

Air Leakage Measurements by the Tracer Dilution Method—A Review

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ABSTRACT: Air leakage (infiltration) represents an important part of the heating and cooling load of residential, commercial and industrial buildings. It is also an important parameter in indoor-outdoor air pollution relationships. Air leakage is difficult to quantify because it is not only a function of building tightness and configuration, but also of inside-outside temperature differences, wind speed, and of workmanship in construction. Standard formulas for calculating air leakage do exist, but they are at best rough approximations.

The tracer dilution method has been used for a number of years to infer air leakage rates. This technique entails introducing small amounts of tracer gas into a structure and measuring the rate of change in tracer concentration. The air change rate can then be determined from the exponential decay rate in tracer concentration with respect to time.

There exists no perfect or ideal tracer. Thus, the choice of tracer gas is dependent upon the characteristics inherent in the measurement, the structure being measured, and in the relative familiarity of the experimenter with a variety of experimental techniques. The various gases that have been used for performing tracer dilution measurements in the past are presented along with their methods of measurement. In addition, the basic experimental methodology for performing a tracer dilution measurement utilizing any tracer is discussed. The limitations and advantages of the method are described and recommendations for its use are made. The need for standard test methodology is explored with an emphasis on the ability to produce and provide data that can be intercompared at some later time. An uncertainty analysis of the method is provided.

KEY WORDS: air leakage, infiltration, carbon dioxide, carbon monoxide, ethane, helium, hydrogen, methane, nitrous oxide, sulfur hexafluoride, tracer gas, air infiltration, measurements

Air leakage (infiltration) represents an important part of the heating and cooling load of residential, commercial, and industrial buildings. It is also an important parameter in indoor-outdoor air pollution relationships. The

heat loss associated with air leakage through the enclosure of a typical house may be as much as 40 percent of the total heat load [1,2].²

Air leakage (infiltration) is difficult to quantify because it is not only a function of building tightness and configuration but also of inside-outside temperature differences, wind speed, and direction, and possibly other factors. Standard formulas exist to estimate air-exchange rates [3], but they are at best rough approximations since actual leakage rates often depend on noncalculable quantities, such as the quality of workmanship in construction.

Significant contributions to residential air leakage are depicted in Fig. 1. All of these components shown contribute to the overall air leakage in a complex and usually noncalculable way. Thus, it is important that one have a technique for reliably assessing the air leakage rate within a structure of interest.

There are two major methods of quantifying the air leakage rate or air tightness of a structure, namely, the tracer dilution method and the fan pressurization technique. The tracer dilution method is a direct way of measuring the air leakage rate of a structure under the variables of ambient wind and temperature conditions. The induced pressure technique is an indirect method; that is, it measures the total air flow. This parameter, however, can be related to the air leakage rate under the same pressure.

Background

The tracer dilution method has been used for a number of years to measure air leakage rates [4-11]. The technique entails introducing a small amount of tracer gas into a structure and measuring the rate of change

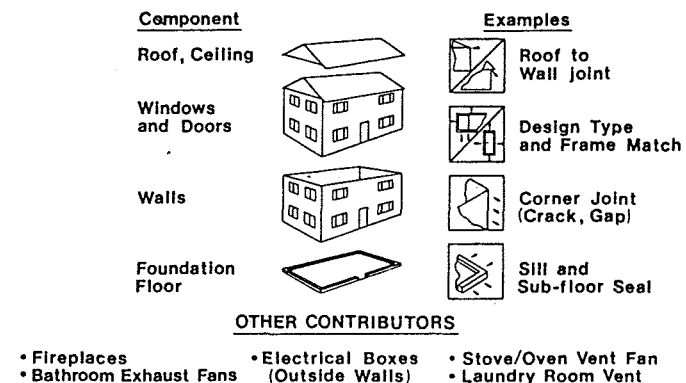


FIG. 1—Significant contributors to residential air leakage.

²The italic numbers in brackets refer to the list of references appended to this paper.

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(decay) in tracer concentration. The air change rate (generally air changes per hour (ACPH)) can be determined from the logarithmic decay rate of tracer concentration with respect to time.

