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Measuring Ventilation

using Tracer-gases

Brüel & Kjær

MEASURING VENTILATION USING TRACER-GASES

by

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This booklet answers some basic questions about measuring ventilation using tracer-gas. It explains some of the techniques and terminology used and gives some application examples.

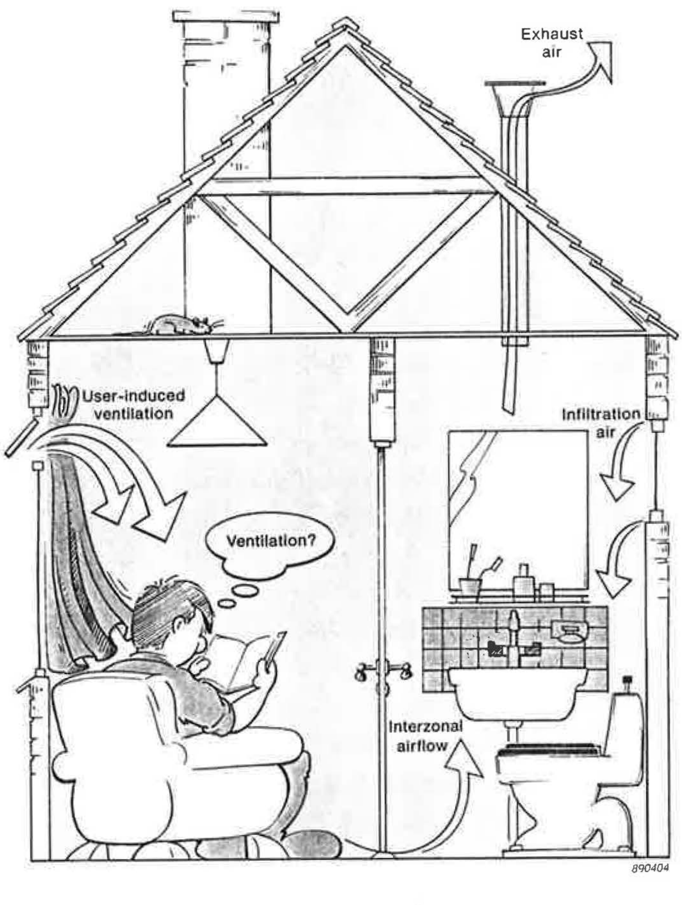
October 1989

What is ventilation?

Most people have some idea of what ventilation is all about in general terms but are not quite so sure about its importance to us in our everyday lives, or of the terms used to describe the different types of ventilation that can occur. *Ventilation is the process of supplying and removing air by natural or mechanical means to and from any space.* This word is then, all-encompassing and other terms are used to describe individual components of ventilation. Some of these components are illustrated in the drawing.

The term "natural ventilation" covers both the uncontrolled inward and outward air-leakage through cracks and interstices (i.e. infiltration and exfiltration) and the air entering and leaving the enclosure through openings provided intentionally such as open windows and doors, and vents. Infiltration and exfiltration are caused by the weather or other pressure-difference forces exerted on a building.

"Mechanical" or "forced" ventilation, on the other hand, is ventilation air provided by electric fans. These fans are often part of an air-conditioning system and may drive the supply airflow, the exhaust airflow, or both the supply and exhaust airflows.

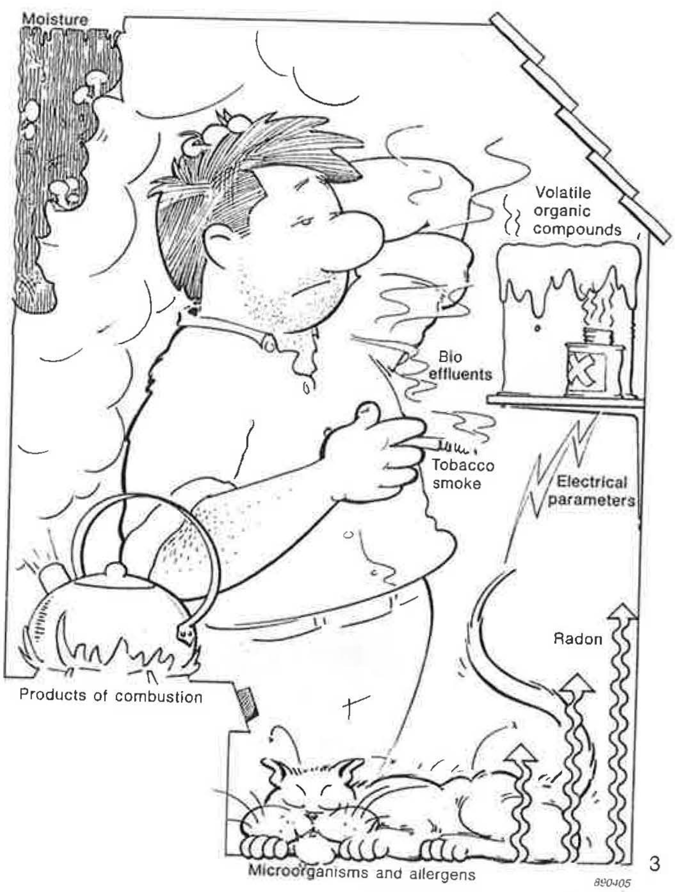


Why do we need ventilation ?

Over the past two decades many new building techniques have been developed in an effort to reduce energy consumption. Unfortunately, this often resulted in buildings being so air-tight that very little natural ventilation was able to take place and increased indoor-air pollution resulted. Other factors which have increased indoor-air pollution are the many new materials used in the construction and furnishing of buildings. Ventilation removes indoor air pollutants and thereby improves the quality of indoor air.

Indoor-air pollutants are often only recognised in the form of tobacco smoke or fumes and dust from industrial processes. There are however, many other important indoor-air pollutants — volatile organic compounds from glues, paints, and varnishes; products of combustion and moisture from heating and cooking; and bioeffluents, micro-organisms, allergens, and fibres from people, pets, or supply-air.

Condensation of moisture and infiltration of radon, are particularly worrying pollutant problems. Condensation of moisture on the inside surfaces of building structures causes mould and fungus growth and has rendered many almost-new buildings uninhabitable. Radon, a radioactive gas present in many naturally-occurring rocks and soils, is a more recently recognised indoor-air pollutant problem. This pollutant can represent a serious health risk to the inhabitants of houses built in areas with high ground concentrations and has, by many, come to be considered the most serious indoor-air pollutant of all.

