Airtightness – measurements and measurement methods

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Byggforskningsrådet

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Layout: Elisabeth Sedig,
Informationsprojekt AB

D8:1980

ISBN 91-540-3201-6

Swedish Council for Building Research, Stockholm, Sweden.

Spångbergs Tryckerier AB, Stockholm 1980.

Preface

In June, 1977 the Airtightness Group of the Swedish Council for Building Research appointed a number of reference groups to deal with different problem areas within the overall field of airtightness. One of these groups worked on problems gathered under the heading of ”Measurements and measurement methods”, with myself as project leader. Much of the contents of this publication has developed within the group, and I am extremely grateful to all the group members for their help with ideas and work in general.

Almost all the personnel in the Division of Building Technology of the Lund Institute of Technology have been engaged, in one way or another, in the research work into airtightness aspects which has been done here during the last few years, and I would like to thank them for their efforts.

Johnny Kronvall

Contents

1 Introduction

This paper describes different methods of measuring the airtightness of whole buildings, and reproduces the greater part of the results of measurements which have been made in different places, primarily using the pressure method but also using the tracer gas method to some extent.

The pressure method is described together with the recommended method (SP 1977:1) published by the National Swedish Authority for Testing, Inspection and Meteorology, which is explained and commented upon where necessary.

A number of variations of the tracer gas method, as used for measuring the ventilation in a building, whether continuously or occasionally, are described, together with descriptions of suitable equipment.

Calculations of the possible error magnitudes have been made for both methods, and can serve as bases for qualified evaluations of the accuracy of the methods.

An up-to-date version of the computer-processed data file relating to airtightness measurements which have been made forms one appendix, while a standard form used for recording field data and measurements forms the other. The computerized data schedule is at present operated by the Division of Building Technology of the Lund Institute of Technology.

2 Methods of measurement

2.1 QUANTITATIVE MEASUREMENTS

Two methods are at present available for the measurement of airtightness of entire buildings: the tracer gas method and the pressure method. The tracer gas method is used to measure the ventilation rate of a building under ambient weather conditions. The principle of the pressure method is that a powerful fan is employed to create a pressure difference across the building envelope (walls, roof, floor structures etc.), and the resulting air flow through the fan is measured at constant pressure difference.

2.1.1 Tracer gas method

The tracer gas method can be used to measure the amount of ventilation in delimited spaces, such as (semi-detached) houses, apartments in apartment buildings, offices etc. The ventilation rate is usually dependent upon the ambient weather conditions, and so the results of tracer gas measurements can therefore vary considerably with weather and wind.

It can be seriously questioned whether tracer gas measurements are properly representative of the airtightness characteristics of a building. The term 'ventilation rate', expressed as the number of air changes per unit time, is also confusing and, to a certain degree, misleading, even when it is used to describe natural ventilation.

The mixing action between outdoor air leaking into a building and the indoor air lies somewhere between the limits of perfect mixing (immediate and homogeneous) and no mixing at all. This latter extreme can mean that the outdoor air either passes the indoor air in some way without mixing with it, or that it propels the 'old' air before it like a front. However, this is a problem which is more closely related to air quality than to the energy losses due to (uncontrolled) ventilation.

The main elements in tracer gas measurements are a suitable gas and an instrument (a gas analyser) which can measure the concentration of the tracer gas in the volume under investigation (the house, apartment etc.). Time must also be measured. Depending upon the actual details of the equipment and methods, measurements can be made in accordance with one of the following variants:

- ☐ decreasing gas concentration
- ☐ constant gas concentration
- ☐ constant gas emission.

Decreasing gas concentration

This method is that which is most commonly used in Sweden.

A small quantity of gas is discharged in the house, apartment, etc., sufficient to enable it to be measured by a gas analyser. When the concentration has (hopefully) become uniform throughout the test volume – which can be accelerated by 'mixing' the air, by some means such as by using fibre-board sheets as paddles or by placing small propeller fans here and there – measurements are made of how the concentration of tracer gas decreases with time. The ventilation rate of the test volume can then be calculated from the following expression:

$$n = \frac{1}{t} \cdot \ln \frac{c_0}{c_t} \qquad [1]$$

where:

n = ventilation rate, air changes/h
t = time from when gas concentration = c_0, h
c_0 = gas concentration at the start of the period
c_t = gas concentration at time t, h

As the mixing between the tracer gas and the air in the building can never be essentially perfect, measurements made at a single point in the test space are not reliable measures of the condition of the space as a whole. This problem can be dealt with in practice – or rather, got round of – by means of one of the following three alternatives.

1. Air is collected at a number of points and mixed together, after which the concentration of tracer gas in the mixture is used in calculating the ventilation rate.
2. The rate of decrease of concentration is measured at several points, and the measurement point which exhibits a rate of decrease which is nearest to the average rate from all points is selected and used thereafter.
3. The decrease in concentration is measured at several points and the average value is used when calculating the ventilation rate.

If the 'average rate of decrease' is the function which is required, then Alternatives 2 and 3, with 3 being the more reliable, are reasonable approximations. Estimations derived from Alternative 1 are hampered by a time-dependent 'displacement error' which is affected by how the fresh air mixes with the air in the building. In spite of this, this alternative is that which is most often used, presumably due to the simple procedure.

Advantages of the decreasing gas concentration method are:

- □ It is relatively easy to perform the measurements and to analyse the result.

The disadvantages are:

- □ It is difficult to evaluate how reliably the measured results reflect the actual ventilation rate of the space under investigation.
- □ Sometimes (e.g. if there is a significant volume of tracer gas trapped in enclosed volumes such as furniture etc.), the gas concentration does not decrease exponentially, which makes it difficult to analyse the results.
- □ The initial preparations in attaining a uniform concentration of tracer gas require either a complicated system of hoses for discharging the gas at many points simultaneously or an artificial agitation of the air in the space under investigation which to some extent can alter the natural equilibrium conditions.

Constant gas concentration

This variant is suitable for continuous measurement of the ventilation rate in a given space. Tracer gas is supplied to the space under investigation in one place and the gas concentration is measured in another. The gas discharge is controlled so that the gas concentration level at the point of measurement is stable. This can be arranged by some form of automatic control equipment. In the ideal case of 'complete mixing', it is possible to calculate the ventilation rate directly from the known discharge rate of the tracer gas. An alternative method is to permit the gas concentration to vary between an upper and a lower limit. When the concentration reaches the lower limit (c_u), more tracer gas is released to bring the gas concentration up to the upper limit ($c_ö$). Tracer gas emission is then stopped. The time between these toppings-up is then a measure of the rate of ventilation. See Figure 1.

The advantage of the constant gas concentration method are:

- □ The method permits continuous measurement of the ventilation rate to be performed.

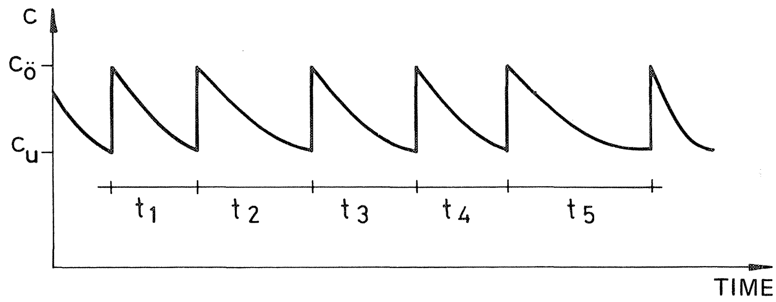

FIG. 1. Tracer gas concentration as a function of time with intermittent supply of tracer gas controlled by the gas concentration.

The disadvantages are:

□ The apparatus and auxiliary equipment are more complicated than in the other tracer gas measurement methods.
□ There is always a time lag between the gas release and reaction of the gas analyser, which can introduce errors into the analysis.

Constant gas emission

This variant is very similar to the previous method. It is thus also suitable for continuous measurements. The emission of tracer gas is constant during the measurement process, and the gas concentration which can be read off from the gas analyser serves as a measure of the ventilation rate. A reduced ventilation rate gives an increased gas concentration and vice-versa.

The advantages of the constant gas emission method are:

□ The method permits continuous measurement of the ventilation rate.
□ The instrumentation is simpler than for the constant gas concentration method.

The disadvantages are:

□ Considerable variations in the gas concentration can arise due to changing weather conditions around the building, and few gas analysers have a sufficiently long scale to cover these variations.
□ Quite a long stabilisation period is necessary before the main measurements can start, i.e. when equilibrium concentration has been attained. Tracer gas is consumed during this period and this method is the most wasteful of gas of the three methods.
□ It is not particularly easy to arrange a completely constant rate of gas emission.

Measuring equipment and measurement procedure

Some equipment is common to all three methods:

- □ a suitable tracer gas,
- □ a gas analyser and
- □ some means of measuring time.

What gases are suitable for use as tracers, and what are the requirements for such gases? A number of characteristics of an ideal tracer gas have been defined by various people, among them Bargetzi et al.(1977) and Honma (1975).

- □ The gas concentration must be measurable with good accuracy, even when highly diluted.
- □ The gases present in ordinary air should not affect the tracer gas analysis.
- □ The gas should be cheap and easily available.
- □ Adsorption and absorption of the gas in walls and furniture etc. should be insignificant.
- □ The tracer gas should have good chemical stability and not react chemically with the air or the surroundings.
- □ The gas should not be a health hazard when breathed in the concentrations used in measuring.
- □ The gas must not be flammable or explosive.
- □ The density of the gas should be as close to that of air as possible.
- □ The gas should not normally be present in ordinary air.
- □ There should be no 'natural' source of the tracer gas in the test space during measuring.

Hitchin and Wilson (1967) have prepared a table of several of these parameters for a number of possible tracer gases. See Table 1.

As far as is known, there is no tracer gas which meets all these requirements, but the gases which have been used and are used do at least meet some of them. Previously, hydrogen and helium were used to a large extent. However, both these gases have densities which differ considerably from that of air. Hydrogen is also flammable and, in certain concentrations with air, explosive. However, both are easy to detect with a katharometer which measures the thermal conductivity of the gas mixture.

Sulphur hexafluoride (SF_6) is the most commonly used tracer gas in North America for ventilation investigations. See, for example, Harrje et al.(1975). Concentrations as low as $10^{-7}\%$ can be measured with a gas analyser based on the electron capture principle. This means that, in a typical house, a volume of gas equal to that of half a ping-pong ball is sufficient to enable a measurement to be made. A disadvantage, however, is that a gas analyser of this type is relatively expensive. Sulphur hexafluoride has been successfully used in the USA and Canada for continuous measurements of building ventilation rates. The reference mentioned gives a

Vapour or gas	Density compared to dry air at NTP	Maximum concentration possible (% by vol)	Top limit to concentration	Minimum concentration detectable (% by vol)	Method of measurement of minimum	Notes
Hydrogen (H_2)	0·07	1·1	a	0·02	i	I
Helium (He)	0·14	1·2	a	0·03	i	
Water gas (H_2 and CO)	0·5	0·08 (2)	d (a)	0·001	iii	I II III
Water vapour (H_2O)	0·6	2·5	a	0·2	iii	IV
Ammonia (NH_3)	0·6	10^{-3} (2·5)	d (a)	$\sim 10^{-4}$	vi	I III
Carbon monoxide (CO)	1·0	0·04 (13)	d (b)	0·0005	iii	I III
Ethane (C_2H_6)	1·0	2·5	b	0·5	i	I
Argon (^{41}A)	1·4	$\sim 10^{-10}$	c	$\sim 10^{-9}$	ii	
Carbon dioxide (CO_2)	1·5	2	a & d	0·0001	iii	IV
Nitrous oxide (N_2O)	1·5	2	a	0·0001	iii	
Acetone (C_3H_6O)	2·0	1	a	0·01	iv	II
Krypton (^{85}Kr)	2·9	$\sim 10^{-10}$	c	$\sim 10^{-9}$	ii	
Chloroform ($CHCl_3$)	4·2	0·001 (0·3)	d (a)	0·05	v	III
Xenon (^{133}Xe)	4·6	$\sim 10^{-10}$	c	$\sim 10^{-9}$	ii	

Key: a—To maintain density of air/tracer mixture within 1 per cent of air density
b—Inflammable limit
c—Permissible radiation level in occupied area
d—Maximum safe concentration for occupied area
i—Katharometer
ii—Geiger counter
iii—Infra-red absorption
v—Analysis
v—Acoustic
vi—Colorimetric
I—Combustible (but not inflammable at these concentrations)
II—Odour
III—Toxic
IV—Unsteady background concentration

Table 1. List of important properties of a number of tracer gases. Source: Hitchin and Wilson (1967).

good description of the type of equipment which has been used for this application. North American homes often have hot air heating, i.e. hot air is circulated by a fan or fans from a hot air boiler to the various rooms. It is thus easy to inject the necessary small quantity of tracer gas into the air stream close to the boiler, from where the air and gas mixture is distributed to the various rooms. The measuring point is situated at the air inlet for the air returning to the boiler, to which the air/gas mixture, which has not disappeared through ventilation, returns.

Nitrous oxide, N_2O, also known as laughing gas, is the most commonly used tracer gas in Europe. The gas analyser used with this gas is based on the principle of measuring the change in the infra-red absorption characteristic of the air/nitrous oxide mixture. The analyser which is often used – at least in Sweden – works with tracer gas concentrations up to 0.1%, a range which has shown itself suitable for this type of measurement. For an individual single-family house with a volume of, say, 300 m^3, this means that 0.3 m^3 of nitrous oxide are required, or about 0.5 kg of gas. Nitrous oxide is available in cylinders of various sizes, of which the most suitable in terms of capacity and ease of handling is probably the 7.5 kg cylinder. In September 1978, the cost of one of these cylinders was about Skr. 200 (US$ 50). The density of the gas is 1.7 kg/m^3 at NTP, and so is fairly near that of air. As far as is known, no problems have been reported with stratification or in mixing the gas to a homogeneous mixture with air. A gas analyser which is commonly used is shown in Figure 2.

Strictly, time measurement requires nothing more complicated than an ordinary watch, although some form of recorder is strongly recommended. This plots the gas concentration while the paper is fed out at a known velocity. This recommendation is particularly relevant for the constant gas concentration and constant gas emission methods, although it also helps when using the decreasing gas concentration method. Typical traces are shown in Figure 3.

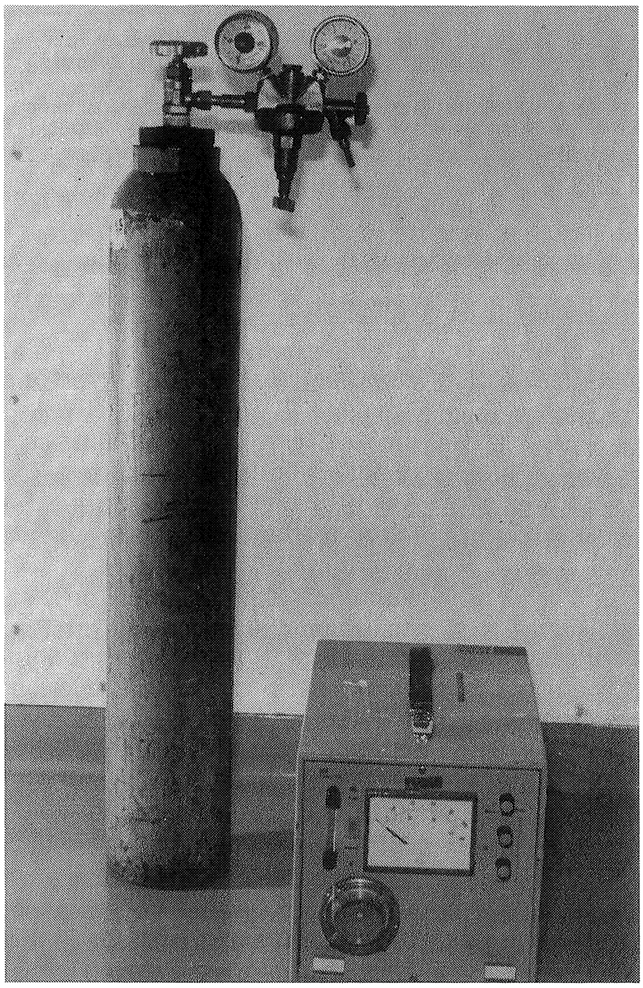

FIG.2. Gas analyser (URAS 7 N) and 7.5 kg cylinder of nitrous oxide (N_2O).