The principle of the tracer dilution method of measuring air exchange rates may be developed briefly by considering the average rate (L) at which air leaks into a structure. This must equal the average rate at which air leaks out unless there is a steady increase or decrease in pressure. The rate of change in the total amount of tracer in the structure is

$$\frac{dQ}{dt} = (C_{out} - C_{in})L \quad (1)$$

where Q is the total amount of tracer, and C_{out} and C_{in} are the concentrations of tracer outside and inside. If V is the total internal volume of the structure, and if the outside concentration of tracer is small enough to be neglected, Eq 1 reduces to

$$\frac{dC}{dt} = -C \frac{L}{V} \quad (2)$$

where we have suppressed the subscripts and tacitly assumed that C always refers to the inside concentration.

Integrating Eq 2 leads to

$$C = C_0 e^{-(L/V)t} \quad (3)$$

where C_0 is the concentration at time $t = 0$. Equation 3 may be rewritten to give

$$I = L/V = 1/t \ln(C_0/C). \quad (4)$$

This equation is the theoretical basis of tracer studies of room and building air exchange.

Stated another way, we have shown that the air change rate in an enclosed space during a selected time interval is directly proportional to the natural logarithm of the ratio of the concentrations of the tracer gas at the beginning and end of the time interval, assuming that the factors causing air leakage (infiltration) remain constant.

Published information [5] on air change measurements in two test houses at the University of Illinois, one a two-story brick veneer structure over a basement and the other a one-story frame structure over a basement, indicated that a mathematical form in which air leakage varies linearly and independently with wind speed and indoor-outdoor temperature difference,

may be a reasonable empirical relation to facilitate air leakage calculations and intercomparison.

The experiments leading to this linear dependence of air change rate on wind speed and indoor-outdoor temperature difference have never been repeated under controlled conditions.

Other forms have been suggested that allow functional variations in temperature and wind speed different from linear [12-15].

Summary of Method

To initiate a tracer dilution measurement, a small amount of tracer gas is introduced into the test structure, thoroughly mixed, and the rate of change (decay) in tracer concentration is measured. The air change rate can be determined from the exponential decay rate of tracer concentration with respect to time.

A quantity of tracer is released at one or more points in the test building. The amount of tracer released should be sufficient to produce an easily discernible response in the gas measuring instrument. Under no circumstances should the initial tracer gas concentration exceed the Occupational Safety and Health Administration's (OSHA) time weighted average for substances included in the latest OSHA standards. Fans should be used to circulate the air within the room or structure in order to mix the gas thoroughly. Connecting doors, closet doors, and the like should be opened to allow unobstructed internal air flow. Several minutes should be allowed for mixing, and the decay in tracer concentration as a function of time is then monitored.

Values of concentration and time are used in Eq 4 to calculate an air leakage rate.

Use of Eq 4 implies perfect mixing of air and tracer throughout the measurement interval. In multiroom structures this may not always be a good approximation. Measurements of samples taken from a number of sites will reveal the degree of uniformity of tracer concentration. In a building with central heating and air conditioning the main fan is operated continuously. Tracer is introduced slowly into the return air, and samples are drawn from a supply outlet at timed intervals. This method has convenience and lends itself particularly to automated procedures. Also in occupied homes it may be the only method available for continuous monitoring. However, due to leaks in ductwork or elsewhere in the system, it may produce an incremental increase in the air infiltration rate. An alternate procedure is to operate fans at strategic points in the building, release tracer at several points, and perform multipoint sampling.

When multipoint sampling is used, sensors are placed at strategic points in the test structure and fed to a central measuring terminal. Measurement of helium and sulfur hexafluoride (SF_6) in air has been performed in this

way. However, for methods that analyze air with a single measurement device, a sampling network may be used to bring blended air samples to the analyzer. A diagram of such a sampling network is shown in Fig. 2. If the dilution rate in different rooms is different, samples drawn in this way give infiltration rates slightly less than the true average rate.