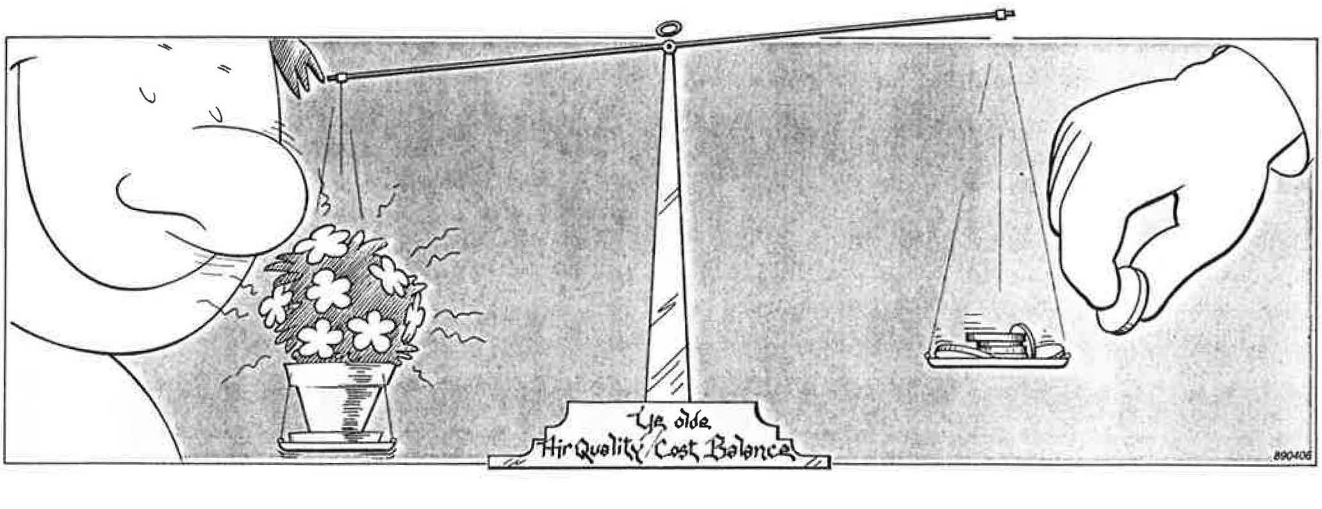


Why analyse the ventilation in buildings ?

The reduced productivity of personnel, and the increased maintenance costs for a building structure which can be caused by poor indoor air quality have to be balanced against the costs of improving ventilation.

Ventilation systems can be very costly to install, and to run once installed. It is therefore very important to be able to monitor a ventilation system to ensure that it is able to do the job was commissioned to do and that it does it efficiently. It is also important to be able to check a ventilation-system's efficiency at regular intervals after installation.

When outdoor temperatures are considerably below the optimum indoor temperature, the heat lost from buildings due to air infiltration and ventilation can account for a considerable part of a buildings space-heating requirement. In the same way, when outdoor temperatures are high, or too much heat is generated within the building, cooling the supply air becomes a big drain on resources. By making measurements on ventilation systems we can both check to see that the people in a building are getting the required amount of outdoor air, and check that this air is distributed in an economical way.



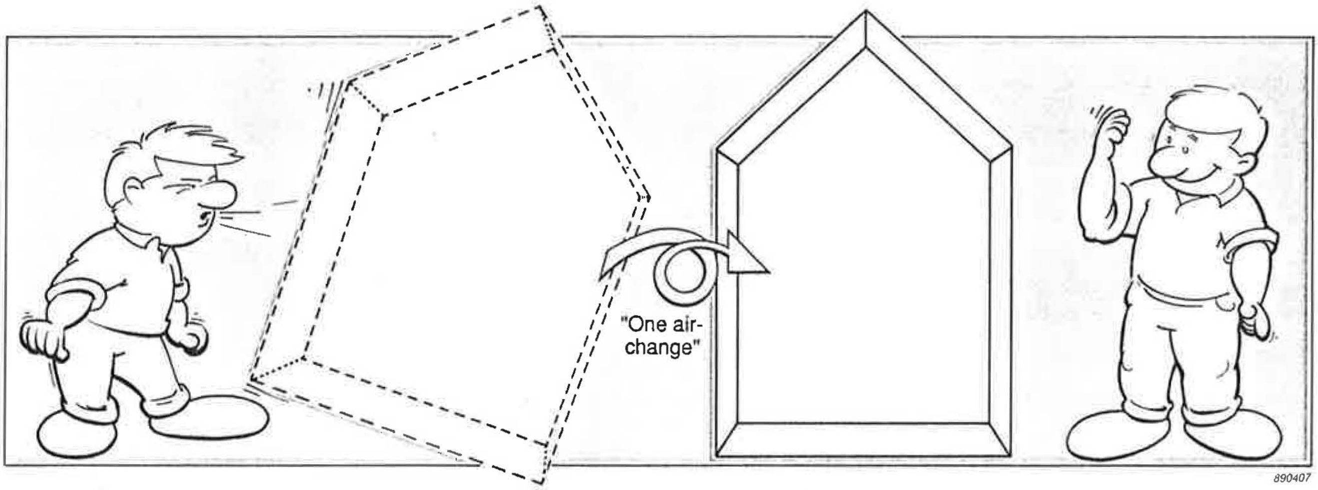
How is ventilation quantified ?

Ventilation standards normally quote either the outdoor-air supply-requirement (volume per time per capita), or the outdoor-air exchange-rate (h^{-1}), or both. The "efficiency of ventilation" is a fairly recent innovation in defining air-quality and is growing in importance. This parameter is discussed in greater detail in the later sections concerning the measurement of the age-of-air.

The outdoor-air exchange-rate is defined as *the ratio of the volume of outdoor-air entering an enclosure per hour to the effective* volume of the enclosure.* In other words, it is the number of times an hour that the room-air is replaced with outdoor air. The outdoor air-exchange rate is the most often quoted requirement in the evaluation of ventilation since it takes into account the enormous variations in the volume of enclosures. The size of an office may, for example, vary from a small single office to a very large open plan office.

The outdoor-air supply-requirement defines the volume of outdoor-air each person in an enclosure should receive per unit of time. This requirement takes into account the fact that each person in an enclosure is also a source of indoor-air pollution. Some standards therefore list recommendations for both the outdoor air supply requirement and the outdoor air-exchange rate.

* see Glossary



What is tracer-gas monitoring ?

The use of tracers in many types of research and especially in fault-finding activities is very widespread. Just a few examples that spring to mind include following the course of fluids in the human body, leak testing, and even the "ringing" of birds. In hydrological research it would not be unusual for a researcher to mark pebbles with brightly coloured paint or with a radioactive isotope in order to study the movement of sediment along a coastline or along a river bed. The basic idea is the same for ventilation measurements: the air in a building is marked with something easily identifiable so that its movement can be traced.

The type of tracers used in ventilation measurements are usually colourless, odourless, inert gases, not normally present in the environment. The idea behind tracer-gas analysis can be envisaged more easily if we imagine what happens when soap bubbles are blown in a room. The bubbles move around the room and through open doors, up stairways, and perhaps into other rooms around the building. This bubble-method is sometimes used to aid visualization when a qualitative method of studying air flows is needed. A major disadvantage of this method is that the bubbles cannot follow the room air through cracks and pores in the walls. Perhaps the most frequently used simple qualitative technique is smoke visualization but many other methods can be used. Even smells can be used as tracers!

Why use tracer-gas techniques ?