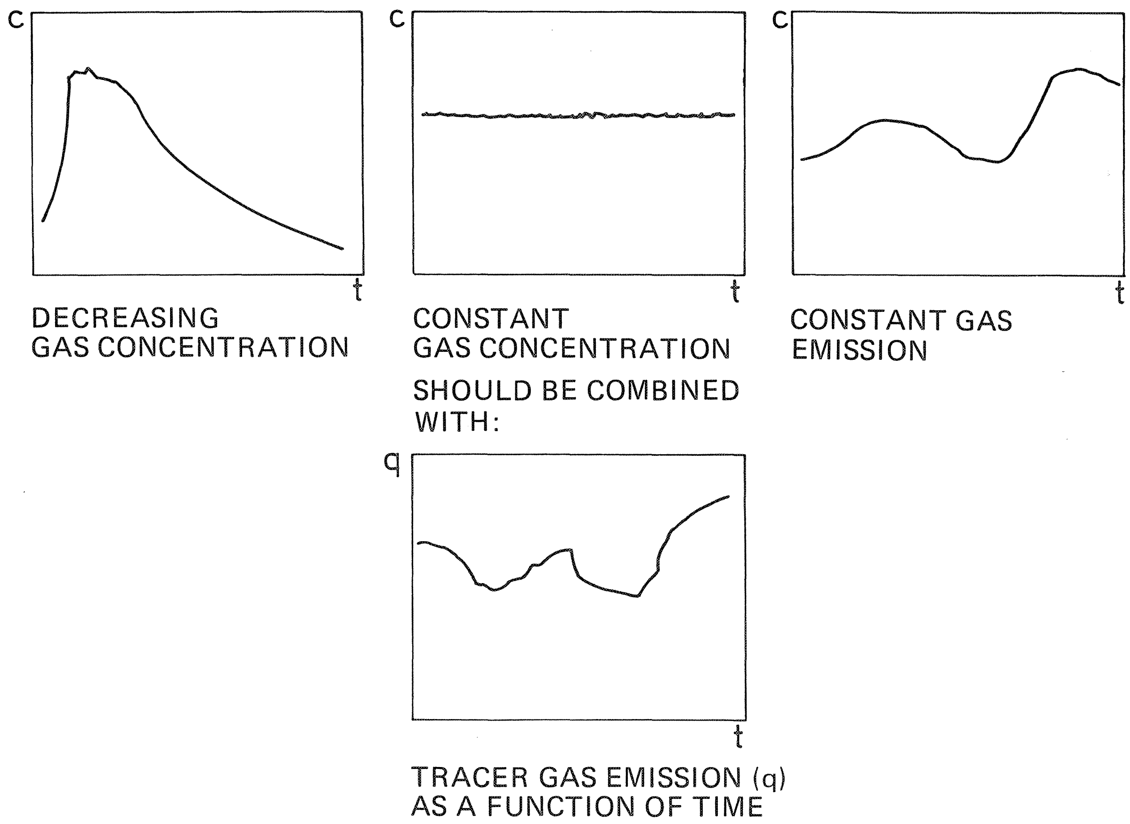

FIG.3. Typical traces from pen recorders for different measurement methods.

Measurement principles

The concentration of tracer gas in a test space can be expressed by:

$$c_t = c_b + \frac{q}{nV}(1 - e^{-nt}) + c_0 \cdot e^{-nt} \qquad [2]$$

where:

c_t = tracer gas concentration at time t, h
q = any addition of tracer gas, m^3/h
n = rate of ventilation, air changes/h
V = volume of the space investigated, m^3
t = time, h
c_0 = tracer gas concentration at time $t = 0$ (over and above c_b)
c_b = background concentration of tracer gas in normal air

Derivation:

Tracer gas production q is started at time t = 0. This assumes that at t = 0:

$$c_t = c_b + c_0$$

The following balance equation can be derived:

$$q \cdot dt - (c_t - c_b) \cdot n \cdot V \cdot dt = \frac{dc}{dt} dt \cdot V$$

$$\frac{dc}{dt} + n\,(c_t - c_b) = \frac{q}{V}$$

$$\frac{dc}{dt} + n \cdot c_t = n\,c_b + \frac{q}{V}$$

This is a first order non-homogeneous differential equation. It can be solved by adding the solution of the homogeneous equation to the solution of the non-homogeneous equation.

The homogeneous equation is:

$$\frac{dc}{dt} + n\,c = 0$$

Put $c = A \cdot e^{-\lambda t}$

$$-\lambda A e^{-\lambda t} + n\,A\,e^{-\lambda t} = 0 \quad \Rightarrow \quad \lambda = n \quad \Rightarrow \quad c = A \cdot e^{-nt}$$

The non-homogeneous equation is satisfied by:

$$c = \frac{1}{n}\left(n \cdot c_b + \frac{q}{V}\right) = c_b + \frac{q}{nV}$$

Adding gives:

$$c = A \cdot e^{-nt} + c_b + \frac{q}{nV}$$

The initial condition $c = c_b + c_0$ when $t = 0$ gives:

$$c_b + c_0 = A \cdot 1 + c_b + \frac{q}{nV} \Leftrightarrow A = c_0 - \frac{q}{nV}$$

$$c = \left(c_0 - \frac{q}{nV}\right)e^{-nt} + c_b + \frac{q}{nV} = c_b + \frac{q}{nV}\left(1 - e^{-nt}\right) + c_0\,e^{-nt}$$

Decreasing gas concentration

In this case there is no gas emission (q) during measurement, i.e. q = 0. Equation (2) then becomes:

$$c_t = c_b + c_0\,e^{-nt} \qquad [3]$$

The gas analyser is calibrated before measurement so that the background concentration c_b gives a scale zero indication, which means that the instrument readings are the same as $c_t - c_b$, which magnitude is here called c.

$$c = c_0 \cdot e^{-nt}$$

$$\frac{c}{c_0} = e^{-nt}$$

Taking logarithms, we get:

$$\ln c - \ln c_0 = -nt$$

$$\ln c_0 - \ln c = nt$$

$$n = \frac{1}{t} \cdot \ln \frac{c_0}{c} \qquad [4]$$

Plotting the tracer gas concentration as a function of time on a linear/logarithmic graph makes it easy to check that the gas concentration is falling off exponentially and thus there is no local gas source or sink which is distorting the results.

As $\ln \frac{c_0}{c}$ can be written as $\ln c_0 - \ln c$, the quantity n is the same as the slope of the line in a linear/logarithmic graph connecting the plotted readings. See Figure 4.

Statistical theory enables us to determine how many measurements of ln c are necessary to give the required degree

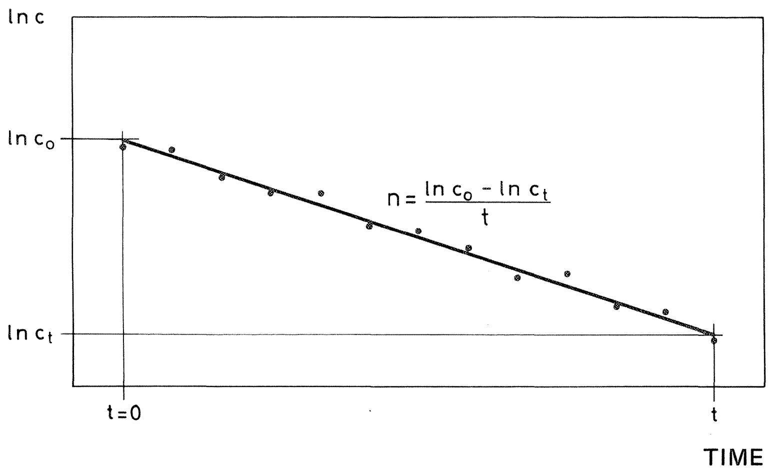

FIG. 4. Evaluation of tracer gas measurements from the decreasing gas concentration method by extracting a straight line from the measurement results when plotted on a linear/logarithmic graph.

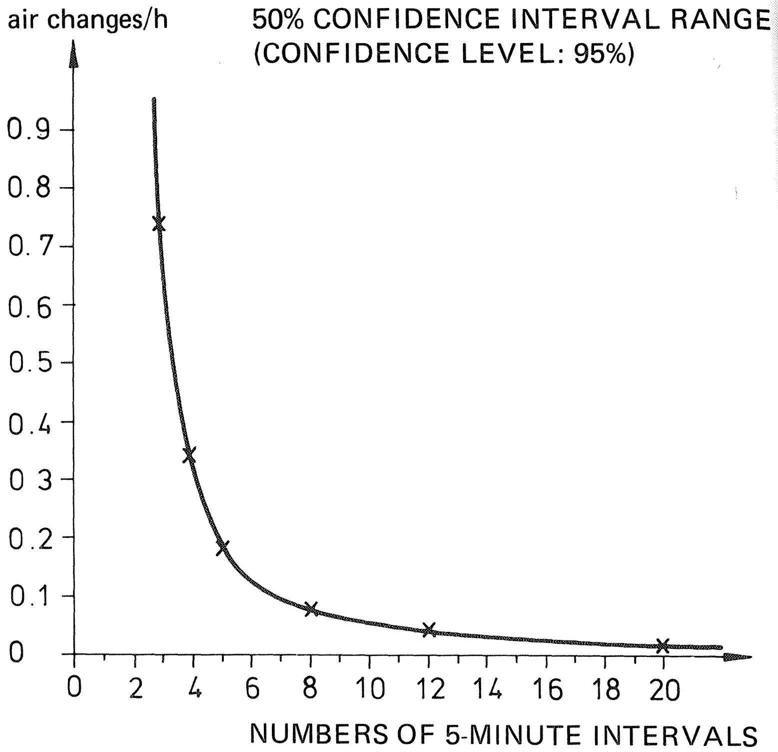

FIG.5. The 50% confidence interval expressed in ventilation rate for different numbers of 5-minute intervals during the measurement period.

Table 2. Time required for ventilation rate measurements for different ventilation rates.

Ventilation rate, air changes/h	f_{max}, air changes/h	Necessary number of 5-minute intervals	Time required, h
0.1	0.01	25	2.1
0.2	0.02	18	1.5
0.4	0.04	12	1.0
0.6	0.06	10	0.8
0.8	0.08	8	0.7
1.0	0.10	7	0.6

for accuracy for n. This can be determined as follows:

If we assume that the gas analyser and recorder together introduce an error in the concentration measurements, equal to the standard deviation, of ±2.5% of full-scale deflection, the result is that the standard deviation with the commonly used gas analyser is ±25 ppm. As logarithms are taken first after this, we must investigate the effect which it can have on ln c for c = 1025 and for c = 975 ppm. The respective values of ln c are 6.932 and 6.882, i.e. ± s = 0.049, where s is the standard deviation. The error in the time measurement is assumed to be zero.

Blom (1969), for example, states the following confidence interval for slope determination using linear regression methods:

$$I_n = n^* \pm t_{p/2}(N-2)_* \; s/\sqrt{S_{uu}}$$

where

n^* = estimated slope magnitude

$t_{p/2}(N-2)$ = the value of the so-called t-distribution, where p is the confidence level and N is the number of intervals

$$S_{uu} = \sum_{k=1}^{n} (k \cdot \Delta t)^2 - \frac{\left\{\sum_{k=1}^{n} k\right\}^2}{n}$$

If the confidence level is set at 95%, i.e. that the result, in simple terms, is 95% certain, the graph in Figure 5 can be drawn.

If we wish to measure the ventilation rate n with error limits of $\pm f_{max}$ (= the confidence interval), and if f_{max} must not exceed 0.1 n, i.e. it must not deviate from n by more than 10%, the number of intervals must exceed or be the same as the number of intervals given in Table 2 for the different ventilation rates. (Table 2 is derived from Figure 5.)

Constant gas concentration

In this case, $c_t - c_b = c$ is held at a constant level by adjusting q to the ventilation rate n. A flow balance equation for this case then becomes:

$$\frac{dc}{dt} \cdot V \cdot dt = \frac{dq}{dt} dt - \frac{dn}{dt} \cdot dt \cdot c \cdot V \qquad [5]$$

We maintain dc/dt = 0

$\Rightarrow$

$$\frac{dq}{dt} = c \cdot V \cdot \frac{dn}{dt}$$

$$\frac{dq}{dt} \cdot \frac{dt}{dn} = c \cdot V$$

$$\frac{dq}{dn} = c \cdot V$$

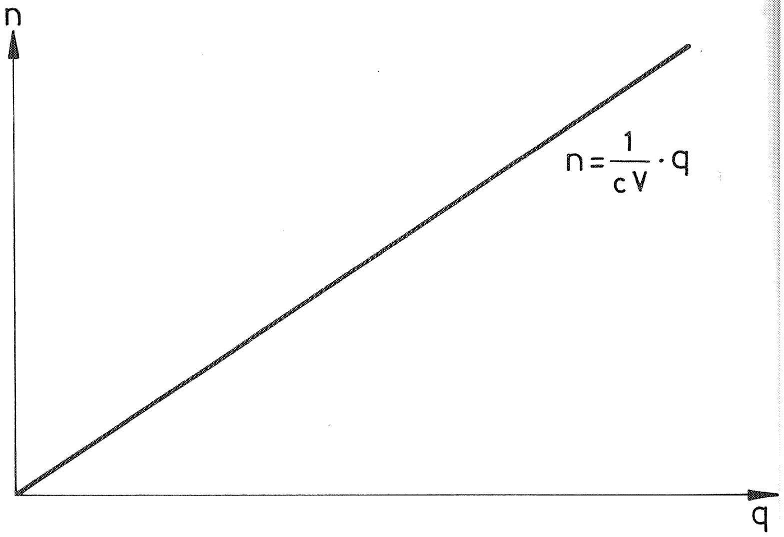

FIG.6. Ventilation rate as a function of the supply of tracer gas.

The relationship between q and n is thus linear, as shown in Figure 6.

It is thus necessary to choose a suitable value of tracer gas concentration so that the ventilation rates which are expected can be held, allowing for the possibilities of variations in q and of the volume concerned. (Alter the slope of the line

$n = \frac{1}{c} \cdot \frac{1}{V} \cdot q$.)

Measurements cannot start until a constant gas concentration has been attained. How long can this take? With a gas supply rate of q, the concentration c is given by:

$$c = \frac{q}{nV}(1 - e^{-nt})$$

Figure 7 shows how the $(1 - e^{-nt})$ factor increases with time for different values of n. The figure shows that the time until equilibrium is attained can be considerable at low ventilation rates.

Constant gas emission

Tracer gas is supplied at a uniform rate q (m^3/s) during measurements. From equation (2)

$$c_t = c_b + \frac{q}{nV}(1 - e^{-nt}) + c_0 \cdot e^{-nt}$$

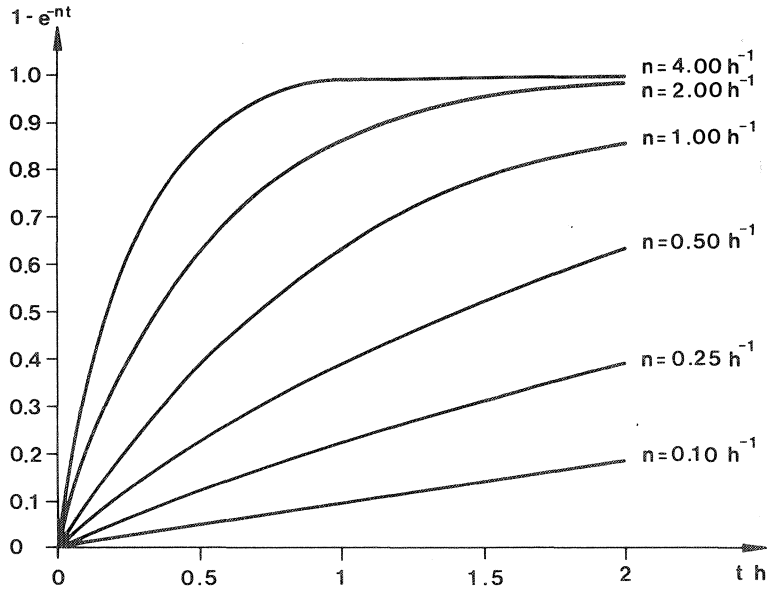

FIG.7. (1 - e^{-nt}) as a function of time for different values of ventilation rate n.

Put $c_0 = 0$, $c = c_t - c_b$

$$c = \frac{q}{nV}(1 - e^{-nt}) \qquad [6]$$

If the ventilation rate is constant (= n) from the time that the gas is first discharged, the stabilization sequence will be the same as that for the previous variant. See Figure 7.

When $(1 - e^{-nt}) = 1$, the ventilation rate is:

$$n = \frac{q}{c \cdot V} \qquad [7]$$

The ventilation rate n is thus inversely proportional to the gas concentration. The gas concentration q must therefore be chosen so that the concentration c is maintained within the scale range of the gas analyser for the air change rates which are expected.

$q = c \cdot V \cdot n$

The interaction between n, q and c for an individual single-family house or similar building with a volume of 300 m^3 is shown in Figure 8.

