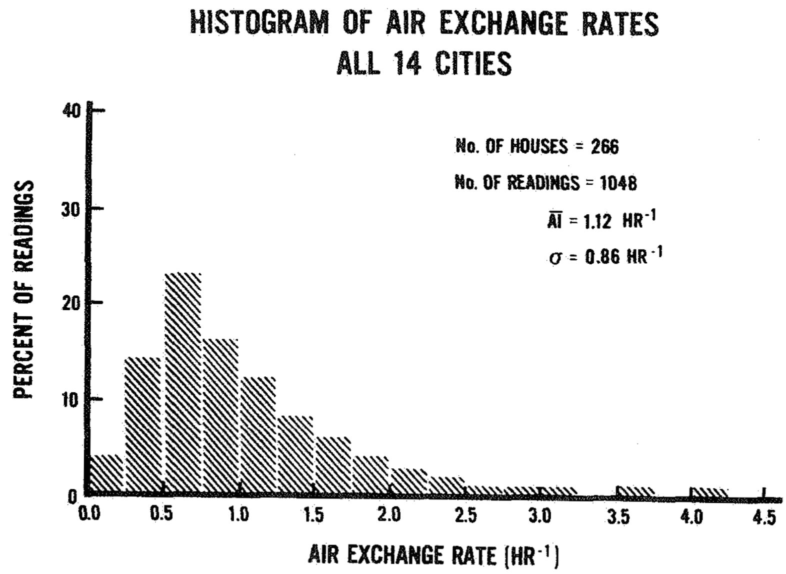

Figure 8. Histogram of Air Infiltration Rates in Homes in CSA/NBS Weatherization Demonstration Project.

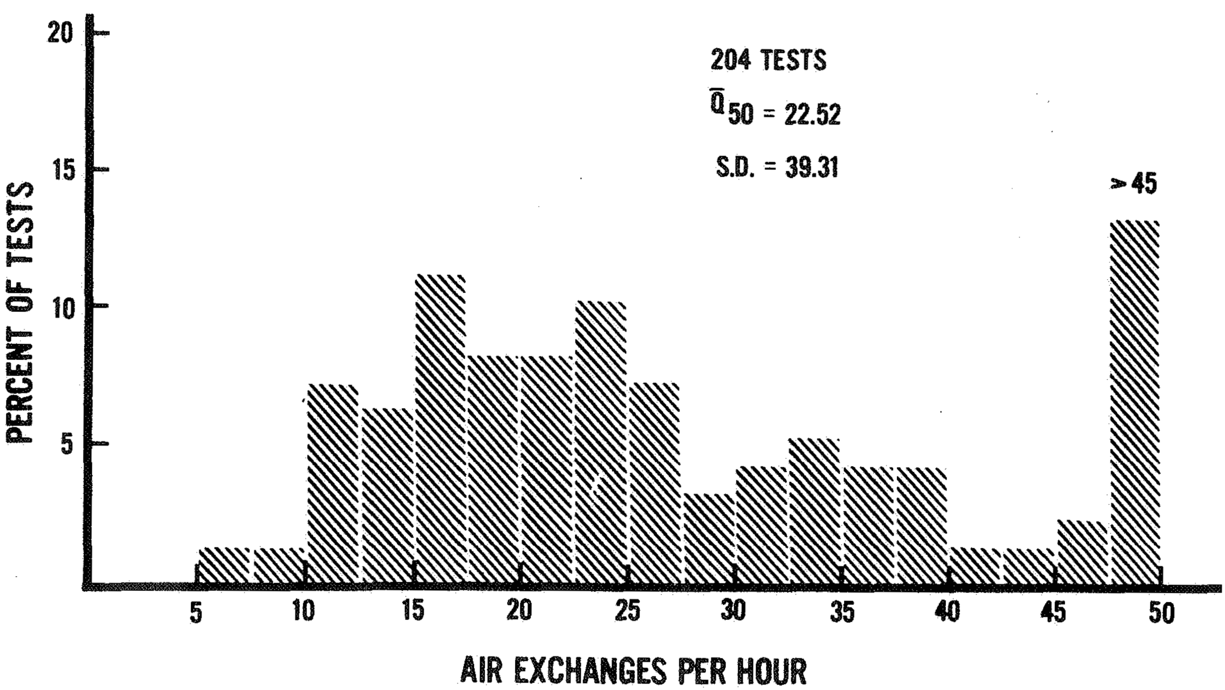

Figure 9. Histogram of Induce Air Exchange Rates at 50 Pa in Homes in CSA/NBS Weatherization Demonstration.