Tracer-gas techniques are the only way of making many types of quantitative measurements of ventilation. These include infiltration and air-exchange measurements, fume extractor efficiencies, and spreading of pollutants. In other cases tracer-gas analysis methods are chosen in preference to other analysis methods because they are more convenient and more accurate. This is often the case when measuring airflow rates in ventilation ducts. Each of these subjects is discussed in later sections of this booklet.

A very important aspect of tracer-gas measurements is that they can be made in occupied buildings. This is not only much more convenient but is also much more accurate since it takes into account the large effect occupancy can have on a building's air-exchange rate — for example, the effect of opening and closing doors and windows. It is, after all, the air-exchange rate of a building under normal working conditions that is important in most cases.

Results from properly conducted tracer-gas measurements on a ventilation system can provide information about the amount of outdoor air brought into each room; the efficiency of heat recovery units; the amount of extract air which is re-circulated into the supply air ducts; the outdoor short-circuit from exhaust to outdoor air intake, and distribution of supply air in rooms. Much wasted energy and many "sick" buildings result from the fact that these parameters have not been taken into account at the planning stage of a building and are not measured as part of regular building maintenance checks.

Air-exchange rate measurement methods

The airflow through a room or a building is normally evaluated using one of three tracer-gas methods: the concentration-decay method, the constant-emission method, or the constant-concentration method. All three methods are based on a simplification of the continuity equation:

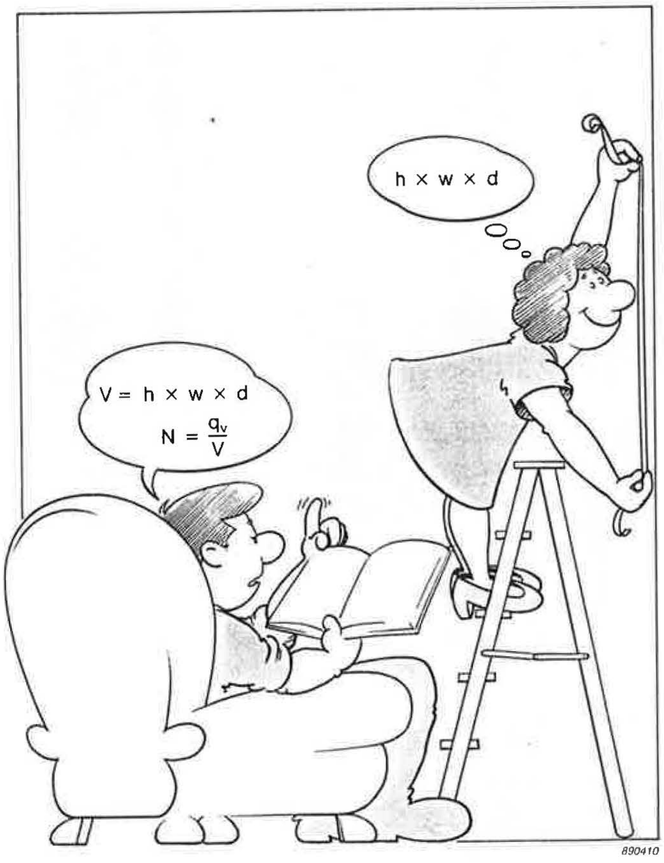
Change in amount of tracer in the room		amount of tracer introduced into the room		amount of tracer which has left the room
$V\dfrac{dC}{d\tau}$	=	$F(\tau) + q_v(\tau)\cdot C_{oa}$	–	$q_v(\tau)\cdot C(\tau)$

V = volume of air in room, m^3
C = concentration of tracer-gas in room-air, m^3/m^3
τ = time, h
F = introduction rate of tracer-gas into room, m^3/h
C_{oa} = concentration of tracer-gas in outside air, m^3/m^3
q_v = air-flow through room, m^3/h

This can be written:

$$q_v(\tau) = \frac{F(\tau) - V\dfrac{dC}{d\tau}}{(C(\tau) - C_{oa})}$$

To find the air-exchange rate, N, the airflow through the room is divided by the effective volume of the room. In the following few pages we will consider, in turn, the three main measurement methods for determining the air-flow through a room or building. In each case we will assume that the outside air does not contain any of the chosen tracer.



This is the most basic method of measuring air-exchange rates and is used to obtain discrete air-exchange rates over short periods of time.

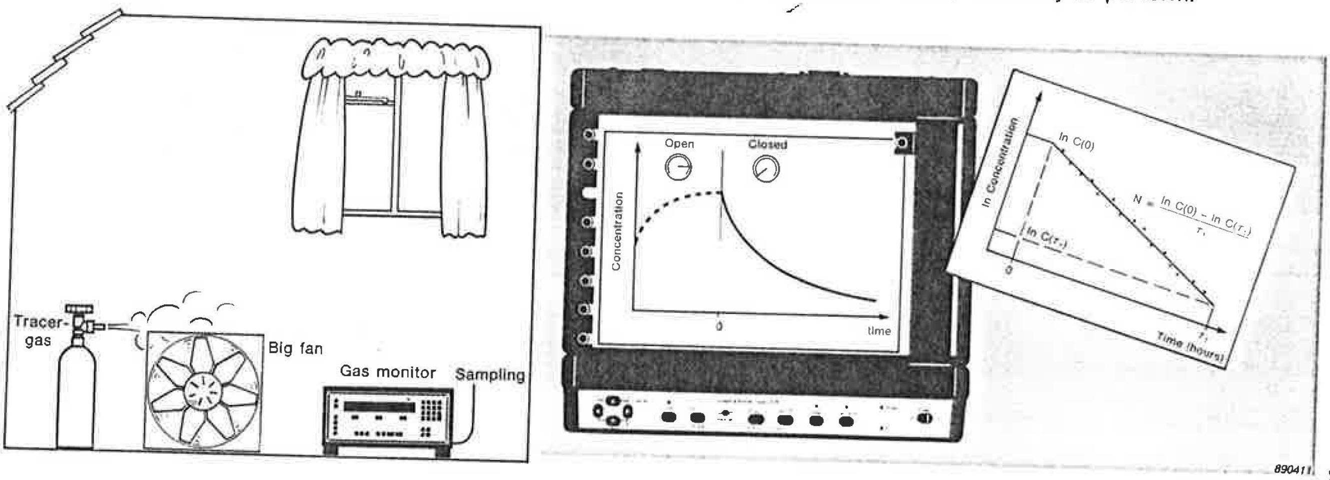
A small quantity of tracer-gas is thoroughly mixed into the room air. The source of gas is then removed and the decay in the concentration of tracer-gas in the room is measured over a period of time. To ensure that the tracer-gas concentration is the same at all points in a room at any particular time a big mixing fan is run throughout the measurement period. Provided that no tracer-gas is supplied to the room during the measurement period and the airflow through the room is constant, the concentration of tracer-gas is found to decay exponentially with time. By plotting the natural logarithm of gas concentrations against time a straight line is obtained and the gradient of the line is the air-exchange rate in the room:

$$\text{Air-exchange rate, } N = \frac{\ln C(0) - \ln C(\tau_1)}{\tau_1} \quad (h^{-1})$$

where $C(0)$ = concentration at time = 0 (m^3/m^3)
$C(\tau_1)$ = concentration at time = τ_1 (m^3/m^3)
τ_1 = total measurement period (h)

If an approximately straight line is not obtained, then the room air cannot be considered well mixed and the results are thus not valid.