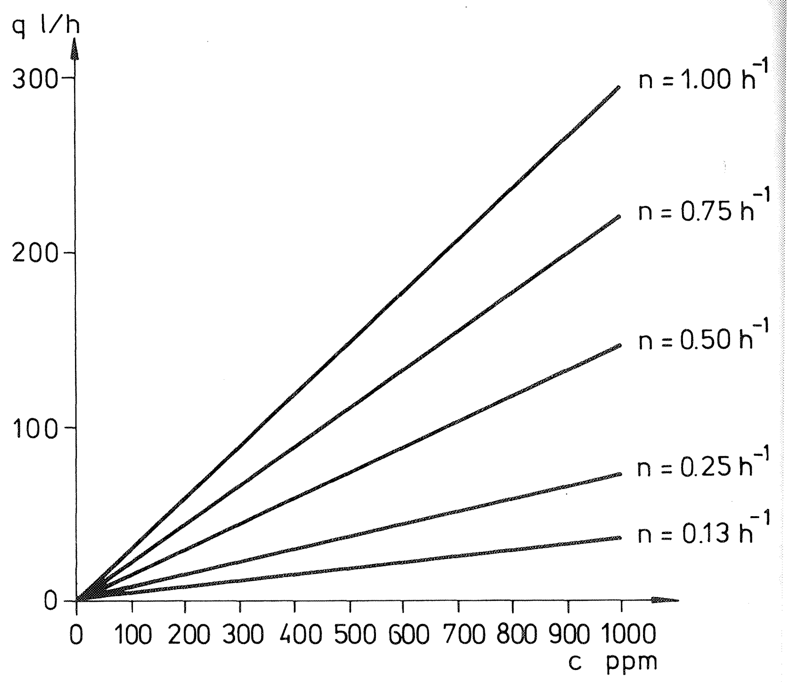

FIG.8. The flow of tracer gas for continuous gas measurement for different ventilation rates and gas concentrations. Volume = 300 m³.

In the interests of accuracy, it is not desirable to work with the absolutely lowest concentrations which can be indicated by the gas analyser. If, however, it is desired to be able to record a wide range of air changes, there is a difficult question of balance to be solved. A low value of q enables a large interval of measurable n to be obtained. From Figure 8 it can be seen that if q = 75 l/h it should be possible to measure ventilation rates down to 0.25 h^{-1} before the gas analyser gives a full-scale deflection. On the other hand, higher ventilation rates would give such a low gas concentration that the accuracy of determining c begins to be in doubt.

2.1.2 Pressure method

A proposal for the formulation of Standard Method Description SP 1977:1, issued by the National Swedish Authority for Testing, Inspection and Meteorology, is presented here to serve as a description of the pressure method. This proposal was prepared by the 'Measurements and Measurement Methods' reference group within the Swedish Council for Building Research airtightness group. It reads as following:

Application

This test method is used to determine the airtightness of the enclosing surfaces of a building or part of a building (e.g. an apartment). The method is primarily applicable to residential buildings.

Principle

The test is performed by generating a pressure difference between the interior and exterior of the building (apartment) and measuring the air leakage which arises due to the pressure difference. The air leakage at a given pressure difference is given as a measure of the tightness of the building.

Test equipment

A suitable controllable fan is required, having sufficient capacity to produce a pressure difference of ±55 Pa. At a back pressure of 55 Pa, the following fan capacities are likely to be necessary:

Apartments in an apartment building	*1200 m^3/h*
Single-family house	*2000 m^3/h*

A flow meter to measure the air flow through the fan is required.

The probable error in flow measurement, m, calculated as below, must not exceed ±6%. However, the accuracy does not need to exceed that corresponding to a value of 0.1 air changes/h.

$$m = \sqrt{m_1^2 + m_2^2 \ldots}$$

where m_1, m_2 . . . represent the errors of the individual components in the measuring chain.

The flow meter should be installed in accordance with its manufacturer's instructions, observing such matters as minimum straight run before the measuring points etc.

A micromanometer for measuring pressure differences between 0 and ±55 Pa with an accurancy of ±2 Pa is required.

The fan and flow meter should be able to be reversed so that measurements can be made in both directions of flow through the walls.

Test conditions

The indoor and outdoor temperatures should be measured, and the wind direction and velocity be determined. Testing should not be carried out if the wind velocity, measured at head height at a (preferably) open place (e.g. on the windward side of the house) exceeds 8 m/s, or if the temperature difference between interior and exterior exceeds 30°C.

Test procedure

All ventilation openings should be sealed before the test. Examples of this work are as follows:

Close all disc valves. (Do not forget the ventilator(s) in a larder.)

Do not alter the settings of present fittings: tape them over instead.

Seal the cooker fan and cooker exhaust canopy.

Seal any ventilators beside or forming part of windows with tape.

Clothes-drying cupboards connected to exhaust ducts should be sealed at the duct.

Fireplaces should be sealed over the grate or in the chimney.

Seal the letterboxes.

Any drain traps (floor drains, sinks, basins, lavatories etc.) not filled with water should be filled or taped over.

All areas which are normally heated to more than + 10° C should be regarded as forming part of the volume to be tested. Doors to boiler rooms, garages etc. should be kept shut, while doors within the test area should be left open.

One external door, or a window, should be replaced by a wooden panel etc. fixed in place and carefully sealed with tape etc.

A hole should be made in the panel to accept the fan discharge duct, and another one for the passage of a small tube or hose. This tube should be connected to the pressure gauge which measures the difference between interior and exterior pressure. For an individual single-family house the end of the tube can be placed a few metres from the wall of the house at ground level. It should be terminated by a tee-piece, and can be fitted with some form of damper such as a box filled with mineral wool etc. Figure 1 shows how the various items are arranged.

The test should consist of a set of at least four sets of readings of the air flow as a function of pressure difference, uniformly distributed over a pressure range of 20-55 Pa and performed for both internal overpressure and internal underpressure.

If the flow meter used is of the type which measures mass flow (e.g. orifice plate, pitot tube etc.), the mass flows should be converted to volume flows. Guidelines for this conversion are given in an appendix.

When calculating the building volume, internal dimensions should be used. Reductions should be made for internal walls and floors within the volume under investigation, but not for cupboards etc.

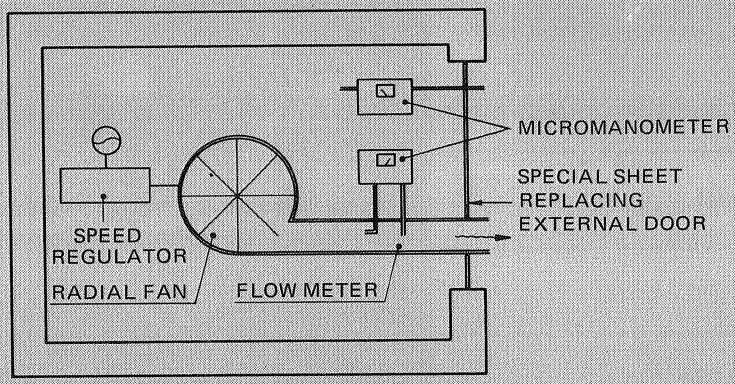

FIG. 1. Measuring equipment: schematic diagram.

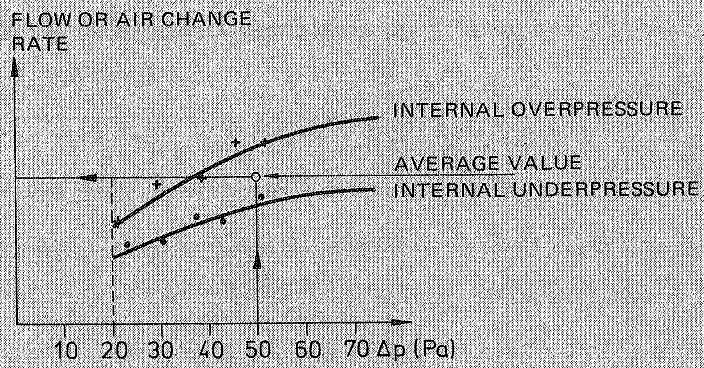

FIG. 2. Example of test results in graph form.

Tightness is normally specified in terms of the average value of the air flows at 50 Pa overpressure and underpressure, as read from the graphs. If the value has to be obtained by means of extrapolation, this should be specifically stated. The graph should be attached to the report.

Commentary

The method is quick and reliable. It produces a quantitative measure of the building tightness which can be used in several contexts, such as manufacturing inspection, comparison between buildings and standard requirements.
It should, however, be realized that the method only provides a measure of the tightness of all the enclosing sur-

faces, and the result is not directly usable for the calculation of the building's air change rate under natural conditions. The natural pressure differences which arise in a building are of different magnitude in different parts of the building. The method described here gives no indication of the size of the individual leaks or where they are situated. However, it is possible to localize the leaks and to evaluate their size by using an infra-red camera or an anemometer during the phase with internal underpressure.

Normally, the air flows resulting from internal overpressure and underpressure are dissimilar. This can be due to the fact that certain leaks behave like non-return valves: outward-opening windows, for example, have a greater leakage with internal overpressure than with internal underpressure. It can also be due to the fact that the natural pressure differences give rise to leakage which is not measured during testing. However, by calculating the average values of the flows, an unambiguous value for the building is obtained.

Correction of measured air flows for temperature

The continuity condition for compressible flow is given by:

$$\dot{m} = \rho \dot{V} = \text{constant} \qquad [8]$$

where

$\dot{m}$ = mass flow, kg/h
ρ = density, kg/m^3
$\dot{V}$ = volume flow, m^3/h

The density of air at different temperatures can be calculated from the general gas laws.

$$p \cdot V = nRT = \frac{m}{M} \cdot R \cdot T \qquad [9]$$

where

p = gas pressure = 101.325 kPa at normal pressure, Pa
V = gas volume, m^3
n = number of mols of the gas
R = general gas constant = 8.3143 J/mol · K (Nm/mol · K)
T = gas temperature, K
m = mass of a given gas quantity, kg
M = molecular mass of the gas = $28.96 \cdot 10^{-3}$ kg/mol for normal air, g/mol

The density $\rho = m/V$ is obtained from:

$$\rho = \frac{P \cdot M}{R \cdot T}$$

Substituting values for dry air at normal pressure, we obtain:

$$\rho = \frac{101.325 \cdot 10^3 \cdot 28.96 \cdot 10^{-3}}{8.3143 \cdot T} = \frac{352.9}{T} \quad [10]$$

i.e.

$$\rho = \text{constant} \cdot \frac{1}{T} \quad [11]$$

When pressure testing, cold air is often blown into the building when testing for internal overpressure, and warm interior air is discharged through the leaks. These temperatures are indicated by T_u and T_i (K) respectively.

Internal overpressure

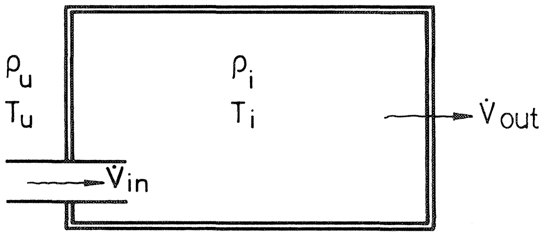

FIG. 9. Internal overpressure: nomenclature.

In order to meet the continuity condition (Equation 8), the following equation must be satisfied:

$$\dot{m}_{in} = \dot{m}_{out} \quad [12]$$

or

$$\rho_u \cdot \dot{V}_{in} = \rho_i \cdot \dot{V}_{out} \quad [13]$$

As the density is inversely proportional to the absolute temperature (Equation 11), we get:

$$\text{constant} \cdot \frac{1}{T_u} \cdot \dot{V}_{in} = \text{constant} \cdot \frac{1}{T_i} \cdot \dot{V}_{out} \qquad [14]$$

$$\dot{V}_{out} = \frac{T_i}{T_u} \dot{V}_{in} \qquad [15]$$

As $\dot{V}_{ut}$ is the interesting quantity, in terms of the building leakage behaviour, the measured volume flow into the building should be corrected in accordance with Equation (15).

If the flow meter used during testing primarily measures the mass flow – which is the case for such measuring devices as orifice plates, pitot tubes etc. – the result must be converted to a volume flow. This type of flow meter normally measures a pressure difference Δp which is a measure of the magnitude of the flow in accordance with:

$$\Delta p = \text{constant} \frac{\rho(T) \cdot V^2}{2 \cdot A} \qquad [16]$$

where:

the constant is specific to the meter used.

A = cross-sectional area of the measuring tube

$$\dot{V} \sim \sqrt{\Delta p \cdot 2 \cdot A / \rho(T)}$$

For two temperatures T_1 and T_2 with the same pressure difference Δp, we get:

$$\dot{V}_{T_1} = \text{constant} / \sqrt{\rho(T_1)} \qquad [17]$$

$$\dot{V}_{T_2} = \text{constant} / \sqrt{\rho(T_2)} \qquad [18]$$

and

$$\frac{\dot{V}_{T_1}}{\dot{V}_{T_2}} = \sqrt{\frac{\rho(T_2)}{\rho(T_1)}} \qquad [19]$$

The temperature for which the measuring device is calibrated is called T_k, and T_1 is replaced by T_u, the outdoor air temperature. This gives:

$$\dot{V}_{T_u} = \sqrt{\frac{\rho(T_k)}{\rho(T_u)}} \cdot \dot{V}_{T_k} \qquad [20]$$

But, from Equation (11)

$\rho(T) = \text{constant}/T$

Which means that we can write:

$$\dot{V}_{T_u} = \dot{V}_{in} = \sqrt{\frac{T_u}{T_k}}\ \dot{V}_{T_k} \qquad [21]$$

If the indoor temperature T_i and the calibration temperature T_k are the same, we get, from Equation (15):

$$\dot{V}_{out} = \frac{T_i}{T_u}\dot{V}_{in} = \frac{T_i}{T_u}\sqrt{\frac{T_u}{T_i}} \cdot \dot{V}_{T_i} = \sqrt{\frac{T_i}{T_u}} \cdot \dot{V}_{T_i} \qquad [22]$$

Internal underpressure

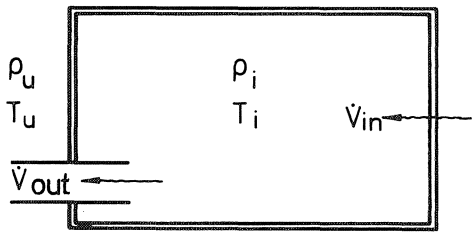

FIG. 10. Internal underpressure: nomenclature.

With corresponding reasoning to that in the internal overpressure case, we get:

$$\dot{V}_{in} = \frac{T_u}{T_i}\ \dot{V}_{out} \qquad [23]$$

As before, this expression is valid for flow meters which measure the mass flow only if $T_i = T_k$, i.e. the temperature for which the flow meter is calibrated.

If $T_i \neq T_k$, V_{out} must be corrected:

$$\dot{V}_{T_i} = \dot{V}_{out} = \sqrt{\frac{T_i}{T_k}}\ \dot{V}_{T_k} \qquad [24]$$

Accuracy of measurement

The final result from an airtightness measurement using the pressure method is the air leakage per unit of volume for a given pressure difference between the interior and exterior of the building. Measurement thus includes two main components: air flow measurement and pressure measurement. According to Svensson (1977), a measurement error can be regarded as consisting of three components, namely the instrument error m_1, the method error m_2 and the read-off error m_3. The Probable Measurement Error $\overline{m}$ is then calculated from the following expression:

$$\overline{m} = \sqrt{m_1^2 + m_2^2 + m_3^2} \qquad [25]$$

Figure 11 shows a block diagram of the different elements of the pressure method.

The air flow measurement and the pressure measurement are regarded as two parallel sequences.