As with all measurement techniques, there are a wide variety of difficulties and uncertainties that can arise in the tracer dilution method. Apart from problems of a nonuniform driving rate, which would invalidate the assumptions leading to Eq 3, there are other noninstrumental difficulties that can arise. Some of these are: loss of tracer by means other than leakage; for instance, condensation can occur or chemical reaction may remove tracer concentration in a manner which confuses results. Some tracers are soluble in water and in areas of high humidity or where large quantities of running or stagnant water are contained, an equilibrium may be obtained between the tracer gas and the water.

Another noninstrumental problem is the removal of a tracer at a different rate from that of air, but by the same process, this can occur because of concentration variations near tracer outflow location. If the concentration of tracer near the outflow of air is different from the mean concentration, the rate of loss of tracer will not be the same as the rate of loss of air. Unless perfect mixing has taken place, there is bound to be some error of this type even when the initial concentration is uniform and stratification is absent.

An additional noninstrumental difficulty can be the uncontrolled production of tracer. This is particularly true in the case of utilizing carbon dioxide (CO_2) in occupied rooms. Since this is a normal constituent of

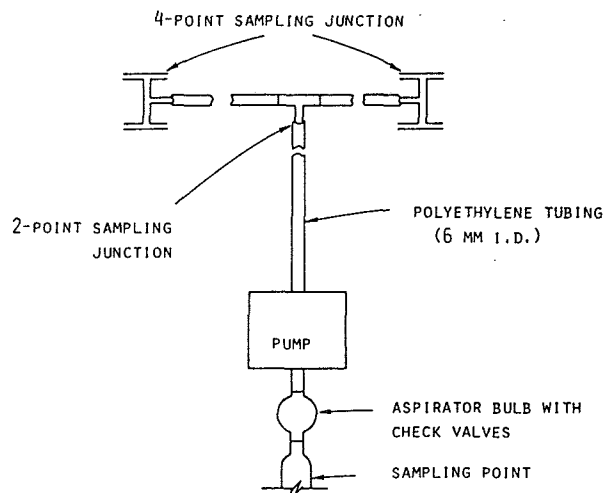


FIG. 2.—Diagrammatic representation of symmetrical eight-point sampling system.

exhalation, utilization of CO_2 can only be performed in structures which are unoccupied or in which the amount of CO_2 produced by human sources is known to be small compared to the amount of CO_2 utilized for tracer dilution method.

One often overlooked noninstrumental difficulty has to do with the recirculation of air and tracer via cupboards, adjoining rooms, and external air intakes. It is often possible for the air containing tracer to be removed from the region of interest and returned at a lower concentration at some later time. This recirculation will result in an air change rate that is lower than the actual air change rate extant in the structure.

An accumulation of measurement errors can lead to uncertainty in an air change rate determination by the tracer dilution method. As shown in the Appendix, both time and concentration uncertainties are important. For early times, the proportional error in air change rate is linearly dependent on the proportional errors in the time and concentration estimates. At later time, the contribution of the proportional error in concentration is less important than the time error.

Since the estimated rate is proportional to the logarithm of the concentration at any time, there is a bias introduced by the errors within the logarithmic term. Thus, averaging of readings cannot be guaranteed to produce an unbiased estimate of the rate. We should note that the tracer dilution method involves the calculation of ratios of concentration. For this method the ratio of the extremes of concentration measurable is more significant than their difference.

Previously, we noted the variation of air change rate due to wind speed and indoor-outdoor temperature difference. There is an additional factor due to the directional nature of wind. Other investigators have also noted this directional nature [16,17].

Recently we have performed measurements in a Southern California structure when wind was the dominant driving force for air leakage. A variation in wind direction as well as speed gave an air leakage increase 10 to 15 percent greater than would be expected from wind increase alone. Clearly, in future work, the wind velocity as a vector quantity should be given more emphasis.

Tracer Gases

Simply stated, a tracer gas is any gas that can be mixed with air and measured in very small concentrations, making it possible to detect air movement and measure air exchange rates.

This section presents a compilation of gases that have been used to perform air leakage measurements. Note that some of these gases may not be suitable for use under present day guidelines for health and safety. Never-

theless, these gases are presented for historical completeness. It should be emphasized that the measurement of air change rate by the tracer dilution method is independent of which tracer is selected.