The only equipment needed for this measurement method is a gas monitor, a bottle of tracer-gas, and a mixing fan. This makes the method cheap and easy to perform.



The constant-emission method

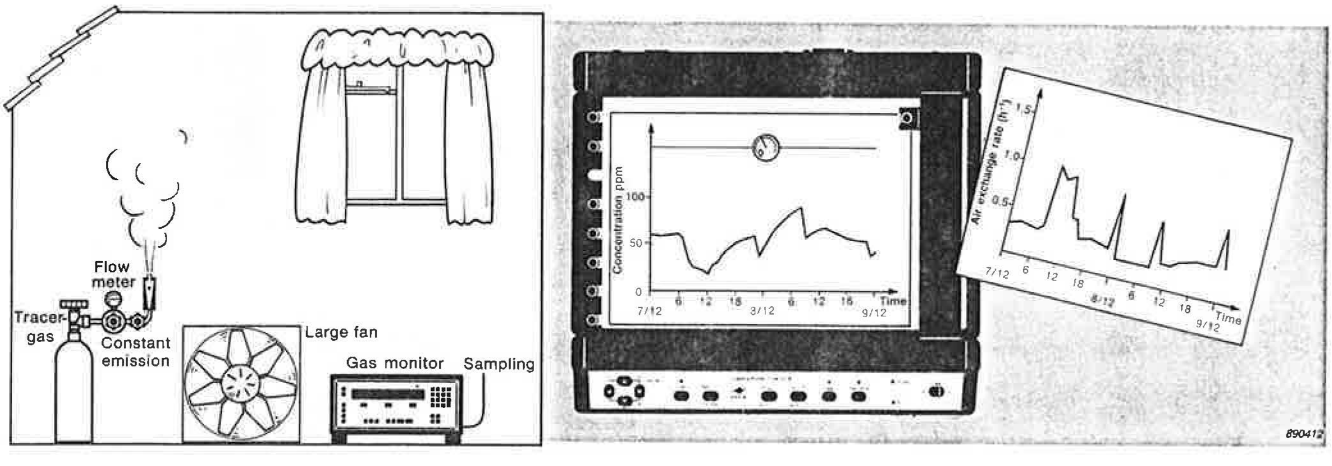
This method is used for long-term, continuous air-exchange rate measurements in single zones (discussed below), or for measurement of the airflow through ventilation ducts (discussed in a later section).

When using the constant-emission method, tracer-gas is emitted at a constant rate for the duration of the measurement period. This means that provided both the air-exchange rate and the tracer-gas concentration in the zone are constant, the continuity equation reduces to:

$$\text{Air-exchange rate, } N = \frac{F}{V \cdot C} \quad (h^{-1})$$

If either the air-exchange rate or the tracer-gas emission vary during a measurement period, then the general continuity equation has to be used to obtain the air-exchange rate. As with the concentration-decay method, the tracer concentration should be the same throughout the zone at any instant of time. The mixing needed to achieve this is done with fairly large mixing fans.

A flow meter is needed to measure the flow of tracer-gas emitted into the room. Since tracer-gas is emitted continuously into the zone throughout the measurement period, special attention should be paid to the cost and amount of tracer-gas used. Using a monitor that allows you to measure cheap tracer gases and/or allows very low concentrations to be detected and measured can help to keep this cost down.



The constant-concentration method

This method is used for continuous air-exchange rate measurements in one or more zones. It is particularly useful for conducting analyses in occupied buildings.

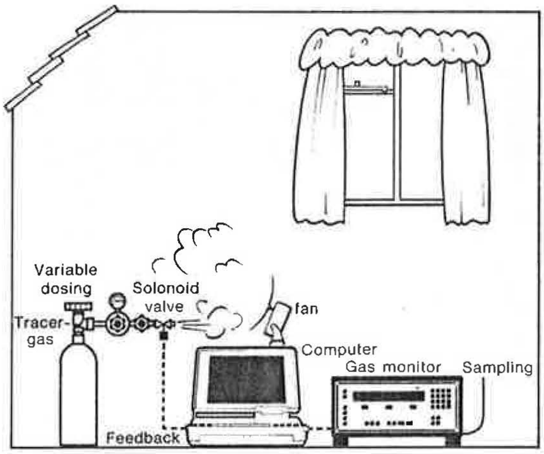
When using a constant-concentration measurement method concentrations of tracer-gas in a zone are measured by a gas monitor. This information is then sent to a computer which controls the amount of tracer-gas "dosed" into the zone in order to keep its concentration constant. A small fan is normally used to help mix the tracer with the room-air. In most cases, however, the air in each zone does not have to be perfectly mixed. Provided that the concentration of tracer-gas in the zone is constant over time, the continuity equation reduces to:

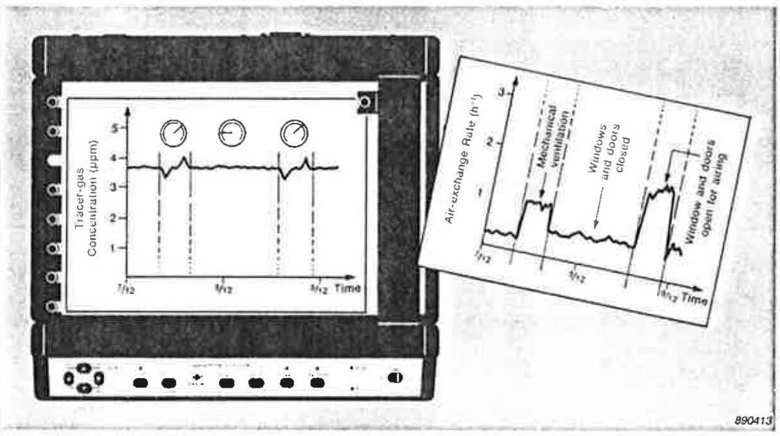
$$\text{Air-exchange rate,} \quad N(\tau) = \frac{F(\tau)}{V \cdot C} \qquad (\text{h}^{-1})$$

The air-exchange rate is directly proportional to the tracer-gas emission rate required to keep the concentration constant.

This method offers two great advantages: not only can it be used to obtain an accurate long-term average air-change rate in situations where the air-exchange rate varies — for example, in occupied buildings; but it can also be used to document these variations in detail. As with the constant-emission method, tracer-gas costs may be an important consideration.

The constant-concentration method is also particularly well suited to the continuous determination of the infiltration of outside air into each individual room in a building.