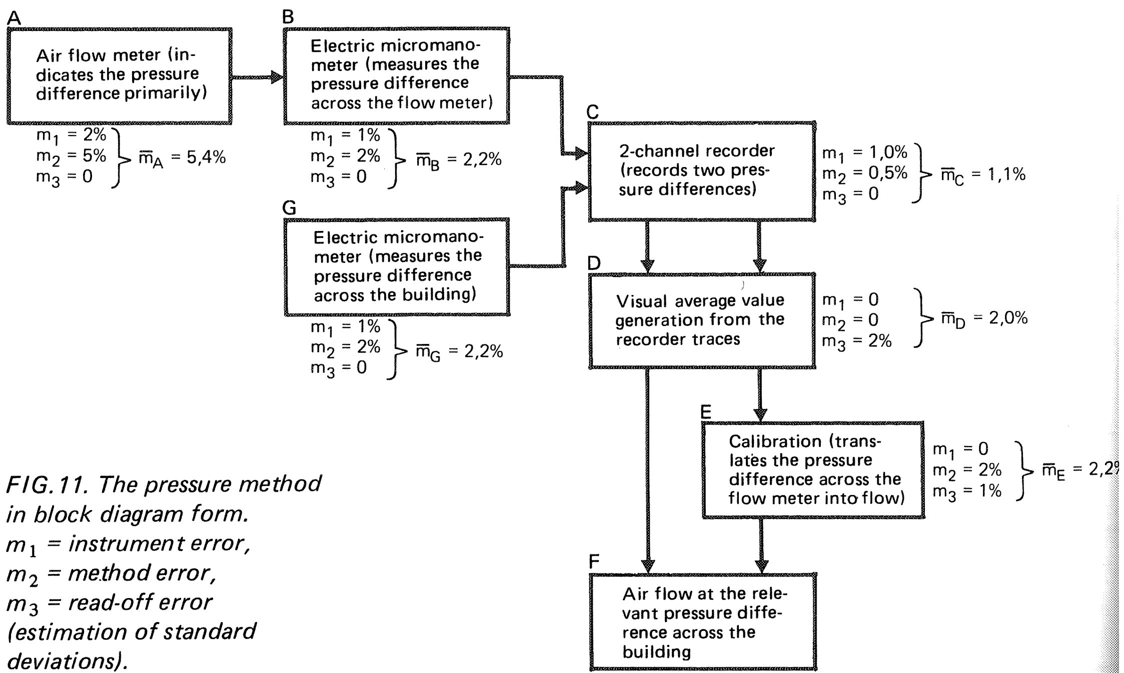

FIG. 11. The pressure method in block diagram form.
m_1 = instrument error,
m_2 = method error,
m_3 = read-off error
(estimation of standard deviations).

Temperature correction of flow measurements — summary

Alternative 1: Flow meter measuring volume flow (hot-wire anemometer etc.)

Internal overpressure

$$Q_{ö} = \frac{T_i}{T_u} Q_{avl}$$

Internal underpressure

$$Q_u = \frac{T_u}{T_i} Q_{avl}$$

Alternative 2: Flow meter measuring mass flow (orifice plate, pitot tube etc.)

Internal overpressure

$$Q_{ö} = \underbrace{\frac{T_i}{T_u} \cdot \sqrt{\frac{T_u}{T_k}}\, Q_{avl}}_{\text{general}} = \underbrace{\sqrt{\frac{T_i}{T_u}} \cdot Q_{avl}}_{\text{if } T_i = T_k}$$

Internal underpressure

$$Q_u = \underbrace{\frac{T_u}{T_i} \cdot \sqrt{\frac{T_i}{T_k}}\, Q_{avl}}_{\text{general}} = \underbrace{\frac{T_u}{T_i}\, Q_{avl}}_{\text{if } T_i = T_k}$$

Where:

$Q_{ö}$ = corrected volume flow for overpressure measurements, m^3/h

Q_u = corrected volume flow for underpressure measurements, m^3/h

T_i = indoor air temperature, K

T_u = outdoor air temperature, K

T_k = the air temperature for which the measuring device is calibrated, K (normally 20°C = 293 K)

Q_{avl} = flow from calibration graph or table, m^3/h, at the calibration temperature

Air flow measurement

From expression [25] the probable measurement error for flow measurement $\bar{m}_Q$ is given by:

$$\bar{m}_Q = \sqrt{\bar{m}_A^2 + \bar{m}_B^2 + \bar{m}_C^2 + \bar{m}_D^2 + \bar{m}_E^2} \quad [26]$$

This treatment regards the errors as statistically independent, which is also likely to be the case in practice. Using the estimated measurement errors given in Figure 11, we get:

$$\bar{m}_Q = \sqrt{5.4^2 + 2.2^2 + 1.1^2 + 2.0^2 + 2.2^2} = \sqrt{44.05} = 6.48\%$$

This is thus the magnitude of the probable error in 'pure' flow determination.

Pressure measurement

Similarly, chain G-C-D-F must be traversed:

$$\bar{m}_{\Delta p} = \sqrt{m_G^2 + m_C^2 + m_D^2} \quad [27]$$

i.e.

$$\bar{m}_{\Delta p} = \sqrt{2.2^2 + 1.1^2 + 2.0^2} = \sqrt{10.05} = 3.2\%$$

This error can probably increase when there is a gusty wind, which would primarily result in the read-off error m_3 in Frame D in Figure 11 increasing. Assume that $m_3^D = 5\%$. This means that $\bar{m}_D = 5\%$, causing $\bar{m}_{\Delta p}$ to increase to

$$\sqrt{2.2^2 + 1.1^2 + 5.0^2} = 5.6\%.$$

The above reasoning has shown that if selected (realistic) conditions are chosen it is possible to determine a pair of values (Δp,Q) within the range ($\Delta p \pm 0.06\ \Delta p$, Q $\pm$ 0.06 Q).

According to the proposed method of working given under Section 2.1.2, at least four such pairs of values should be obtained during the test, uniformly distributed within the range 20–55 Pa (see Figure 12). From these points, a curve can be drawn in.

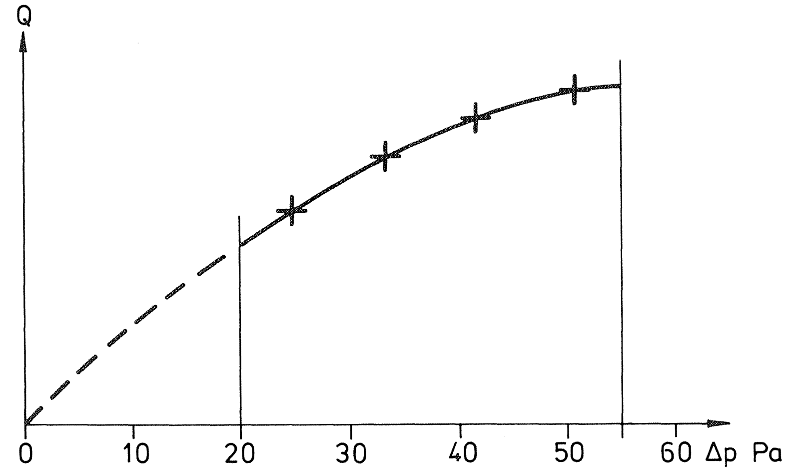

FIG. 12. Q - Δp diagram for pressure testing.

Statistical theory indicates that this should cause the errors (= the standard deviations) in Δp and Q to be reduced:

The new quantities are called $\bar{m}^{tot}_{\Delta p}$ and $\bar{m}^{tot}_{Q}$ respectively.

The number of pairs of values obtained is n.

$$\bar{m}^{tot}_{\Delta p} = \bar{m}_{\Delta p}/\sqrt{n} \qquad [28]$$

$$\bar{m}^{tot}_{Q} = \bar{m}_{Q}/\sqrt{n} \qquad [29]$$

Four pairs of equations give the following numerical result

$\bar{m}^{tot}_{\Delta p} = 0.06/2 = 0.03$

$\bar{m}^{tot}_{Q} = 0.06/2 = 0.03$

The final result

The final result of the test should be an air flow at a pressure difference Δp = 50 Pa across the building. In order to relate the errors in the pressure and flow measurements, the relationship between Q and Δp must be studied. This can often be expressed as:

$$Q = f(\Delta p) = A \cdot \Delta p^B \qquad [30]$$

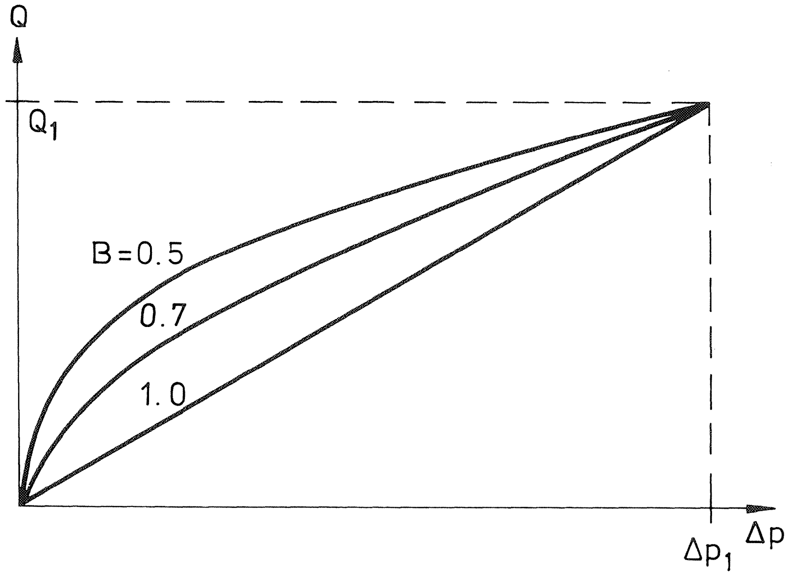

FIG. 13. The leakage flow Q as a function of the pressure difference Δp across the building for different values of exponent B in the expression $Q = A \cdot \Delta p^B$.

The differential of f(Δp) is expressed:

$$dQ = f'(\Delta p)\ d(\Delta p) = A \cdot B \cdot \Delta p^{B-1} \cdot d(\Delta p) \qquad [31]$$

A is calculated so that, for different values of B, Q is equal to a given value of Q_1 at pressure difference Δp_1. See Figure 13.

$$A = \frac{Q_1}{\Delta {p_1}^B} \qquad [32]$$

Substituting the expression for A in (31), we get:

$$dQ = \frac{Q_1}{\Delta {p_1}^B} \cdot B \cdot \Delta p^{B-1}\ d(\Delta p) \qquad [33]$$

This expression makes it possible to study how an error in the determination of the pressure difference across a building, Δp, affects determination of the leakage flow Q.

For $\Delta p = \Delta p_1$

$$dQ = \frac{Q_1}{\Delta p_1^{B}} \cdot B \cdot \Delta p_1^{B-1} \cdot d(\Delta p) = \frac{Q_1 \cdot B}{\Delta p_1} d(\Delta p) \qquad [34]$$

or

$$\frac{dQ}{Q_1} = B \frac{d(\Delta p)}{\Delta p_1} \qquad [35]$$

i.e. the relative errors in Δp and Q are proportional, with the exponent B as the constant of proportionality.

The final probable error $\bar{m}_Q^{final}$ in the air flow consists of an independent component, $\bar{m}_Q^{tot}$, and a portion which is dependent upon the error in Δp and is equal to $B \cdot \bar{m}_{\Delta p}^{tot}$.

$$\bar{m}_Q^{final} = \sqrt{(\bar{m}_Q^{tot})^2 + (B \cdot \bar{m}_{\Delta p}^{tot})^2}$$

Substituting real values, we get:

$$\bar{m}_Q^{final} = \sqrt{0.03^2 + (0.5 \cdot 0.03)^2} = 0.03 \qquad \text{for } B = 0.5$$

$$\bar{m}_Q^{final} = \sqrt{0.03^2 + (0.7 \cdot 0.03)^2} = 0.04 \qquad \text{for } B = 0.7$$

$$\bar{m}_Q^{final} = \sqrt{0.03^2 + (1.0 \cdot 0.03)^2} = 0.04 \qquad \text{for } B = 1.0$$

This calculation thus enables it to be shown that the result of the pressure measurement method – i.e. the air flow at 50 Pa pressure difference – can be given with an accuracy of ±4%.

This is the result obtained if the measuring equipment is composed as indicated in the block diagram in Figure 11. However, in some cases liquid manometers are used for pressure measurement. This means that component C (Figure 11) is eliminated from the flow and pressure measurements. Components B and G are replaced by liquid manometers with the following estimated errors:

B, G: m_1 = 5% instrument error
m_2 = 2% method error
m_3 = 4% read-off error

This means that $\bar{m}_B = \bar{m}_G = \sqrt{25 + 4 + 16} = 6.7\%$

Component D is replaced by manual visual averaging of the height of the liquid columns. With this procedure, m_3 is estimated to (at least) 10%, i.e. m_D = 10% and gives:

$$\bar{m}_Q = \sqrt{\bar{m}_A{}^2 + \bar{m}_B{}^2 + \bar{m}_D{}^2 + \bar{m}_E{}^2} =$$

$$= \sqrt{5.4^2 + 6.7^2 + 10.0^2 + 2.2^2} = 13.3\%$$

Similarly:

$$\bar{m}_{\Delta p} = \sqrt{\bar{m}_G{}^2 + \bar{m}_D{}^2} = \sqrt{6.7^2 + 10.0^2} = 12.0$$

$$\bar{m}_Q^{tot} = 13.3/\sqrt{n} = 13.3/2 = 6.7\%$$

$$\bar{m}_{\Delta p}^{tot} = 12.0/\sqrt{n} = 12.0/2 = 6.0\%$$

$$\bar{m}_Q^{final} = \sqrt{6.7^2 + (0.7 \cdot 6.0)^2} = 7.9\% \qquad \text{if } B = 0.7$$

This means that the final probable error in the determination of the air flow at 50 Pa, using liquid manometers instead of electric manometers with recorders, is 8% instead of the 4% as would be expected in the latter case.

Measurement precision

The above reasoning has been primarily concerned with the likely accuracy (or perhaps more correctly, inaccuracy) of measurement, i.e. how near to a true value it is possible to come for each individual test. However, it is also desirable to be able to use the measurements on other occasions and for other applications. The whole concept of precision is tied to this view.

The wind velocity around a building, together with the temperature difference between internal and external air, generates 'natural' pressure differences across the building envelope. These pressure differences affect the measurement results by superimposing themselves on the pressure difference generated by the fan.

The effect of wind

The wind pressure p acting on a surface is generally expressed by

$$p = \mu \cdot \frac{\rho \cdot v^2}{2} \qquad [36]$$

where:

μ = the shape factor; see Figure 14

ρ = the density of air, kg/m^3

v = the wind velocity, m/s

The magnitude of the shape factor varies from place to place across the external surface of the building. Using a mass balance equation for inward- and outward-flowing air, an internal reference pressure can be calculated. If the building is exposed to wind alone, this internal reference pressure can also be expressed as an internal shape factor, shown as –0.4 in Figure 14.

Starting from Figures 14 and 15 as a basis, Lind et al (1976) have prepared a diagram which shows how the quotient of the air flow in windy conditions, Q_{wind}, and the air flow in calm conditions, Q_{calm}, depends upon the wind velocity and the pressure difference during pressure testing. See Figure 16.

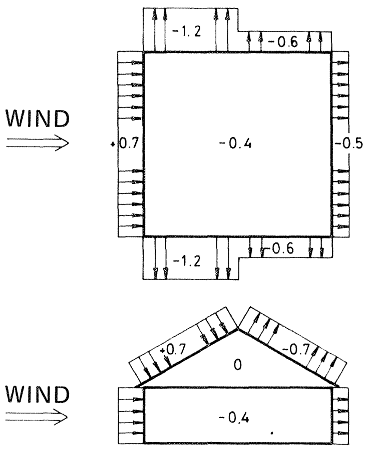

FIG. 14. Shape factors for a building acted upon by wind. Source: Lind et al (1976).

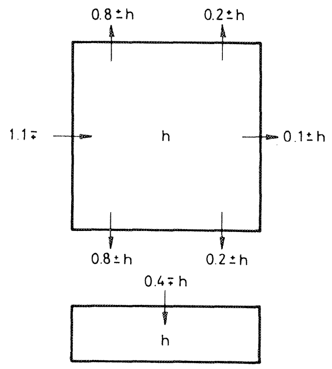

FIG. 15. The resulting shape factors due to overpressure and underpressure measurements. Source: Lind et al (1976).

Figure 16 indicates that the pressure test measurement method is more sensitive to disturbance due to the effects of wind when measuring with internal overpressure than when measuring with internal underpressure. This is due to the fact that underpressure naturally arises inside a building against which the wind is blowing.

When carrying out overpressure measurements, a wind velocity of 8 m/s can create a 10% variation of the flow, whereas for underpressure measurements a wind velocity of 10 m/s is necessary to produce the same effect. (Cf. the limit of 8 m/s in the measurement method proposal in Section 2.1.2.)

The effect of temperature difference

The difference in indoor and outdoor air temperatures causes chimney effect — an air pressure difference between the indoor and outdoor air. There is normally a linear pressure distribution between the top and the bottom of the building so that, depending upon where the leaks in the building envelope are, there must be a height where the pressure difference is zero. See Figure 17.