Desirable characteristics of a tracer gas are: measurable at very low concentrations; inert, nonpolar, and not absorbed; nontoxic, nonallergenic; nonflammable and nonexplosive; easily and inexpensively measurable; not a normal constituent of air; and measurable by a technique that is free of interference by substances normally in air.

No single gas fulfills all these conditions, but some tracer gases, which have been used for air change rate measurements along with the instrumental technique used to sense the tracer, are presented in Table 1. Typical backgrounds for these gases are also presented in Table 2.

Often the choice of tracer gas to be used for a particular measurement program is dictated more by the familiarity of the experimenter with the particular gas or technique for detection than by limits of technological appropriateness. One commonly used measure for selecting a particular tracer gas has to do with the cost per unit volume of the tracer material itself. Representative costs that take into account both the cost per unit volume of the substance along with the reasonable lower limit of detection for the tracer are presented in Table 3. Note that for smaller enclosures cost is probably not an overriding factor. However, in the case of warehouses, multistory office buildings, and the like, cost can become a significant factor in any measurement program. Substances such as nitrous oxide (N₂O) or SF₆ then become very attractive.

Data Analysis

There are a number of ways to obtain an estimate of the air leakage rate from experimental dilution data. Some are more elaborate than others. The choice of which analysis method often depends on the individual experimenter's familiarity with various analysis techniques.

Finite Difference Method

ACPH may be calculated after each sample or over some sampling interval using the finite difference form of Eq 4

$$I = \frac{L}{V} = \frac{1}{(t_{i+1} - t_i)} \ln \frac{C_i}{C_{i+1}} \quad (5)$$

where

L = leakage rate,
 V = room volume,

TABLE 1—Gases and techniques for tracer dilution method.

Tracer	Measuring Apparatus	Maximum Allowable Concentration in Air, (vol/vol)	Minimum Detectable ppm	Toxicology [28]	Chemical Inertness	Comments [28]
H ₂	katharometer [4]	4% (lower explosive limit) /	200	nontoxic	extremely reactive in presence of O ₂ and heat or flame	flammable or explosive in presence of O ₂ and heat or flame
He	katharometer [4,6]	...	300	nontoxic	nontoxic	nontoxic
CO	infrared absorption, heat of absorption measurement [11] gas chromatography followed by reduction to methane and measurement with flame ionization detector [18]	50 ppm	5	nontoxic combines with hemoglobin to produce asphyxia	nontoxic can be dangerous when exposed to open flame	can also react with O ₂ in air in sufficient concentration; may explode when exposed to open flame
CO ₂	infrared absorption [19], gas chromatography with TCD	5000 ppm	1 70	nontoxic	very soluble in water	...
SF ₆	electron capture [9,20,21], gas chromatograph	1000 ppm	0.000002	nontoxic	chemically inert when pure	when heated to decomposition (550°C) toxic by-products may be formed
N ₂ O	infrared absorption [22,23]	...	1	nontoxic	very soluble in water	can form explosive mixtures in air
CH ₃ CH ₃	flame ionization detector [24] gas chromatography with flame ionization detection	3% (lower explosive limit)	5	nontoxic	will burn when exposed to flame	may explode in presence of O ₂ and heat or flame
CH ₄	infrared absorption [25,26,27]	5% (lower explosive limit)	5	nontoxic	will burn when exposed to flame	may explode in presence of O ₂ and heat or flame

t_i = time at i th interval, and

C_i = tracer concentration at i th sample interval.

For measurements over N sampling intervals, one may form a mean and standard deviation according to

$$\text{mean } I = \bar{I} = \frac{1}{N} \sum I \quad (6)$$

$$\text{standard deviation} = S_I = \left(\frac{\sum I^2 - (\sum I)^2/N}{N-1} \right)^{1/2}$$

The air change rate, $I = L/V$, is "best-fit" to the sample values of this

TABLE 2—Atmospheric constituents.