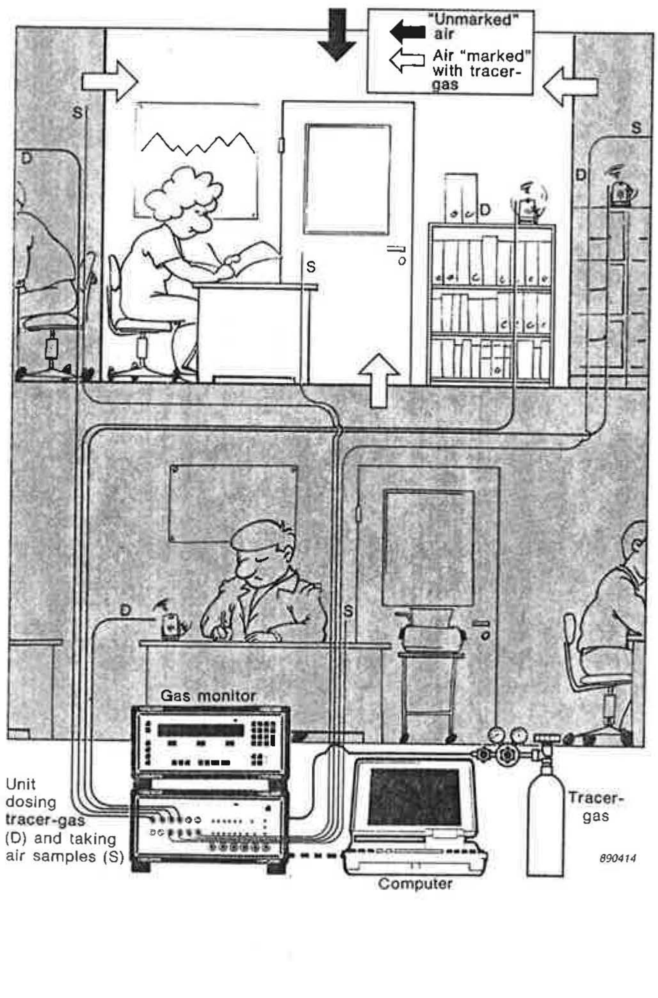
Guarded measurements

Guarded measurements are used to measure the air-exchange between one part of a building and: either another part of that building, or the outside air.

An example of a guarded air-exchange measurement is illustrated in the diagram. The problem is to measure the outside-air supply rate to the office shown in the upper part of the office building. This office is called the measured zone and the zones surrounding it are called guarded zones. Guarded measurements are done by dosing the measured zone and the guarding zones with a certain concentration of tracer gas (5 ppm, for example) and maintaining this concentration for the duration of the measurement period.

During the measurement period, all air exchanged between the guarded zone and measured zone will contain the specified concentration of tracer-gas and will therefore not cause any variation in the emission rate of tracer into the measured zone. Outside air entering the measured zone will, on the other hand, temporarily dilute the tracer-gas concentration there and result in some more tracer being emitted into the measured zone. The amount of tracer emitted into the office is directly proportional to the outdoor air-exchange rate of that office.

The outdoor air-exchange rate is calculated using the equation used for the constant concentration method shown on the previous page.



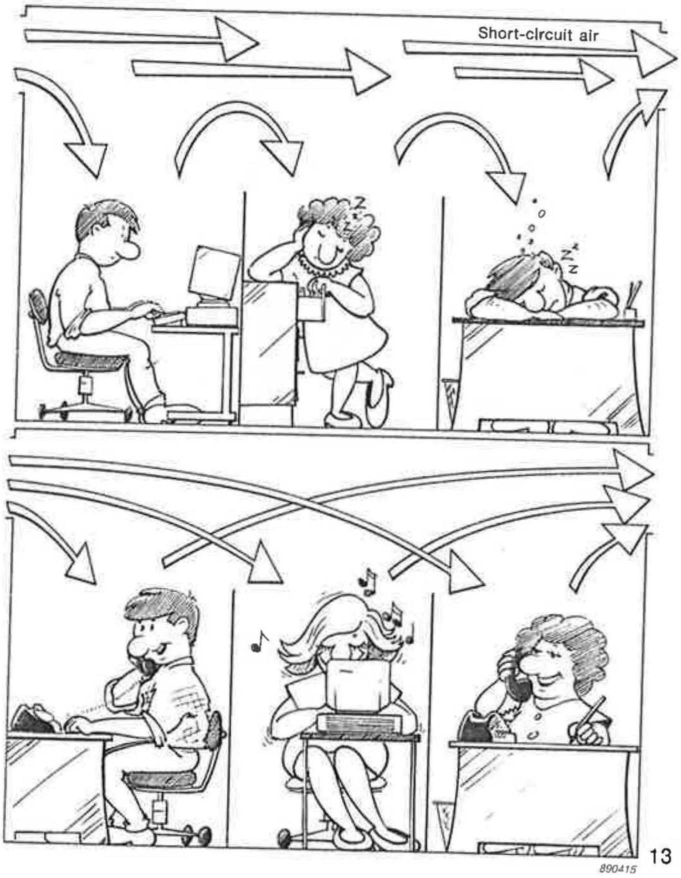
Airflow characteristics in rooms

The air-exchange rate measurement methods tell us the amount of air supplied to a room or building but nothing about the airflow in the room or the distribution of the ventilation air entering the room. In other words, even though we find out if enough ventilation air is supplied to a room we do not know if this air is used efficiently; we do not even know whether this air ever reaches the people occupying the room.

A satisfactory distribution of ventilation-air in a room is essential if you want enough outdoor air and a low air-pollution level at each individual work place in a room. It will often also make it easier to control the thermal environment at each workplace. It should be noted, however, that good distribution does not ensure a good environment but is an important step towards one.

An unsatisfactory airflow pattern may be due to the temperature of the supply air, temperature gradients within the room, type and positioning of supply and extract air-ducts, machines, furniture and other objects within a room.

Detailed information about the distribution of ventilation air in a room can be deduced from the measurement of the age distribution of the air in the room. The methods most commonly used to determine the age-of-air in a room are discussed in the following sections.



The age-of-air

The age-of-air in a room is a measure of the length of time it has been in the room. The "youngest" air is found where the outdoor air comes into the room, the "oldest" air may be found at any other point in the room. The age-of-air can be considered in two different ways: the local-mean age-of-air, and the room-average age-of-air.

Local-mean age-of-air is used if the ventilation of individual work stations, or the distribution of air in naturally ventilated buildings is to be assessed. It is also used in the mapping of airflows through rooms. The big advantage of this method is that results apply to individual points within a room — areas of stagnant air can be located, and the ventilation air supply at head height at an individual's workstation can, for example, be assessed.

Room-average age-of-air is a number which quantifies the performance of a ventilation system. This number takes into account both the amount of ventilation air supplied to the room and the efficiency with which it is distributed around the room.

Room-average age-of-air is measured in the extract air-duct. This measurement is, however, not reliable in cases where a large proportion of air leaves the room by other means, for example, through random exfiltration.

Age-of-air and air-exchange efficiency

The lowest possible room-average age-of-air occurs when there is perfect piston flow through that room. Piston flow is characterised by the fact that the oldest air is found at the extract air ducts.

If the air in the room is perfectly mixed then the room-average age-of-air will be double that of the case with piston flow. The age of air in the extract air duct is the same as that all other points in the room.