The pressure difference, Δp, can approximately be expressed as

$$\Delta p = 4{,}35 \cdot 10^{-2} \cdot h(\upsilon_i - \upsilon_u) \text{ (Pa)} \qquad [37]$$

where:

h = the height to the level where $\Delta p = 0$ m (normally equal to half the height of the building)

υ_i and υ_u = indoor and outdoor air temperatures (°C) respectively

For a single-storey individual house, h can be taken as 1.5 m. This gives

$\Delta p = 4.35 \cdot 10^{-2} \cdot 1.5\,(\upsilon_i - \upsilon_u) = 6.53\,(\upsilon_i - \upsilon_u) \cdot 10^{-2}$

The average pressure difference across the facade is half this magnitude.

$\Delta p = 3.26\,(\upsilon_i - \upsilon_u) \cdot 10^{-2}$

For $\upsilon_i - \upsilon_u = 30°C$, $\Delta p \cong 1$ Pa

In other words, the temperature difference between the indoor and the outdoor air (the chimney effect) evidently has little effect except for high rise buildings.

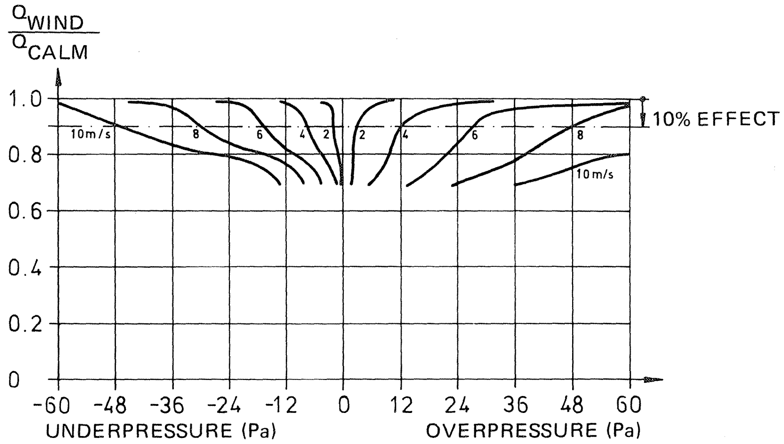

FIG. 16. Diagrammatic illustration of how the measurement precision, when using the pressure test measurement method, depends upon the wind velocity and the magnitude of the overpressure or underpressure during the test. Source: Lind et al (1976).

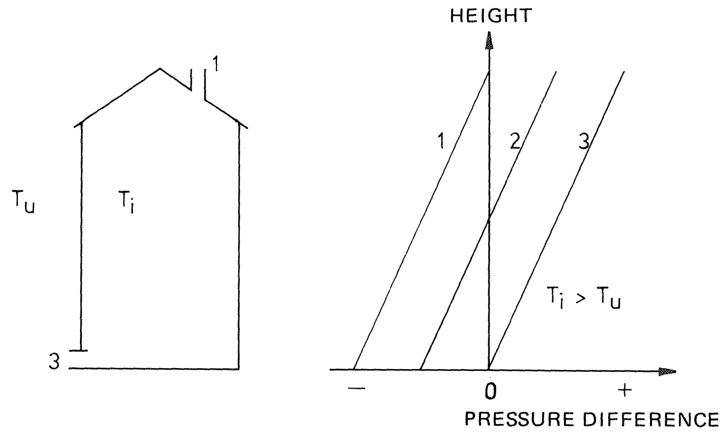

FIG. 17. The pressure conditions in a building due to the chimney effect.
1. An opening only at the top.
2. Openings uniformly distributed (=leaks).
3. An opening only at the bottom.
Source: Nevander & Samuelson (1976).

2.2 QUALITATIVE MEASUREMENTS

2.2.1 Thermography

The most commonly used qualitative testing method for the investigation of airtightness of buildings is the infrared or thermal camera. It is particularly useful for investigating, primarily at site, the position of leaks and, to a certain degree, for quantifying the effect of the leaks. By introducing an underpressure in the building, e.g. by using the cooker exhaust canopy fan, leaks can be easily traced with the camera. This effect, of course, is due to the fact

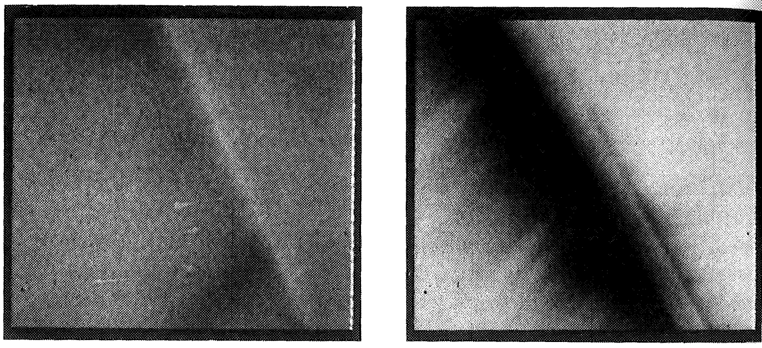

FIG. 18. Thermograph pictures of the joint between an external wall and the sloping ceiling on the upper floor of a 1 1/2-storey single-family house. The picture on the left shows how warm air is leaking through the joint (light grey colour) under natural pressure conditions. When a 50 Pa internal underpressure is applied, a considerable inflow leakage of cold air arises, as can be seen from the dark grey areas in the right-hand picture. The air velocity at the edge of the crack was 0.5–2 m/s.

that the colder external air, in entering the building, cools the surfaces adjacent to the leak, causing them to become 'visible' to the camera. In connection with thermography, measurements are often made with a sensitive anemometer of the air velocity in connection with local leaks revealed and documented by the thermal camera. Figure 18 is an example of the pictures obtained.

The equipment used for thermography, together with a description of the method of working, has been carefully and exhaustively described by Axén and Pettersson (1977 and 1979), so no further description is necessary here.

3 Measurement results

The Division of Building Technology of Lund Institute of Technology administers, for the time being, a computer file of recorded results obtained from actual pressure and/or tracer gas measurements on buildings. At present, information is provided for the file by the various Institutes of Technology, the National Swedish Authority for Testing, Inspection and Meteorology, BPA Byggproduktion AB, the National Association of Tenants' Savings and Building Societies, AB Skånska Cementgjuteriet, Ytong AB and the Tyrén group of companies. At the end of June 1978 the file contained results of measurements on 384 individual single-family houses, 43 apartments and 1 industrial building. Recently constructed buildings dominate among the material, and only a few older buildings have been measured. The printout reproduced in Appendix 1 contains about a further score of individual single-family houses, over and above the 384 as at the end of June, 1978. The file has aroused international interest, and is therefore written in English.

Table 3 is a summary of the measured results at the end of June 1978.

Category	No.	n_{50} Average value	Air changes/h Standard deviation
Detached single-family houses and linked houses made of wood	205	3.66	1.24
single-storey	70	3.79	1.32
1 1/2-storey	135	3.52	1.18
Detached single-family houses of lightweight concrete	12	1.98	1.46
Detached single-family houses and linked houses of lightweight concrete & wood, single-storey	9	2.23	0.67
1 1/2-storey	17	3.74	0.76
Row houses of wood	49	3.14	1.36
single-storey	33	2.89	1.02
1 1/2-storey	16	3.65	1.56
Row houses with party walls and floor structures of concrete. Curtain walls with studding frame.	5	1.72	0.18
Block of flats of concrete and with curtain walls	23	0.96	0.34

Table 3. Summary of results of pressure testing. The data relates to houses built after 1976-01-01.

Appendix 1

Data from measurements of airtightness

Description of and commentaries on the data file on the following pages

Col. 1 Object number.
Indicates the sequential number in an arbitrary number series chosen by each testing group.

Col. 2 Year of building.
Gives the two last figures in the year.

Col. 3 The number of floors in the building tested.

Col. 4 Production method.
P = Prefabricated
- V = Volume elements
- S = Surface elements

S = Site-built

Col. 5 Type of building
D = Detached house
R = Row house
L = Linked house
S = Split level house

Col. 6 Predominant structural material.
W = Wood
L = Lightweight concrete
V = Lightweight concrete and wood
C = Concrete
B = Brick
M = Concrete with curtain walls.

Col. 7 Ventilation system.
S = Natural ventilation
F = Mechanical exhaust
FT = Mechanical supply and exhaust
X = FT + heat exchanger

Col. 8 Window opening direction.
O = Outwards
I = Inwards
B = Both directions used

Col. 9 Foundation type.
C = Crawl space
F = Floor slab on ground
B = Cellar (basement)

Col. 10 Volume of building in m^3 (i.e. volume tested). Determined in accordance with SP 1977:1.

Col. 11 Envelope area of the building in m^2 (test volume). This includes all surfaces through which air can leak and which bound the test volume. Walls and floors below ground level are not included, nor is the area of the foundation raft where the house is founded directly on the ground.

Col. 12 Ratio of volume and envelope area. Given to one decimal place.

Col. 13 Total window and door area, m^2, calculated from the external dimensions over frames, jambs, etc.

Col. 14 Air leakage at 50 Pa, internal overpressure, m^3/h.

Col. 15 Air leakage at 50 Pa, internal underpressure, m^3/h.

Col. 16 Air leakage at 50 Pa per volume unit, $m^3/m^3 \cdot h$, or air changes/h, internal overpressure. Given to one decimal place.

Col. 17 Air leakage at 50 Pa per volume unit, $m^3/m^3 \cdot h$, or air changes/h, internal underpressure. Given to one decimal place.

Col. 18 Air leakage at 50 Pa per unit surface area (envelope area), $m^3/m^2 \cdot h$, internal overpressure. Given to one decimal place.

Col. 19 Air leakage at 50 Pa per unit surface area (envelope area), $m^3/m^2 \cdot h$, internal underpressure. Given to one decimal place.

Col. 20 Air changes rate, air changes/h, under ambient weather conditions. Multiplied by 100. This indicates the ventilation rate with the controlled ventilation system and devices sealed.

Col. 21 Outdoor air temperature, °C. Given in whole degrees with + or – as required.

Col. 22 Indoor air temperature, °C.

Col. 23 Wind velocity in the vicinity of the building, m/s.

Col. 24 Wind direction, given as N, NE, E, SE, S, SW, W, NW.

Separate copies of the data file can be ordered from:
Byggnadsteknik I, LTH, Box 725, S-220 07 LUND, SWEDEN.

1	OBJECT NUMBER		
2	YEAR OF ERECTION		
3	NUMBER OF STOREYS		
4	PRODUCTION	P=PREFABRICATED S=SURFACE ELEMENT S=BUILT ON SITE	V=VOLUME ELEMENT
5	HOUSE SITE	D=DETACHED HOUSE S=SPLIT LEVEL HOUSE	R=ROW HOUSE L=LINKED HOUSE
6	MATERIAL	W=WOOD V=LIGHT WEIGHT CONCRETE & WOOD B=BRICK	L=LIGHT WEIGHT CONCRETE C=CONCRETE M=CONCRETE/CURTAIN WALL
7	VENT. SYSTEM	S=NATURAL VENTILATION FT=BALANCED	F=EXHAUST AIR X=FT & HEAT EXCHANGER
8	WINDOW OPENING DIRECTION	O=OUTWARDS	I=INWARDS B=BOTH DIRECTIONS
9	GROUND	C=CRAWL-SPACE BASEMENT F=FLOOR SLAB ON GROUND	B=BASEMENT STOREY

10 VOLUME, M3
11 AREA OF HOUSE ENCLOSURE, M2
12 VOLUME/AREA
13 AREA OF WINDOWS AND DOORS
14 AIR LEAKAGE AT 50 PA, POSITIVE PRESSURE DIFFERENCE , M3/H
15 AIR LEAKAGE AT 50 PA, NEGATIVE PRESSURE DIFFERENCE , M3/H
16 AIR CHANGE RATE AT 50 PA, POSITIVE PRESSURE DIFFERENCE, M3/M3/H
17 AIR CHANGE RATE AT 50 PA, NEGATIVE PRESSURE DIFFERENCE, M3/M3/H
18 SPECIFIC AIR LEAKAGE AT 50 PA, POSITIVE PRESSURE DIFFERENCE, M3/M2/H
19 SPECIFIC AIR LEAKAGE AT 50 PA, NEGATIVE PRESSURE DIFFERENCE, M3/M2/H
20 VENTILATION RATE AT PREVAILING WEATHER CONDITIONS,(AIR CHANGES/HOUR)*100
21 OUTSIDE TEMPERATURE, CENTIGRADES
22 INSIDE TEMPERATURE, CENTIGRADES
23 WIND VELOCITY, M/S
24 WIND DIRECTION

HOUSES
CTH CHALMERS UNIVERSITY OF TECHNOLOGY

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	77	1.5	PV	D	W	F		C	380	315	1.2		1820	1900	4.8	5.0	5.8	6.0	21	-6	21	1	
1													1640	1500	4.3	4.0	5.2	4.8	6	+20	23	3	
2	77	1.5	PV	D	W	F		C	381	315	1.2		1475	1400	3.9	3.7	4.7	4.4	12	+2	23	3	
2	77	1.5	PV	D	W	F		C	381	315	1.2		1310	1310	3.4	3.4	4.2	4.2	9	+13	23	3	
3	77	1.5	PV	D	W	F		C	370	315	1.2		2370	2270	6.4	6.1	7.5	7.2	22	0	21	1	
3	77	1.5	PV	D	W	F		C	370	315	1.2		1930	2030	5 2	5.4	6.1	6.3	42	+20	26	10	
4	77	1.5	PV	D	W	F		C	379	315	1.2		1860	1840	4.9	4.9	5.8	5.7	32	+2	21	12	
4	77	1.5	PV	D	W	F		C	379	315	1.2		1850	1810	4.9	4.8	5.9	5.7	11	+11	22	3	
5	77	1.5	PV	D	W	F		C	375		1.2		1950	2015	5.2	5.4	6.2	6.4	29	+4	21	3	
5	77	1.5	PV	D	W	F		C	375		1.2		1870	1960	5.0	5.2	5.9	6.2	19	+23	25	10	
6	77	1.5	PV	D	W	F		C	381	315	1.2		1710	1760	4.5	4.6	5.4	5.6	15	+2	22	2	
6	77	1.5	PV	D	W	F		C	381	315	1.2		1540	1500	4.0	3.9	4.9	4.8	12	+14	21	2	
7	77	1.5	PV	D	W	F		C	379	315	1.2		1415	1440	3.7	3.8	4.5	4.6	19	+3	21	5	
7	77	1.5	PV	D	W	F		C	379	315	1.2		1350	1330	3.6	3.5	4.3	4.2	9	+12	20	6	
8	77	1.5	PV	D	W	F		C	380	315	1.2		1600	1540	4.2	4.1	5.1	4.9	13	+7	23	4	
8	77	1.5	PV	D	W	F		C	380	315	1.2		1500	1420	4.0	3.77	4.8	4.5	8	+13	22	2	
9	77	1.5	PV	D	W	F		C	373	315			1870	1970	4.9	5.2	5.8	6.1	22	+3	23	1	
9	77	1.5	PV	D	W	F		C	373	315			2020	2070	5.3	5.5	6.3	6.5	12	+15	21	0	
10	77	1.5	PV	D	W	F		C	379	315			1290	1310	3.4	3.5	4.1	4.2	10	+7	22	3	
10	77	1.5	PV	D	W	F		C	379	315	1.2		1290	1310	3.4	3.5	4.1	4.2	6	+12	22	3	
11	77	1.5	PV	D	W	F		C	381	315	1.2		1450	1530	3.8	4.0	4.6	4.9	18	-3	20	3	
11	77	1.5	PV	D	W	F		C	381	315	1.2		1440	1510	3.8	4.0	4.5	4.8	13	+18	26	5	
12	77	1.5	PV	D	W	F		C	380	315	1.2		1520	1710	4.0	4.5	4.8	5.4	21	+3	22	4	
12	77	1.5	PV	D	W	F		C	380	315	1.2		1620	1670	4.3	4.4	5.2	5.3	7	+22	28	3	
13	77	1.5	PV	D	W	F		C	379	315	1.2		1560	1580	4.1	4.2	5.0	5.0	32	-2	22	5	
13	77	1.5	PV	D	W	F		C	379	315	1.2		1590	1550	4.2	4.1	5.1	4.9	9	+22	26	2	
14	77	1.5	PV	D	W	F		C	380	315	1.2		1350	1460	3.6	3.8	4.3	4.6	13	+2	23	2	
14	77	1.5	PV	D	W	F		C	380	315	1.2		1360	1380	3.6	3.6	4.3	4.3	8	+17	23	5	
15	77	1.5	PV	D	W	F		C	380	315	1.2		1550	1810	4.1	4.8	4.9	5.8	12	+7	21	2	
15	77	1.5	PV	D	W	F		C	380	315	1.2		1520	1500	4.0	4.0	4.8	4.8	9	+16	22	4	
16	77	1.5	PV	D	W	F		C	379	315	1.2		1550	1620	4.1	4.3	4.9	5.2	12	+11	21	2	
16	77	1.5	PV	D	W	F		C	379	315	1.2		1580	1500	4.2	4.0	5.1	4.8	7	+16	23	3	