Compound	Average Tropospheric Background Concentrations, ppm	Typical Indoor and Urban Ambient Concentrations, ppm	Anthropogenic Sources	Refs
H ₂	0.5	0.5	...	29
He	5.2	5.2	...	29
CO	0.1	5 to 50	combustion	29
CO ₂	320	30 to 5000	combustion	29
N ₂ O	0.3	0.3 to several ppm	combustion	30,31,32,33
CH ₃ CH ₃	1.5 × 10 ⁻³	0.1	incomplete combustion	30,34
CH ₄	1.5	2 to 5	incomplete combustion	34,38
SF ₆	10 ⁻⁸	< 10 ⁻⁵	telephone switching stations	30,35,36

TABLE 3—Relative gas cost for tracer dilution study taking account of detectability.^a

Gas	Gas Volume Per Dollar ^b	Maximum Volume Measurable Per Dollar Spent on Tracer Gas ^b
He	3 ft ³ /s	10 ⁴ ft ³
CO ₂	52 ft ³ /s	5 × 10 ⁷ ft ³
CO	5.6 ft ³ /s	5 × 10 ⁶ ft ³
CH ₃ CH ₃	13 ft ³ /s	10 ⁶ ft ³
N ₂ O	12 ft ³ /s	10 ⁷ ft ³
SF ₆	2 ft ³ /s	10 ¹² ft ³

^a Gas costs figured on June 1977, prices on West Coast of United States.

^b 1 ft³ = 0.0283 m³.

parameter. The best-fit for I is the mean, and is determined from the test data as per Eq 6. This method has the advantage of simplicity, but it is very sensitive to errors in concentration or the effects of poor mixing, especially when short sampling intervals are used.

Decay Method

Concentration decay usually occurs quickly. This fact allows for a rapid means of estimating I . For example, with time measured in minutes, the time for one half of the initial concentration to decay is noted as $t_{1/2}$ and the I estimated is given by $41.59/t_{1/2}$. Similar ratios are given for other decay fractions and are shown in Table 4.

These ratios are simply computed for C/C_0 ratios of $3/4$, $2/3$, $1/2$, etc. The measurer has to record the time that a desired ratio is encountered.

Graphical Methods

Plot the natural logarithm of the concentration (on a linear scale) against time (in hours) on a linear scale. The measurements should fall on a straight line with time provided the air exchange rate remains constant. Scatter of points is expected, and a straight line may have to be faired in the best-fit sense. Pick two points on the line, with coordinates (C_1, t_1) and (C_2, t_2) where C_i is the concentration at time i . I is given by

$$I = \frac{\ln C_2 - \ln C_1}{t_2 - t_1} \quad (7)$$

The graphical method (see Fig. 3) is less sensitive to errors in concentration than the previous methods. It has the further advantage that the graph provides a visual display of any departures from the exponential decay law. For a large number of tests or measurements, a multipurpose computer program is useful.

TABLE 4—Decay ratios to compute air leakage rate.

Concentration Ratio	Decay Time (t), min	I, ACPH
3:4	$t_{3/4}$	17.27/ $t_{3/4}$
2:3	$t_{2/3}$	24.33/ $t_{2/3}$
1:2	$t_{1/2}$	41.59/ $t_{1/2}$
1:3	$t_{1/3}$	65.92/ $t_{1/3}$
1:4	$t_{1/4}$	83.18/ $t_{1/4}$
1:8	$t_{1/8}$	124.77/ $t_{1/8}$