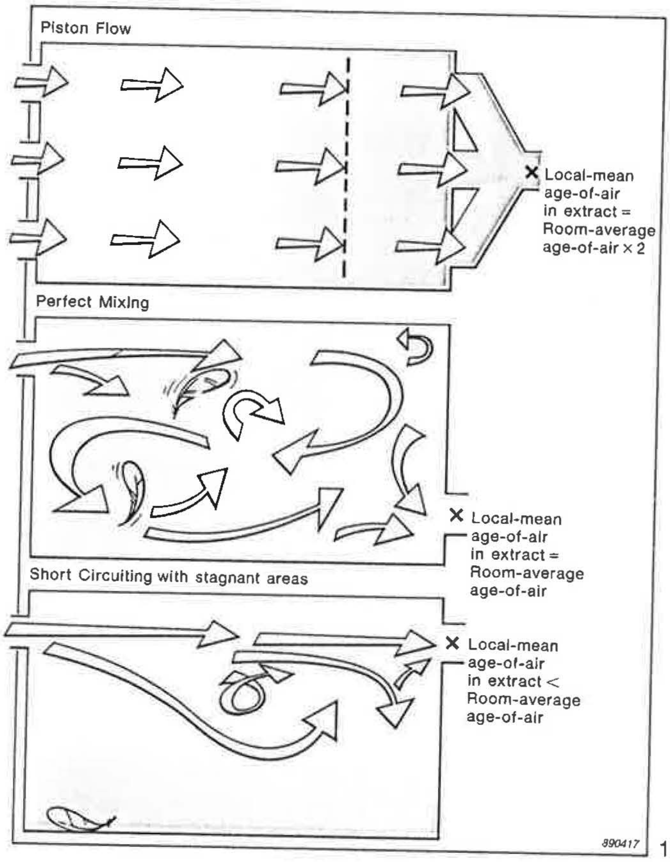
If there are areas of stagnant air in a room — due the short-circuiting of supply air — then the room-average age-of-air will be greater than the perfectly mixed case. Stagnant areas are characterised by the extract air being younger than the room-average age-of-air.

The advantages of piston flow (or displacement ventilation*) and disadvantage of short-circuiting can be illustrated by considering a room in which both pollutants and heat are generated uniformly. With piston flow, extracted air will be hotter than and contain a higher concentration of pollutants than the average in the room. Conversely, with a less efficient short-circuiting pattern, extracted air will be both cooler, and contain a lower concentration of pollutants than the average in the room.

The efficiency with which the ventilation system exchanges the room air can be calculated by dividing the local-mean age-of-air in the extract by twice the room-average age-of-air.

The local-mean age-of-air in the extract is equal to the effective volume of the room divided by the airflow rate through it.

* see Glossary



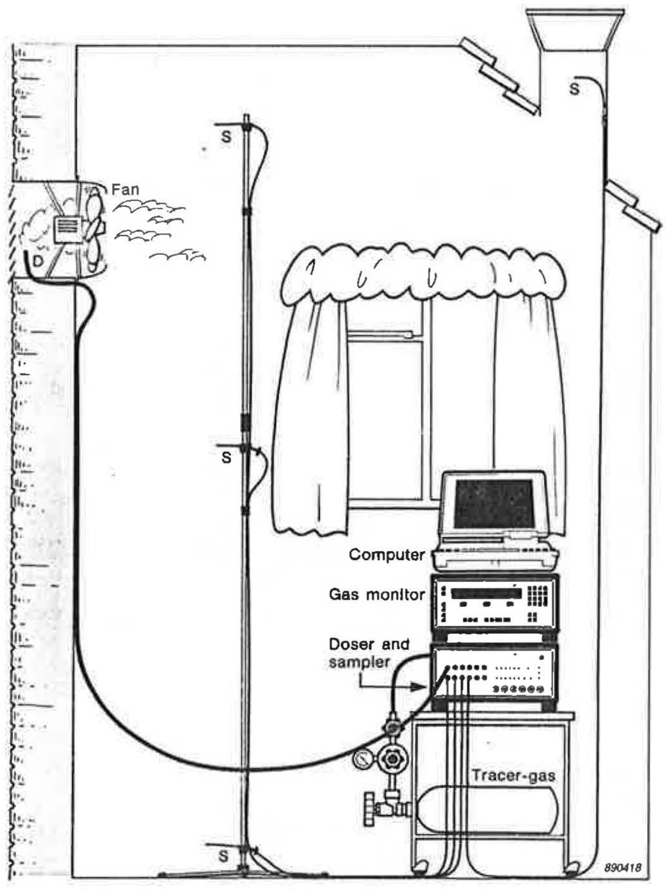
Age-of-air measurement methods

There are three tracer-gas methods for measuring the age of the air: pulsed injection; concentration-growth; and concentration-decay. The equation which allows age-of-air to be calculated can be found in Appendix A.

With the pulsed injection method, ventilation air entering the room is marked with pulses of tracer-gas (pt. D in figure) at definite times and the tracer-gas concentration in the extract duct and at points of interest in the room monitored (pts. S). The advantages of this method are that it is quick and comparatively little tracer-gas is used. The main disadvantage is that it is difficult to obtain rapid enough measurements of tracer-gas concentration in the room.

With the tracer-gas concentration-growth method, ventilation air is continuously marked with tracer-gas as it enters the room and the growth of tracer-gas concentration in the room studied. This method is useful in cases where a uniform concentration of tracer-gas throughout the room is difficult to achieve — for example, in very large rooms such as assembly shops or aircraft hangars. A big disadvantage of the method is that only the distribution of supply-air provided by the ventilation system which is measured.

Measurement with tracer-gas concentration-decay is the most popular age-of-air method. It is very similar to the air-exchange rate concentration-decay method except that no room-air mixing takes place after the tracer has first been perfectly mixed into the room air. The concentration-decay method of measuring age-of-air is discussed in more detail in the next section.