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17 77 1.5 PV D W  F   C 378 315 1.2     1930 2010 5.1 5.3 6.1 6.4 11 +11 19  2
17 77 1.5 PV D W  F   C 379 315 1.2     1840 1980 4.9 5.0 5.8 6.0 18 +10 18  8
18 77 1.5 PV D W  F   C 382 315 1.2     1240 1360 3.3 3.6 4.0 4.3  8  +7 24  3
19 77 1.5 PV D W  F   C 380 315 1.2     1380 1270 3.6 3.3 4.3 4.0 12 +26 24  4
20 77 1.5 PV D W  F   C 380 315 1.2     1920 1870 5.1 4.9 6.1 6.0 18 +10 24  2
20 77 1.5 PV D W  F   C 379 315 1.2     1790 1790 4.7 4.7 5.7 5.7 23  +6 20  3
21 77 1.5 PV D W  F   C 382 315 1.2      970  930 2.5 2.4 3.1 2.9  8 +12 22  3
21 77 1.5 PV D W  F   C 382 315 1.2     1010 1070 2.6 2.8 3.2 3.4  8 +20 25  3
22 77  2  PV D W  F   B 415             2000 2080 4.8 5.0         11 +12 23  0
22 AFTER TIGHTENING MEASURES            1800 1700 4.3 4.1         15 +18 22  0
23 77  2  PV D W  F   B 491             2450 2500 5.0 5.1         30  +1 21  5
23 AFTER TIGHTENING MEASURES            1860 1690 3.8 3.4          9 +19 19  5
24 77  1  PV D W  F   C 276             1710 1740 6.2 6.3         18  +5 20  1
24 77  1  PV D W  F   C 276             1730 1530 6.3 5.5          6 +16 21  1
25 77  2  PV D W  F   B 419             2370 2290 5.7 5.5         32  +3 21  3
25 77  2  PV D W  F   B 419             2340 2110 5.6 5.0          6 +17 23  2
26 77  2  PV D W  F   B 415             2100 2040 5.1 4.9         16  +7 20  1
26 77  2  PV D W  F   B 415             2080 1940 5.0 4.7         18 +14 18  4
27 77   1 PS D B  F O F 336 245 1.4 29 1510 1360 4.5 4.0 6.2 5.6 10  -4 17  1  E
28 77   1 PS D B  X O F 285 243 1.2 29  920  860 3.2 3.0 3.8 3.5  8   0 21  2 SE
29 77   2 PS D B  X O B 545 345 1.6 29 1400 1290 2.6 2.4 4.1 3.7 10  -2 20  1  E
30 77 1.5 PS D W  F O F 324 214 1.5 31 2580 2340 8.0 7.2  12  11 22  -2 19  1  E
31 78 1.5 PS D W  S B F 334             1500 1360 4.5 4.1             -3 20  1
32 77 1.5 PS D W  S B F 324             1530 1220 4.7 3.8             -6 21  3
33 78 1.5 PS D W  S B F 324             1540 1280 4.8 4.0             -4 19  2
34 78 1.5 PS D W  S B F 334             1500 1360 4.5 4.1             -3 20  1
35 78 1.5 PS D W  F B F 292 292 1.0 22  280  240 1.0 0.8 1.0 0.8      +1 21  1
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 1  2   3  4 5 6  7 8 9  10  11  12 13   14   15  16  17  18  19 20  21 22 23 24
 1 76  1  PS R C     F         0.9             1.2     1 1                 1
 2 76  1  PS R C     F         0.9             1.2     1 1                 1
 3 76  1  PS R C     F         0.9             1.5     1.4                 1
 4 76  1  PS D C     F         1.0             1.7     1.6                 1
 5 76  1  PS D C     F         1.0             1.0     1.0                 1
 6 76  1  PS D C     F         1.0             0.8     0.7                 1
 7 76  1  PS D C     F         1.3             2.0     2.7                 2
 8 76  1  PS D C     F         1.3             2.2     3.0                 2
 9 76  1  PS D C     F         1.3             2.1     2.7                 2
10 76  1  PS R W     F                             2.8                     2
11 76 1.5  S D W     F         1.4             4.7     6.5                 4
12 76 1.5  S D W     F         1.4             5.1     7.0                 4
13 76  1  PS D W     F         1.1             3.1     3.4                 3
14 76  1  PS D W     F         1.1             3.1     3.4                 3
15 76  1  PS D W     F         1.1             3.8     4.1                 3
16 76  1  PS D W     F         1.1             3.8     4.2                 3
17 76  1  PS D W     F         1.1             4.1     4.5                 3
LTH  LUND INSTITUTE OF TECHNOLOGY
 1  2   3  4 5 6  7 8 9  10  11  12 13   14   15  16  17  18  19 20  21 22 23 24
 1 76 1.5 PV D W FT O C 374 312 1.2     1930 1594 5.2 4.3 6.2 5 1 20  +1 12  7
 2 75  1  PV D W FT O C 288 353 0.8     1730      5.9     4.9     16  +5 20  6
 3 69 1.5 PS D W  S O C 418 369 1.1     1770      4.2     4.8     29 +10 21  5
 4 69 1.5 PS D W  S O C 418 369 1.1                               39  +9 20  7
 5 69  1  PV R W  F O F 122 126 1.0      800      6.6     6.4     18 +10 23  8
 6 76 1.5 PV D W  F O F 215 190 1.1      740      3.5     3.9      7 +18 24  9
 7 76 1.5 SV D W  F O F 215 190 1.1      740      3.5     3.9     10 +14 22  6
 8 65  1   S D W  S O C 300 380 0.8     3190      9.9     8.4     34  +9 22  7
 9 76  1  PS D W FT O F 285 349 0.8      940      3.4     2.7      6 +19 23  4
10 76  1  PS D W FT O F 285 349 0.8      660      2.4     1.9      3 +18 24  4
11 76  2   S D L FT O C 393 346 1.1      490      1.2     1 4      6  +9 17 <2
12 74  2   S D L  F O B 548 244 2.2      850      1.6     3.5        +14 23 <2
13 77  1  PS D W  S O F 218 345         1050      4.8     3.0      6  +4 10  4
14 77  1  PS D W  S O F 214 180 1.2           485     2.3     2.7 15  +6 11  4
15 76 1.5 PV D W FT O F 457 338 1.4     2106      4.8     6.5     33  +4 22  2
16 77 1.5  S D W  F O F 497 308 1.6     1421 1511 2.9 3.0 4.6 4.9 15  +2 10  2
17 77 1.5  S D W  F O F 345 243 1.4     1350 1269 3.9 3.7 5.6 5.2 22  +1 22  4
18 77  1   S D W  F O F 214 181 1.2      583  598 2.7 2.8 3.2 3.3  9  +7 21  2
19 76  1  PS D W  F O C 252 313 0.8      709  690 2.8 2.7 2 3 2.2 19  +2 22  6
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20	77	1.5	PS	D	L	F	I	F	409	286	1.4		2810	2115	6.9	5.2	9.8	9.6	41	+6	20	5	
21	77	1.5	S	D	W	F	O	F	378	281	1.4		1859	1675	4.9	4.4	6.6	6.0	20	+8	21	2	
22	77	1.5	S	D	W	F	O	F	378	281	1.4		1740	1524	4.6	4.0	6.2	5.4	12	+10	22	2	
23	77	1.5	PS	D	W	F	O	F	276	201	1.4		1160	1239	4.2	4.5	5.8	4.5	22	+10	15	4	
24	77	1.5	S	D	W	F	I	F	347	251	1.4		938	919	2.7	2.6	3.7	3.7	10	+11	20	0	
25	77	1.5	PS	R	W	F	O	C	238	228	1.0		2180	2180	9.2	9.2	9 6	9.6	41	+12	21	2	
26	77	1.5	PS	R	W	F	O	C	238	228	1.0		1440	1220	6.1	5.1	6.8	5.7	17	+19	21	6	
27	77	1	S	D	W	F	O	F	327	255	1.3		670	690	2.1	2.1	2.6	2 7	12	+14	18	2	
28	75	1.5	PS	D	W	S	I	F	366	262	1.4		1585	1446	4.3	4.0	6.0	5.5	20	+18	22	2	
29	77	1.5	PS	D	W	FT	O	F	431	273	1.6		912	910	2.1	2.1	3.3	3.3	3	+18	14	2	
30	76	1.5	S	D	W	S		F	280	225	1.2		620	MEAN	2.5		3.1						
31	76	1.5	S	D	W	S		F	342	222	1.5		923	MEAN	2.7		4.2						
32	76	1.5	S	D	W	S		F	342	222	1.5		1505	MEAN	4.4		6.7						
33	77	1.5	PS	D	W	F		C	377	298	1.3		1450	1092	3.8	2.9	4.9	3.7	23	+6	20	3	SW
34	77	1.5	PS	D	W	F		C	412	315	1.3		1304	1362	3.2	3.3	4.1	4.3	22	+6	20	3	W
35	77	1.5	PS	D	W	F		C	377	298	1.3		1386	1499	3.7	4.0	4.7	5.0	30	+6	20	3	SW
36	77	1.5	S	D	W	F	O	F	378	281	1.4		605	397	1.6	1.1	2.2	1.4	12	0	20	4	E
37	77	1.5	S	D	W	F	O	F	378	281	1.4		726	559	1.9	1.5	2.6	2.0	09	0	20	6	E
38	77	1.5	PS	D	C	F	O	F	371	266	1.4	24	1100	MEAN	3.0		4.5		13				
39	77	1	PS	D	C	F	O	F	256	214	1.2	19	1025	MEAN	4.0		4.8		11				
40	77	1.5	PS	D	C	F	O	F	440	292	1.5	28	1150	MEAN	2.6		3.9		17				
41	78	1	PS	R	W	S	I	F	165	150	1.1		548	469	3.3	2.8	3.6	3.1	15	-6	18	2	SW
42	78	1	PS	R	W	S	I	F	193	167	1.2		598	510	3.0	2.6	3.5	3.0	05	-6	18	2	SW
43	78	1.5	PS	D	W	F	I	F	306	225	1.4		1551	1125	5.1	3.7	6.9	5.0	11	-2	20	4	NE
44	78	1.5	PS	D	W	F	I	F	306	225	1.4		2239	2713	7.3	8.9	10	12	27	-2	17	4	NE
45	78	2	PS	R	W	F	I	F	270	226	1.2		956	821	3.5	3.0	4.2	3.6	06	+10	18	6	NE
46	76	2	S	R	W	F	O	B	202	222	0.9		593	475	2.9	2 4	2.7	2.1	16	+2	20	0	

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1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	67	1	PS	D	W	S		C	280				2505		9.0					-1			
2	67	1	PS	D	W	S		C	280				1560		5.6					+3			
3	67	1	PS	L	W	S		C	260				4030		15.5					+5			
4	67	1	PS	L	W	S		C	260				3430		13.2					+5			
5	75	1	S	D	W	S		B	260				2010		7.7					-2			
6	75	2	S	D	W	S		B	335				2340		7.0					+1			
7	75	2	S	D	W	S		B	335				2135		6.4					+1			
8	75	2	S	D	W	S		B	335				2210		6.6					+8			
9	70	1	S	D	W	S		C	300				825		2.8					+2			
10	70	1	S	D	W	S		C	300				775		2.6					+2			

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1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	72	1	PS	R	W	S	I	F	300	271	1.1	28	1205	1425	4.0	4.8				-4	19	0	
2	76	2	PS	D	L	S	I	C	371	397	0.9	27		550		1.5				-1	20	3	
3	76	1.5	PS	D	L	S	I	F	277	187	1.5	26	880	830	3.2	3.0				-2	20	3	
3	76	1.5	PS	D	L	S	I	F	277	187	1.5	26	1010	985	3.7	3.6				-2	20	3	
3	76	1.5	PS	D	L	S	I	F	277	187	1.5	26	800		2.9					-2	20	3	
3	76	1.5	PS	D	L	S	I	F	277	187	1.5	26	714		2.6					-2	20	3	
4	77	1.5	PS	L	W	F	B	F	305	201	1.5	20	1060	817	3.5	2.7				-3	21	2	
5	77	1.5	PS	L	W	F	B	F	305	201	1.5	20	1130	1040	3.7	3.4				+1	20	2	
6	77	1.5	PS	L	W	F	B	F	305	201	1.5	20	920	705	3.0	2.3				+1	18	2	
6	77	1.5	PS	L	W	F	B	F	305	201	1.5	20	662	633	2.2	2.1				+1	18	2	
7	77	1.5	PS	L	W	F	B	F	305	201	1.5	20	1235	1070	4.0	3.5				+1	19	2	
8	77	1.5	PS	D	V	F	B	F	330	232	1.4	28	1530	1450	4.6	4.4				-1	18	1	
9	77	1.5	PS	D	V	F	B	F	327	231	1.4	26	1360	1405	4.2	4.3				+2	17	1	
10	77	1.5	PS	D	V	F	B	F	327	231	1.4	26										1	
11	77	1.5	PS	D	V	F	B	F	333	232	1.4	28	1410	1290	4.2	3.9				+2	17	1	
12	77	1.5	PS	D	V	F	B	F	336	233	1.4	30	1280	1250	3.8	3.7				+2	16	1	
13	77	1.5	PS	D	V	F	B	F	327	231	1.4	26	1290	1240	3.9	3.8				+2	16	1	
13	77	1.5	PS	D	V	F	B	F	327	231	1.4	26	1010	990	3.1	3.0				+2	16	1	
14	77	1.5	PS	L	W	F	B	F	308				1170	1085	3.8	3.3				+14	21	2	
15	77	1.5	PS	L	W	F	B	F	308				950	720	3.1	2 3				+14	21	2	
16	77	1.5	PS	L	V	F	B	F	390	258	1.5	29	1460	1370	3.7	3.5				+15	22	2	
17	77	1.5	PS	L	V	F	B	F	393	260	1.5	30	1410	1360	3.6	3.5				+15	18	2	
17	77	1.5	PS	L	V	F	B	F	393	260	1.5	30	1410	1360	3.6	3.5				+15	18	2	
18	76	1.5	PS	L	V		B	F	312			22	1390	1360	4.5	4.4				+16	23	2	
23	77	1		R			O	B	580					1960		3.4				+20	19	1	

24	73	1.5	S	D	W	S	I	F	300				1240	1180	4.1	3 9				+13	20	1	
25		1.5	PS	D					265				1280	1020	4.8	3.8				+23	23	1	
26		1.5	PS	D					387				1500	1290	3.9	3.3				+23	23	1	
27	77	1	PS	D	W	F	O	C	295				1260	1050	4.3	3.6				+24	23	1	
28	74	1	PS	D	W	F	B	B	420				1340	1170	3.2	2.9				+20	20		
29	77	1	S	D	V	S		B	460				1500	1420	3.3	3.1				+18	26		
29	77	1	S	D	V	S		B	450				1060	1100	2.3	2.4				+18	26		
30	68	1	PS	D	W	S	B	B	590	319	1.8	24	2020	1850	3.4	3.1				+15	21	0	
31	69	1	S	D	L	S	B	B	530	256	2.1	21	2300	1880	4.3	3.5				+17	20	3	
32		2	PS	R	V		O	B	320				820	760	2.6	2.4				+20	21	3	
33	77	1.5	P	D	W	F	B	F	375				1800	1440	4.8	3.8				+14	20	3	
34	72	1	P	D	W	S	B	B	480				2350	2000	4.8	4.1				+16	21	0	
35	74	1	PS	D	W	S	B	B	505				1970	1770	3.9	3.5				+14	20	3	
36	77	1	PS	L	V			B	525				990	900	1.9	1.7				+16	19	2	
37	64	1.5	P	L	W	S	B	B	385	210	1.8	26	2380	2450	6.2	6.4				+8	21	1	
38	49	2	P	D	W	S	O	B	440			31	2340	2050	5.3	4.7				+10	20	0	
39	69	1	PS	D	W	S	O	B	485	245	2.0	23	2900	2300	6.0	4.7				+14	20	1	
41					L		I		320				1050	1100	3.3	3.4				+13	15		
42	77	1.5	PS	D	W			O	400	374	1.1	29	1070	1020	2.7	2.6				+1	22	1	
43	77	1	PS	D				B	426	222	1.9	25	1580	1360	3.7	3.2				+1	22	1	
44	77	1	PS	D				B	426	222	1.9	25	1780	1360	4.2	3.2				+1	22	1	
45	77	1	PS	D				B	426	222	1.9	25	1480	1300	3.5	3.1				+1	22	1	
46	77	1.5	PS	D				C	290	340	0.9	20	1760	1600	6.1	5.5				0	21	4	
47	77	1	PS	D				F	280	234	1.1	21	1170	980	4.2	3.5				0	20	4	
48	77	1	PS	D	W	F	O	B	430	232	1.9	29	2960	2980	6.9	6.9				-4	19	1	
49	77	1.5	PS	D	W	F	B	F	378	305	1.2	34	2410	2660	6.4	7.0				-4	20	1	
50	77	1.5	PS	D	W	F	B	F	378	305	1.2	34								-4	21	1	
51	77	1	PS	D	W	F	B	B	394	375	1.1	24	1270	1550	3.1	3.8				-4	20	1	
52	77	2	P	R	W	F	B	F	338	246	1.4	21	740	670	2.2	2.0				-2	17	1	
53	77	2	P	L	W	F	B	F	338	246	1.4	21	640	600	1.9	1.8				-2	18	1	
54	77	2	P	L	W	F	B	F	290	243	1.2	35	805	740	2.8	2.6				-2	19	1	
55	77	2	P	L	W	F	B	F	290	243	1.2	35	660	740	2.3	2.6				-2	19	1	
56	77	2	P	L	W	F	B	F	340	281	1.2	31	1080	1300	3.2	3.8				-2	18	1	
57	77	2	PS	R	W	F		F	295	213	1.4	28	860	1020	2.9	3.5				0	21	1	
58	77	2	PS	R	W	F		F	295	213	1.4	28	1430	1450	4.8	4.9				0	19	1	
59	77	1	PS	R	W	F		F	294	267	1.1	28	870	980	3.0	3.3				0	20	1	
60	78	2	P	L	W	F	I	F	340	281	1.2	31	900	990	2.6	2.9				+1	18	3	
61	78	2	P	L	W	F	I	F	340	281	1.2	31	906	950	2.7	2.8				+1	20	3	
62	78	1.5	P	L	W	F	I	F	346	244	1.4	32	530	560	1.5	1.6				+1	16	1	
63	78	1.5	P	L	W	F	I	F	346	244	1.4	32	510	580	1.5	1 7				+1	18	1	