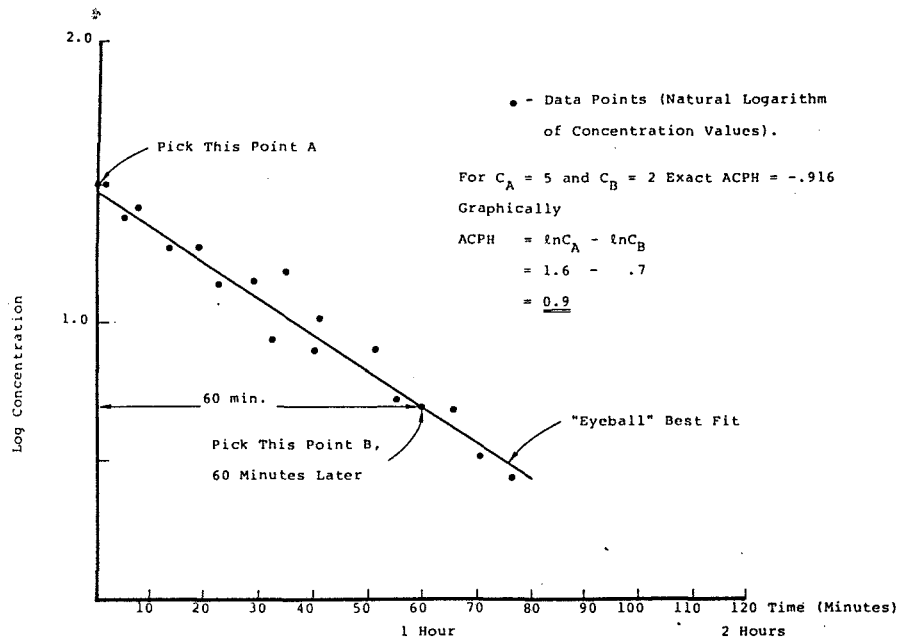


FIG. 3—Graphical determination of air change rate.

Conclusion

There are two major advantages to the tracer dilution technique. The first is that one obtains directly a measure of the air change rate within a structure of interest. The second applies to large structures such as warehouses where it appears that the tracer dilution technique is the only viable method of obtaining air leakage data.

The major drawbacks of the method are that a significant amount of time is required to perform a measurement. In addition, a considerable amount of experimental skill is required to perform measurements with any degree of certainty.

In summary, the tracer dilution method for determining air leakage is a straightforward technique and can provide one with a data base from which to make intelligent choices regarding a wide variety of leakage related matters in diverse areas such as energy conservation, air pollution, toxicology, and the like.

APPENDIX

In this appendix we briefly examine the uncertainty in air change rate determination induced by the uncertainties in time and concentration measurement. We begin with Eq 5

$$I = \frac{1}{t} \ln \left(\frac{C_0}{C} \right)$$

Taking absolute values of differentials according to the prescriptions of Baird [38] we find

$$\frac{\Delta I}{I} = \frac{\Delta t}{t^2} \left[\ln \left(\frac{C_0}{C} \right) \right] + \frac{1}{t} \left[\frac{\Delta C}{C} + \frac{\Delta C_0}{C_0} \right] \quad (8)$$

Dividing again by Eq 5 in the appropriate form, one obtains

$$\frac{\Delta I}{I} = \frac{\Delta t}{t} + \frac{\left[\frac{\Delta C}{C} + \frac{\Delta C_0}{C_0} \right]}{\ln \frac{C_0}{C}} \quad (9)$$

For $C \sim C_0$, (that is, ϵ small)

$$C = C_0 - \epsilon C_0 = C_0 (1 - \epsilon). \quad (10)$$

Then using appropriate approximations, one finds that

$$\ln \frac{C_0}{C} = \ln \frac{1}{1 - \epsilon} \sim 1 + \epsilon \quad (11)$$

$$\frac{\Delta I}{I} = \frac{\Delta t}{t} + \frac{1}{1 + \epsilon} \left[\frac{\Delta C}{C} + \frac{\Delta C_0}{C_0} \right] \quad (12)$$

So, for times near zero (that is, ϵ near zero), one finds that uncertainty in air change rate varies linearly and proportionately to errors in concentration and time. Mathematically this is given as

$$\frac{\Delta I}{I} \approx \frac{\Delta t}{t} + \frac{\Delta C}{C} + \frac{\Delta C_0}{C_0} \quad (13)$$

At a later time, say when $C_0/C \sim 100$, the proportional contribution of concentration uncertainty decreases. One finds for this particular case that errors in concentration are only about one fifth as important as uncertainties in time measurement; and, for this case, one finds that the uncertainty in the air change rate is given approximately by

$$\frac{\Delta I}{I} \approx \frac{\Delta t}{t} + \frac{1}{5} \left[\frac{\Delta C}{C} + \frac{\Delta C_0}{C_0} \right] \quad (14)$$

These two relations, Eqs 13 and 14 give us the approximate limits of variability and sensitivity of uncertainties in the various parameters as they affect the overall uncertainty in the measured air change rate.

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