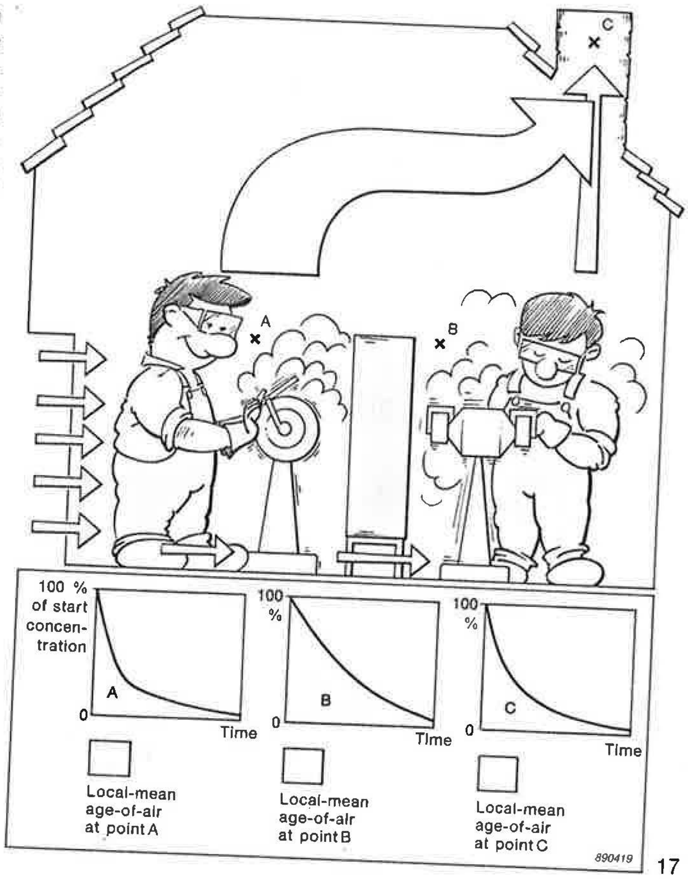


Age-of-air measurement with concentration-decay

With the tracer-gas concentration-decay method the air in the room is marked with tracer-gas and the decay of the gas concentration due to the infiltration of unmarked outdoor air into the room is studied. The local-mean age-of-air is simply the area under the concentration versus time curve. This method is preferred by many researchers because difficulties in marking all of the infiltration air are avoided. The concentration-decay method is also the only usable method where a space is naturally ventilated.

Typical plots of the tracer-gas concentration as a function of time are shown in the illustration. At the beginning there is a region with a non-exponential decay, but after a certain period of time, the gas concentration decays exponentially. In practice the measurements are stopped when the concentration begins to decay exponentially, since the residual area under the curve can be calculated with good accuracy using a simple equation (See Appendix A).

If the point at which the concentration change has been studied is in the extract air duct then the room-average age-of-air can be calculated. We can also calculate the air-change rate for the room as a whole (1/local-mean age-of-air in extract) and see whether or not there are areas of stagnant air in the room. By measuring the local-mean age-of-air at different points in a room areas of stagnant air can be located (see pt. B in figure).

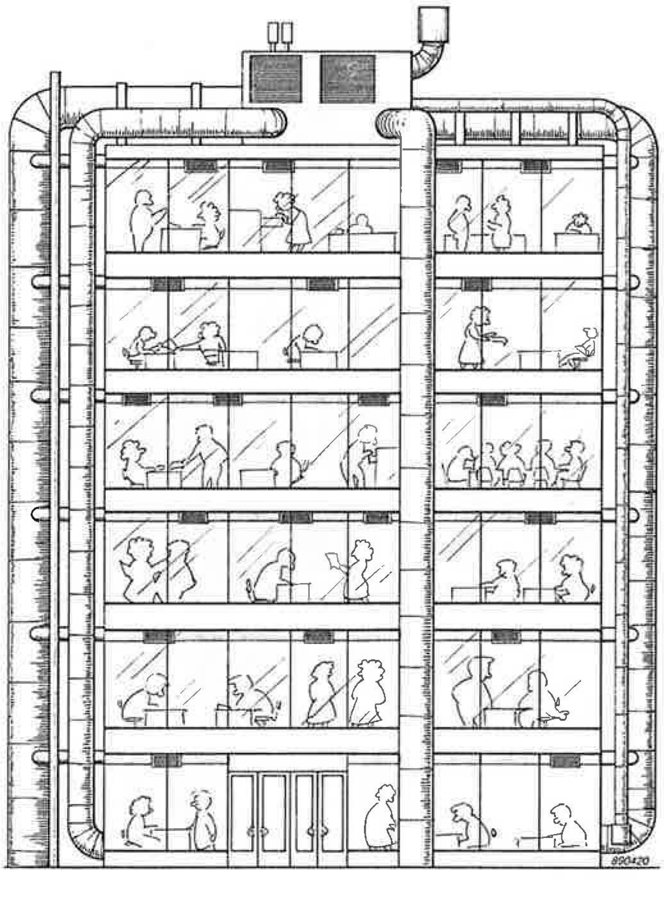


Measurements on ventilation systems

Airflow measurements are required during the design, commissioning and maintenance of ventilation systems. One of the most important pieces of information in connection with mechanically ventilated offices and dwellings is the volume of outdoor air reaching each room. It is often impossible to measure the airflow in the outdoor air intake duct directly because this duct is often too short. However, there is an alternative method of making this measurement using tracer-gas (see the section "Short-circuit of ventilation air").

In industry, the most important consideration is that the workers are not exposed to concentrations of toxic gases which may damage their health. Removal of toxic gases at source is the most effective way of reducing worker's exposure to them. In these cases it is often the effectivity (or "capture efficiency") of point-source fume-extractors that is the main determinant of indoor air quality.

In the following sections determination of these ventilation system parameters using tracer-gas techniques will be considered.



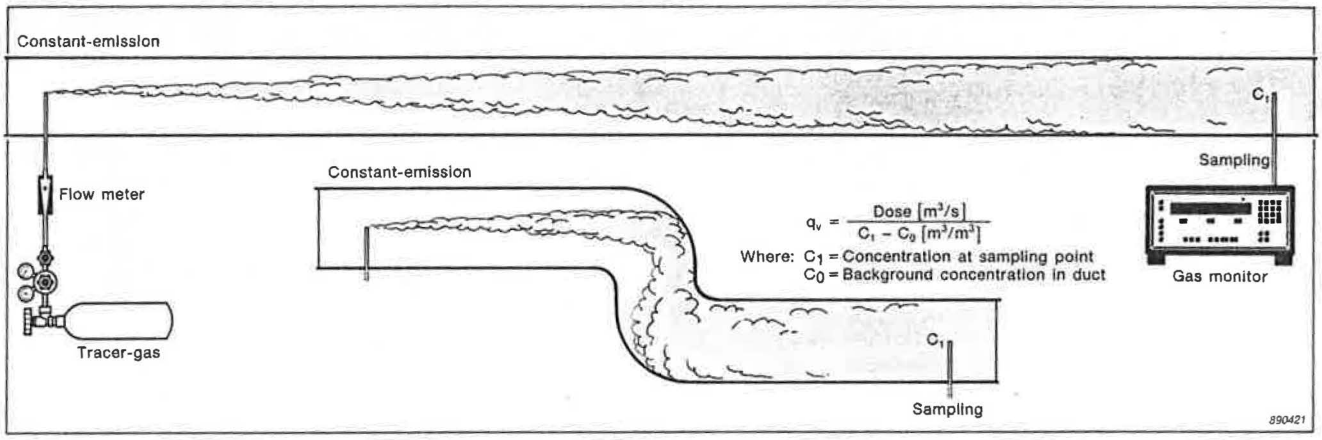
Airflow measurements in ducts

Accurate airflow measurement in ducts with many bends is very difficult with Pitot* tubes but can be measured easily and accurately using a constant emission of tracer-gas technique. Unlike measurement techniques using Pitot tubes or air velocity probes the measurement of airflow in ducts with tracer gases is actually made easier with bends and turbulence in the ducts. When making these kind of measurements, however, it is important to ensure that the distance between dosing and sampling points is large enough to enable good mixing of the tracer-gas across the diameter of the duct.