BPA BYGGPRODUKTION AB

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	76	1.5	S	D	W	F		F	440				1630		3.7								
2	76	1.5	S	D	W	F		F	440				1410		3.2								
3	76	1.5	S	D	W	F		F	440				1450		3.3								
4	76	1.5	S	D	W	F		F	440				1500		3.4								
5	76	1	S	D	W	F		F	259				1010		3.9								
6	76	1	S	D	W	F		F	259				1399		5.4								
7	76	1	S	D	W	F		F	259				1166		4.5								
8	76	1	S	D	W	F		F	259				1554		6.0								
9	76	1.5	S	D	W	F		F	380					1672		4.4							
10	76	1	S	D	W	F		F	278				584		2.1								
11	76	1	S	D	W	F		F	278				778		2.8								
12	76	1	S	D	W	F		F	353				1694		4.8								
13	76	1	S	D	W	F		F	353				1730		4.9								
14	76	1	S	D	W	F		F	353				1624		4.6								
15	76	1	S	D	W	F		F	366				1647		4.5								
16	76	1	S	D	W	F		F	366				1720		4.7								
17	76	1	S	D	W	F		F	366				1720		4.7								
18	76	1	S	D	W	F		F	286				944		3.3								
19	76	1	S	D	W	F		F	286				887		3.1								
20	76	1.5	S	D	W	F		F	450				1215		2.7								
21	76	1.5	S	D	W	F		F	355				994		2.8								
22	76	1.5	S	D	W	F		F	470				1692		3.6								
23	76	1	S	D	W	F		F	148				533		3.6								
24	76	1.5	S	D	W	F		F	213				1683		7.9								
25	76	1.5	S	D	W	F		F	213				1598		7.5								

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26 76  2    S D W  F    F 244          1220       5.0
27 76  2    S D W  F    F 244          1269       5.2
28 76 1.5   S D W  F    F 396          1346       3.4
29 76 1.5   S D W  F    F 396          1183       3.0
30 76  1    S D W  F    F 146           496       3.4
31 76  2    S D W  F    F 230          1244       5.4
32 76  2    S D W  F    F 230          1405       6.1
33 76 1.5   S D W  F    F 342          1163       3.4
34 76 1.5   S D W  F    F 342          1163       3.4
35 76 1.5   S D W  F    F 348          1044       3.0
36 76 1.5   S D W  F    F 348          1148       3.3
37 76 1.5   S D W  F    F 348           940       2.7
38 76 1.5   S D W  F    F 456          1140       2.5
39 76 1.5   S D W  F    F 456          1322       2.9
40 76  1   PS D W  F    F 281           731       2.6
41 76 1.5  PS D W  F    F 331           563            1.7
42 76 1.5  PS D W  F    F 331           596       1.8
43 76 1.5  PS D W  F    F 331           530       1.6
44 76  1   PS D W  F    F 200           380       1.9
45 76 1.5  PS D W  F    F 396          1119       2.9
46 76 1.5  PS D W  F    F 386          1235       3.2
47 76 1.5  PS D W  F    F 386           926     2.4
48 76 1.5  PS D W  F    F 282                846       3.0
49 76 1.5  PS D W  F    F 282                959       3.4
50 76 1.5  PS D W  F    F 373               1194       3.2
51 76 1.5  PS D W  F    F 373               1231       3.3
52 76 1.5  PS D W  F    F 331                927       2.8
53 76 1.5  PS D W  F    F 331                927       2.8
54 76 1.5  PS D W  F    F 386                998       2.3
55 76  1   PS D W  F    F 230           391       1.7
56 76  1   PS D W  F    F 230           414       1.8
57 76  1   PS D W  F    F 230           391       1.7
58 76  1   PS D W  F    F 230           483       2.1
59 76 1.5  PS D W  F    F 374           748       2.0
60 76 1.5  PS D W  F    F 374           785       2.1
61 76 1.5  PS D W  F    F 288           576       2.0
62 76 1.5  PS D W  F    F 288           605       2.1
63 76  2   PS D W  F    B 319           479       1.5
64 76  2   PS D W  F    B 319           446       1.4
65 76  2   PS D W  F    B 402           603       1.5
66 76  2   PS D W  F    B 402           563       1.4
67 76 1.5   S R W  F    F 223          1160       5.2
68 76  1    S R W  F    F 190           589       3.1
69 76  1    S R W  F    F 190           760       4.0
70 76 1.5   S R W  F    F 254           711       2.8
71 76 1.5   S R W  F    F 203           731       3.6
72 76 1.5   S R W  F    F 203           832       4.1
73 76  1    S R W  F    F 110           451       4.1
74 76 1.5  PS R W  F    F 281           618       2.2
75 76 1.5  PS R W  F    F 281           646       2.3
76 76 1.5  PS R W  F    F 281           618       2.2
77 76  2   PS R W  F    F 404           606       1.5
78 76  2   PS R W  F    F 404           606       1.5
79 77 1.5  PS D W  F    F 331           430 MEAN 1.3
80 77    2 PS S W  F    F 359          1005 MEAN 2.8
81 77    2 PS S W  F    F 359          1113 MEAN 3.1
82 77 1.5   S R W  F    F 274          1480 MEAN 5.4
83 77 1.5   S R W  F    F 239          1243 MEAN 5.2
84 77 1.5   S R W  F    F 274          1370 MEAN 5.0
85 77    2  S D W  F    F 255           893 MEAN 3.5
86 77    2  S D W  F    F 203           670 MEAN 3.3
AB SKANSKA CEMENTGJUTERIET
 1  2  3    4 5 6  7 8 9  10   11   12 13   14    15    16   17   18   19 20   21 22 23 24
 1 77 1.5   S L W       F 364                MEAN 2.7
 2 77 1.5   S L W       F 364                MEAN 5.0
 3 77 1.5   S L W       F 297                MEAN 3.8
 4 77 1.5   S D W       F 283                MEAN 3.1
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5	77	2	S	R	W	C	315	MEAN	2.5
6	77	2	S	R	W	C	315	MEAN	2.2
7	77	2	S	R	W	F	315	MEAN	4.3
8	77	2	S	R	W	F	315	MEAN	4.6
9	77	1.5	S	D	W	F	327	MEAN	6.7
10	77	1.5	S	D	W	F	327	MEAN	5.2
11	77	2	S	D	V	F	372	MEAN	2.9
12	77	2	S	D	V	F	372	MEAN	2.8
13	77	1.5	S	D	W	F	379	MEAN	6.1
14	77	1.5	S	D	W	F	379	MEAN	6.3
15	77	1.5	S	D	W	F	300	MEAN	6.1
16	77	1	S	D	W	F	376	MEAN	2.4
17	77	1.5	S	D	W	F	412	MEAN	4.5
18	77	1.5	S	D	W	F	258	MEAN	3.4
19	77	1.5	S	D	W	F	412	MEAN	4.9
20	77	1.5	S	S	V	B	361	MEAN	4.4
21	77	1.5	S	S	V	B	361	MEAN	5.2
22	77	1.5	S	S	V	B	361	MEAN	4.3
23	77	1.5	S	S	V	B	361	MEAN	4.4
24	77	2	S	D	W	F	281	MEAN	3.3
25	77	2	S	D	W	F	281	MEAN	3.1
26	77	2	S	D	W	F	281	MEAN	3.6
27	77	2	S	D	W	F	281	MEAN	4.1
28	76	2	S	L	W	F	329	MEAN	4.0
29	77	1.5	S	L	W	F	317	MEAN	2.7
30	77	1.5	S	L	W	F	317	MEAN	2.9
31	77	1.5	S	L	W	F	317	MEAN	2.8
32	77	1.5	S	L	W	F	222	MEAN	3.8
33	77	1.5	S	L	W	F	222	MEAN	3.6
34	77	1.5	S	L	W	F	222	MEAN	4.2
35	77	1	PS	D	W	F	311	MEAN	2.1
36	75	1.5	S	S	V	B	361	MEAN	5.1
37	78	1	S	R	W	F	141	MEAN	2.3
38	78	2	S	R	W	F	215	MEAN	1.8
39	78	2	S	R	W	F	215	MEAN	1.8
40	78	2	S	R	W	F	239	MEAN	1.5
41	78	2	S	R	W	F	239	MEAN	1.6
42	78	2	S	R	W	F	239	MEAN	1.9
43	78	1	PS	D	C	F	331	MEAN	2.5
44	78	1.5	S	L	W	F	317	MEAN	2.5
45	78	1.5	S	L	W	F	317	MEAN	3.0
46	78	2	S	R	W	F	322	MEAN	3.9
47	78	2	S	R	W	F	322	MEAN	3.3
48	78	2	S	R	W	F	239	MEAN	1.9
49	78	2	S	R	W	F	215	MEAN	1.6
50	78	1.5	S	R	W	F	319	MEAN	2.3
51	78	1.5	S	R	W	F	319	MEAN	3.3
52	78	1.5	S	R	W	F	319	MEAN	2.9
53	78	1.5	S	D	W	F	324	MEAN	3.3
54	78	1.5	S	D	W	F	324	MEAN	2.4
55	78	1.5	S	D	W	F	318	MEAN	3.9
56	78	1.5	S	D	W	F	376	MEAN	4.1
57	78	2	S	R	W	F	397	MEAN	4.4
58	78	2	S	R	W	F	397	MEAN	3.2
59	78	2	S	R	W	F	397	MEAN	3.4
60	78	1.5	S	D	W	F	294	MEAN	4.8
61	78	1.5	S	D	W	F	294	MEAN	5.0
62	78	1.5	S	D	W	F	338	MEAN	4.7
63	78	1.5	S	D	W	F	341	MEAN	2.0
64	78	1.5	S	D	W	F	341	MEAN	2.1
65	78	2	S	L	W	F	322	MEAN	2.6
66	78	2	S	D	W	F	468	MEAN	4.6
67	78	1	S	L	W	F	301	MEAN	4.5
68	78	1	S	L	W	F	301	MEAN	4.4
69	78	1.5	PS	D	W	F	393	MEAN	3.1
70	78	1.5	PS	D	W	F	393	MEAN	3.2
71	77	1.5	S	L	W	F	317	MEAN	2.5

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72 77 1.5  S L W      F 317                MEAN 2.8
73 77 1.5  S L W      F 317                MEAN 3.1
74 77 1.5  S L W      F 317                MEAN 2.7
75 77 1.5  S L W      F 317                MEAN 2.5
76 77 1.5  S L W      F 317                MEAN 2.5
77 77 1.5  S L V      F 403                MEAN 2.7
78 78 1.5  S D W      F 357                MEAN 1.5
79 78   2  S R W      F 191                MEAN 3.6
80 78   2  S R W      F 247                MEAN 3.4
81 78 1.5 PS D W      F 371                MEAN 3.0
82 78 1.5 PS D W      F 371                MEAN 3.2
83 78   1  S S W      F 340                MEAN 1.3
84 78   2  S S V      F 319                MEAN 1.1
YTONG  AB
 1  2  3    4 5 6  7 8 9  10  11  12 13   14   15   16  17  18  19 20  21 22 23 24
 2 76   2  S D L  F I C 393 346 1.1       490       1.2      1.4        6  +9 17 <2
 3 76 1.5 PS D V  F I F 293               880  830 3.0 2.8                 -2 20  3
 4 74   2 PS D L  S O B 548 244 2.2       850       1.6      3.5          +14 23 <2
 5 76 2.5 PV D W  F O B 614              1850 1850 3.0 3.0
 6 77   1 PS R L  F   F 307 262 1.2       520  555 1.7 1.8 2.0 2.1
 6 77   1 PS R L  F   F 307 262 1.2       500  475 1.6 1.6 1.9 1.8
 7 77 1.5 PS R V  S I F 296               870  870 2.9 2.9
 8 75   2  S D V  S   B 522              1670 1690 3.2 3.2
 9 75 2.5  S D V  S   B 670              1740 1880 2.6 2.8
10 75   2 PS D L  S I S 459               595  595 1.3 1.3
11 77 1.5 PS R V  S I F 296               755  750 2.6 2.5
12 77   2 PS D V  S O B 449               800  750 1.8 1.7
13 75 1.5  S D W  S O F 362              1100 1140 3.0 3.2
14 75 1.5  S D W  S O F 376              1220 1140 3.2 3.0
15 76   1  S D W  S O F 248              1140 1080 3.8 3.6
16 77   2 PS D L  F I B 418               600  700 1.4 1.7
17 77   2 PS D W      B 375               940  860 2.4 2.3
18 75   1  S D V  F I F 221               510  455 2.3 2.0
19 77   2  S R V  S O C 336              1000 1040 3.0 3.1
20 77   2  S R V  S O C 336               910  970 2.7 2.9
21 76 1.5  S R W  S   F 282               770  820 2.7 2.9
22 76 1.5  S R W  S   F 285               880  970 3.1 3.4
24 75 1.5  S D W  S O F 400              1100 1170 2.8 2.9
25 77   2  S D V  S O F 314               780  820 2.5 2.6
25 77   2  S D V  S O F 314               520  540 1.7 1.7
26 77   2 PS D L  F I F 533               400  435 0.8 0.9
27 77 1.5 PS R V  S I F 296               740  690 2.5 2.3
28 77 2.5 PS R V  F O F 461               930  870 2.0 1.9
29 77   2 PS D V  F I S 509 334 1.5 35 1360 1420 2.6 2.8 4.1 4.3     -6 21 10 NE
30 78 1.5  S R V  F I F 302 204 1.5 16  730  750 2.4 2.5 3.6 3.7    -10 15  2 SW
31 78   1 PS D L  F I F 281 226 1.2 23  470  450 1.7 1.6 2.1 2.0
32 78   2  S S L  F I B 569 308 1.9 35  775  850 1.4 1.5 2.5 2.8     +3 20  2 NW
33 77   2 PS D V  F O F 466 287 1.6 33 1020 1025 2.2 2.2 3.6 3.6     +5 20  3 NW
30 COMPLETED                            590  530 2.0 1.8 2.9 2.6    +20 20
34 78 1.5 PS D V  F O F 275 211 1.3     940  870 3.4 3.2 4.5 4.1    +10 15
35 78 1.5  S D W  F O F 356 254 1.4 25 1450 1450 4.1 4.1 5.7 5.7     +2 13
36 78 1.5  S D W  F O F 356 254 1.4 25 1560 1560 4.4 4.4 6.1 6.1     +2 10
37 78   2 PS S W  F B B 354 171 2.1 23  545  540 1.5 1.5 3.2 3.2     +5 10  3  E
38 78   2  S S L  F I B 502 282 1.8 33  850  820 1.7 1.6 3.0 2.9
39 78   2 PS S V  F B B 419 260 1.6 21  660  680 1.6 1.6 2.5 2.6
40 78   2 PS D L  F I F 330 248 1.3 24  420  410 1.3 1.2 1.7 1.7    +18 18  1
41 78 1.5  S D W  F O F 340 229 1.5    1000 1000 2.9 2.9 4.4 4.4    +18 20  2
42 78 1.5  S D W  F O F 420 314 1.3 25 1300 1300 3.1 3.1 4.1 4.1    +18 20  2
43 78   2 PS S L  F I B 535 313 1.7 32  390  430 0.7 0.8 1.3 1.4    +20 20  2
44 77   2 PS D V  F I B 595 298 2.8 27 1600 1650 2.7 2.8 5.4 5.5    +20 20  2
45 78 1.5  S D W  X O F 267 275 1.0 18  640  560 2.4 2.1 2.3 2.0    +20 20  3
46 78 1.5  S D W  X O F 358 307 1.2 23  630  595 1.8 1.7 2.1 1.9    +20 20  3
BLOCK OF FLATS
KTH
 1  2   3  4 5 6  7 8 9  10  11  12 13   14   15  16  17  18  19 20  21 22 23 24
 1 65      S                                           17                  2
 2 40      S   B  S                            1.6                         1
```

```
 3 40      S   B  S                              2.8                        1
 4 40      S   B  S                              1.5                        1
 5 40      S   B  S                              3.4                        1
 6 40      S   B  S                              1.2                        1
 7 40      S   B  S                              1.4                        1
 8 40      S   B  S                              1.5                        1
 9 40      S   B  S                              1.2                        1
10        PS   C                                 1.1                        2
11        PS   C                                 1.1                        2
12        PS   C                                 0.8                        3
13         S   M                                 0.8                        3
14         S   M                                 0.7                        3
15         S   M                                 0.7
16         S   M                                 0.5
17         S   M                                 0.8
SP   THE SWEDISH NATIONAL AUTHORITY FOR TESTING, INSPECTION AND METROLOGY
 1  2  3   4 5 6 7 8 9   10  11  12 13  14   15   16  17  18  19 20  21 22 23 24
 1 69   6 PS   C  F I F 190             485  470 2.6 2.5            +15 18  0
 2 69   6 PS   C  F I F 190             510  370 2.7 1 9            +15 18  0
 3 69   6 PS   C  F I F 190             450  430 2.4 2.3            +15 18  0
 4 69   4 PS   C  F I F 205             220  610 1.1 3.0            +15 20  0
 5      2               153            1300 1230 8.5 8.0            +16 20  0
BPA BYGGPRODUKTION AB
22        PS   C        257                      1.5
23        PS   C        257                      1.1
24        PS   C        257                      0 8
25     2                238                      0.3
26     2                238                      0.4
HSB:S RIKSF\RBUND
 1        PS   M        208                   70     0.3
 2        PS   M        208                   62     0.3
 3        PS   M        197                  275     1.4
 4        PS   M        197                  195     1.0
 5        PS   M        197                  240     1.2
 6        PS   M        197                  270     1.4
 7        PS   M        197                  240     1.2
 8        PS   M        175                  165     0.9
 9        PS   M        197                  150     0.8
10         S   M        197                  250     1.3
11         S   M        197                  245     1.2
12         S   M        197                  230     1.2
TYRENS
 1                      386 250 1.5    1100          2.9     4.4
 2 65   2  S D W      B 577 591 1.0    2600          4.5     4.4
 3  ? 1.5  S D W  S   C 892 676 1.3    5000          5.6     7.4
 4 53  3  PS D W  S   B 400 288 1.4    1325          3.3     4.6
 5 65  2   S D W  S   B 400 400 1.0    1560          3.9     3.9
INDUSTRIAL HALLS
YTONG AB
 1 73   1 PS   L  F 0 F 734            2600 2600 3.6 3.6
EOF:518
0:>
```

Appendix 2

Standard form for recording data

PROTOCOL **AIRTIGHTNESS, WHOLE BUILDING**	Sketch of plot and building. Show North.
Testing company, group etc. (or equivalent).	
Performed by:	Date: Item no. ☐☐ (1–2)
Test ordered by:	Building address

Year of erection: ☐☐ (4–5) No. of storeys: ☐☐☐ (7–9)

Production method: ☐☐ (11–12) P = prefabricated, PV = volume elements, PS = surface elements, S = built on site

Building type: ☐ (14) D = detached, R = row house, L = linked etc. S = split level

Material: ☐ (16) W = wood, L = lightweight concrete, C = concrete, B = brick, M = concrete structure + curtain walls, V = lightweight concrete + wood.

Ventilation system: ☐☐ (18–19) S = natural ventilation, F = mechanical exhaust, FT = balanced ventilation, X = FT + heat exchanger.

Window openings: ☐ (21) O = outwards, I = inwards, B = both.

Foundations: ☐ (23) B = basement, C = crawl space, F = floor slabon ground.

Volume: ☐☐☐ (25–27) m^3. Envelope area: ☐☐☐ (29–31) m^2.

Volume/envelope area: ☐☐☐ (33–35). Area of windows & doors: ☐☐ (37–38) m^2.

Air leakage:	Internal overpressure, 50 Pa	☐☐☐☐	(40–43) m^3/h
	Internal underpressure, 50 Pa	☐☐☐☐	(45–48) m^3/h
Leakage/volume:	Internal overpressure, 50 Pa	☐.☐☐	(50–52) $m^3/m^3 \cdot h$
	Internal underpressure, 50 Pa	☐.☐☐	(54–56) $m^3/m^3 \cdot h$
Leakage/area:	Internal overpressure, 50 Pa	☐.☐☐	(58–60) $m^3/m^2 \cdot h$
	Internal underpressure, 50 Pa	☐.☐☐	(62–64) $m^3/m^2 \cdot h$

Ventilation rate with sealed ventilation system x 100 ☐☐ (66–67) air changes/h

Notes: (1–81), Card 2

Weather:	Outdoor temperature:	☐☐☐	(69–71) °C
	Indoor temperature:	☐☐	(73–74) °C
	Wind velocity:	☐☐	(76–77) m/s
	Wind direction:	☐☐	(79–80) Compass direction

This form should be used when submitting airtightness measurements to the computer file. Copies can be ordered from: Byggnadsteknik I, LTH, Box 725, S-220 07 Lund, Sweden.

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Summary

MEASUREMENTS AND MEASUREMENT METHODS

The two methods which are at present available for measuring the airtightness of entire buildings are the pressure method and the tracer gas method. The latter method enables the building ventilation to be measured under ambient weather conditions. The principle of the pressure method is the creation of a pressure difference, using a powerful fan, across the building envelope (walls, roof, floor structure etc.), accompanied by measurement of the resulting flow through the fan at a constant pressure difference.

TRACER GAS METHOD

The tracer gas method allows the ventilation of a bounded volume, such as an individual single-family house, an apartment or an office, to be measured. The ventilation rate is generally dependent upon the ambient weather conditions, so the results from tracer gas measurements can vary widely from occasion to occasion with weather and wind.

The main elements used in tracer gas measurement are a suitable tracer gas and an instrument (a gas analyser) which can measure the concentration of tracer gas in the volume under investigation. Time must also be measured. Depending upon the detailed arrangement, measurements can be made either as *decreasing gas concentration, constant gas concentration* or *constant gas emission* measurements.

Decreasing gas concentration

This method of tracer gas measurement is that which is commonly used in Sweden.

Measurements are made by releasing a small quantity of gas inside the building concerned, so that the concentration can be measured with a gas analyser. When (hopefully) the concentration has become uniform throughout the test volume, (which can be accelerated by 'mixing' the air, e.g. by using fibre-board sheets as paddles or by the use of small propeller fans), measurements are made of how the concentration of the tracer gas subsequently falls off with time. The ventilation rate of the test volume can then be calculated from the following expression.

$$n = \frac{1}{t} \cdot \ln \frac{c_0}{c_t} \qquad [1]$$

where:

n = the ventilation rate, air changes/h

t = the time from when the gas concentration = c_0, h

c_0 = the gas concentration at the start of timing

c_t = the gas concentration at time t

Constant gas concentration

This variant is suitable for continuous measurement of the ventilation rate of an enclosed volume. Gas emission is controlled so that a constant gas concentration is maintained at the measuring point. This can be done with some form of automatic control gear. In the ideal case, i.e. complete mixing, it is possible to calculate the ventilation rate directly from the known rate of discharge of the tracer gas.

Constant gas emission

This variant is very similar to the previous variant. It is thus also suitable for continuous measurement. The discharge of tracer gas is constant during the measurement sequence, and the gas concentration which can be read off from the gas analyser is a measure of the ventilation rate. A reduced ventilation rate gives an increased gas concentration and vice-versa.

Measuring equipment and methods of measuring

Certain equipment is common to all the variants mentioned: a suitable tracer gas, a gas analyser for the gas chosen and some means of measuring time.

The gas analysers which are commonly used – at least in Sweden – work with nitrous oxide, N_2O (laughing gas), in concentrations of up to 0.1%. For an individual single-family house with a volume of 300 m^3 this means that

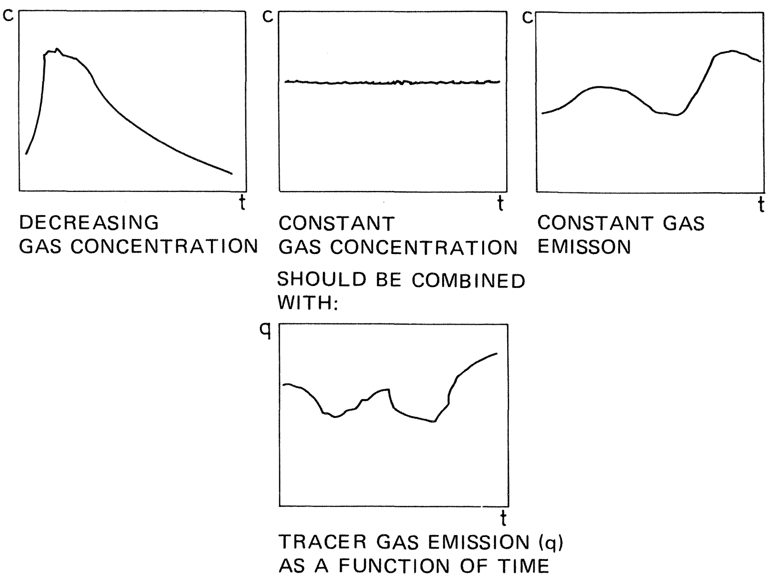

FIG. 1. Typical traces from pen recorders for different measurement methods.

0.3 m^3, or about 0.5 kg, of N_2O will be consumed. Laughing gas is sold in cylinders of various sizes, and that which is probably most convenient, bearing in mind its capacity and ease of handling, is the 7.5 kg cylinder. In September 1978 the cost of such a cylinder was about Skr. 200. The density of the gas is 1.7 kg/m^3 at NTP, i.e. near that of air.

All that is really essential for time measurement is an ordinary clock or watch, although some form of recorder is strongly recommended. This plots the gas concentration while the paper is fed out at a known speed. This applies particularly to the constant gas concentration and constant gas emission measurement variants, although even when using the decreasing gas concentration method the use of a recorder does save work. Typical traces are shown in Figure 1.

When making measurements by the decreasing gas concentration method, the gas concentration normally falls off with an exponential characteristic, which means that if the values of time and gas concentration are plotted on a linear/logarithmic graph, a straight line should be produced. The slope of this line is the same as the measured air change rate n.

Statistical analysis enables the number of measurements of ln c which are required for a given accuracy of n to be determined. A calculation of this kind is described in the paper.

THE PRESSURE METHOD

The pressure method for measuring the tightness of a whole building, as developed by the Division of Building Technology of Lund Institute of Technology and others, is nowadays quite well established and the Swedish National Authority for Testing, Inspection and Meteorology has in its Method Description SP 1977:1 published notes on its area of application, principle, test equipment, test conditions and methods of working, together with comments on the method. Figure 2 shows an example of the pressure testing equipment.

When testing, corresponding values of the interior/exterior pressure difference and air flow are plotted, both for internal overpressure and internal underpressure. Tightness is normally specified in terms of the average value of air flows at a standard pressure of 50 Pa, divided by the building volume (air changes/h). This quantity is normally indicated as n_{50}.

The method is quick, and the results are easy to interpret. It produces a quantitative measure of the building tightness which can be used in several contexts, e.g. manufacturing quality control, comparison between buildings and standards requirements. However, it should be noted that the method gives only a measure of the tightness of all the envelope surfaces together, and the results cannot be used directly to calculate the building's air change rate under natural conditions. The natural pressure differences which occur in a building are of different magnitudes in different parts of the building. The method gives no indication of the size of the individual leaks or of where they are situated.

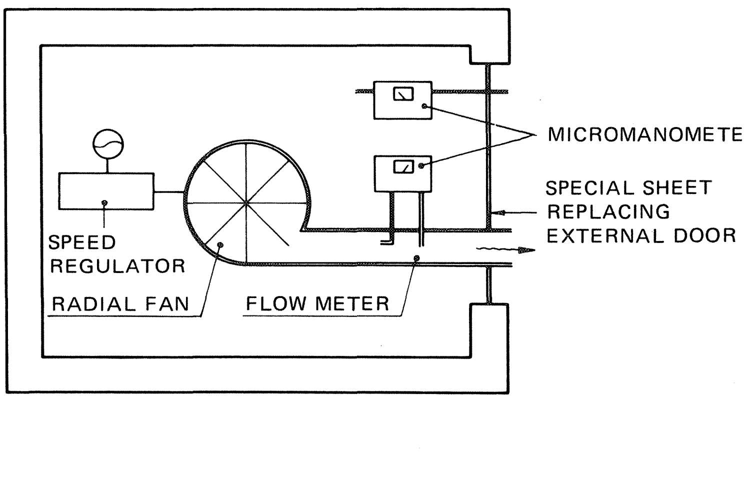

FIG. 2. Measuring equipment: schematic diagram.

However, by using an infra-red camera (thermograph camera) and/or anemometer during the internal underpressure part of the test, it is possible to localize the leaks and to evaluate their size.

Accuracy of measurement

The final result from a pressure method leakage test is the air leakage rate per unit of volume with a given pressure difference across the building envelope. There are thus two components to be measured: air flow and pressure difference.

A complete error analysis, as worked in the paper, indicates that the final probable error in determining the air flow at 50 Pa, and when using liquid manometers, would be about 8% while, if electric manometers with recorders were used, the probable error would be about 4%.

Measurement precision

The paper also describes the sensitivity of the method to the effects of external weather influences (wind and temperature). It can be noted that, when measuring with internal overpressure, a 10% effect upon the flow is caused by a wind velocity of 8 m/s while, when measuring with internal underpressure, an effect of the same magnitude requires a wind velocity of 10 m/s.

The effect of indoor and outdoor temperature differences is small and can often be ignored, except for high rise buildings.

Measurement results

The Division of Building Technology of Lund Institute of Technology at present administers a computer file of measured results obtained from pressure method and/or tracer gas method measurements on buildings. At the end of June 1978 the file contained data from 384 individual single-family houses, 43 apartments and 1 industrial building. Newly-constructed buildings dominate the material, and very few older buildings have been tested. Data is welcome from new sources, and suitable forms for recording measurement data can be obtained from Johnny Kronvall, Byggnadsteknik I, LTH, Box 725, S-220 07 LUND, SWEDEN.

Table 1 is a summary of the results obtained up to June 1978.

Category	No.	n_{50} Average value	Air changes/h Standard deviation
Detached single-family houses and linked houses made of wood	205	3.66	1.24
single-storey	70	3.79	1.32
1 1/2-storey	135	3.52	1.18
Detached single-family houses of lightweight concrete	12	1.98	1.46
Detached single-family houses and linked houses of light-weight concrete & wood, single-storey	9	2.23	0.67
1 1/2-storey	17	3.74	0.76
Row houses of wood	49	3.14	1.36
single-storey	33	2.89	1.02
1 1/2-storey	16	3.65	1.56
Row houses with party walls and floor structures of concrete. Curtain walls with studding frame.	5	1.72	0.18
Block of flats of concrete and with curtain walls	23	0.96	0.34

Table 1. Summary of results of pressure testing. The data relates to houses built after 1976-01-01.

Airtightness – measurement and measurement methods Johnny Kronvall

D8:1980	**Distribution:**	
ISBN 91-540-3201-6 Swedish Council for Building Research, Stockholm, Sweden	**Svensk Byggtjänst** Box 7853 S-103 99 Stockholm, Sweden Art.nr. 6702008	**Price:** 45 Skr + moms

Swedish Council for Building Research