In the case of a length of straight duct a distance between dosing and sampling point of 25 times the duct diameter is recommended. This will give a deviation in tracer-gas concentration across the diameter of the duct at the sampling point of around 7%. If their are one or two bends in the duct then more turbulence is created and a distance between dosing and sampling point of only 10 times the duct diameter is normally enough to ensure a deviation in tracer-gas concentration across the diameter of the duct of less than 2%.

These distances depend on many factors and can only provide a rough guide. When making the measurements the degree of mixing at the sampling point can easily be assessed by sampling at various points across the diameter of the duct. If there is a lot of variation in the concentration of tracer-gas across the diameter, then the sampling point should be moved further down the duct.

* see Glossary



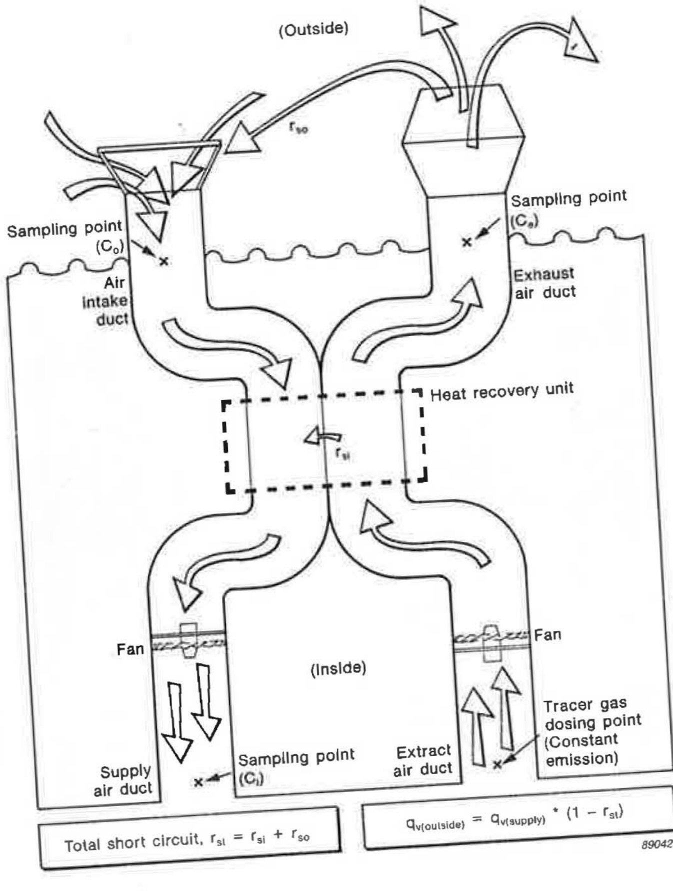
Short-circuit of ventilation air

To calculate the percentage of extracted air recirculated into the supply air duct, tracer-gas is injected into the extract air duct upstream of the extract fan and the concentration of tracer-gas is measured downstream of the fan — where the tracer is well mixed into the exhaust air — as well as in the air intake duct and in the supply air duct, downstream of the supply air fan.

The ratio of the concentration of tracer-gas in the outdoor air-intake, C_o, to the concentration in the exhaust, C_e, gives us the short-circuit of exhaust air into the outdoor air intake duct, r_{so}.

The ratio of the concentration of tracer-gas in the supply air duct, C_i, to the concentration in the exhaust air duct, C_e, gives us the total short-circuit of extracted air back into the supply-air. This total short-circuit for the ventilation system, r_{st}, is made up of both the outdoor short-circuit and the short-circuit of air inside the system, r_{si}. Short-circuiting of extracted air inside the system may be intentional, or due to the unintentional leaking of air whilst passing through a heat-recovery unit. The leakage or extract-air diversion inside the system is simply the total short-circuit, r_{st}, minus the outdoor short-circuit, r_{so}. This value can be used in the optimisation of the percentage of extract-air recirculated in an economiser*.

The outdoor air brought into a building by a ventilation system can be calculated from the air flow-rate in the supply ducts, and the percent of the supply air that is outdoor air and not recirculated or short-circuited extract-air.



* see Glossary

Effectiveness of fume-hoods

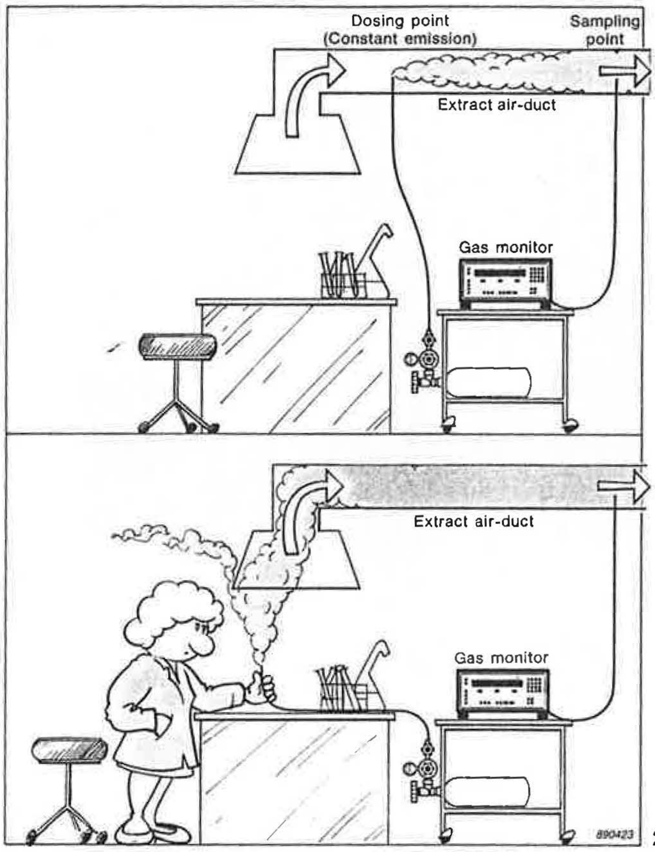
When working with noxious gases it is essential that the worker is well protected. Whether in a factory or in a laboratory this protection commonly consists of fume-hoods. The purpose of these hoods is to capture, extract and then dispose of enough noxious gas to ensure that occupants can work without risk to their health.

The performance of the extractor should be checked *in situ* since it will be affected by its position in relation to doors, air-conditioning systems, gangways, and other extractors. It is also important to take into account the effect the body of the technician will have on the airflow.

The effectiveness of the extractor is assessed according to its capture efficiency and this is measured using tracer-gas techniques. A typical set-up is shown in the diagram.

Constant-emission of tracer-gas and concentration monitoring are carried out on the section of duct just downstream of the hood as in an ordinary duct air-flow determination. The mean concentration measured during this part of the test represents a fume-hood capture-efficiency of 100%. The same volume flow rate of tracer-gas is then dosed at the position which, under normal working conditions, would be the source of noxious gas or pollutant. A simple ratio of the concentration of tracer measured in the duct during this second stage of the test to the concentration measured during the first stage represents the capture efficiency of the hood for that dosing point. When a detailed study is made, a map of capture efficiencies, for an area under or around the hood, can be drawn up.

As with all tracer-gas investigations the density of the tracer-gas should not be too different from the density of the gas being investigated. See Appendix B.

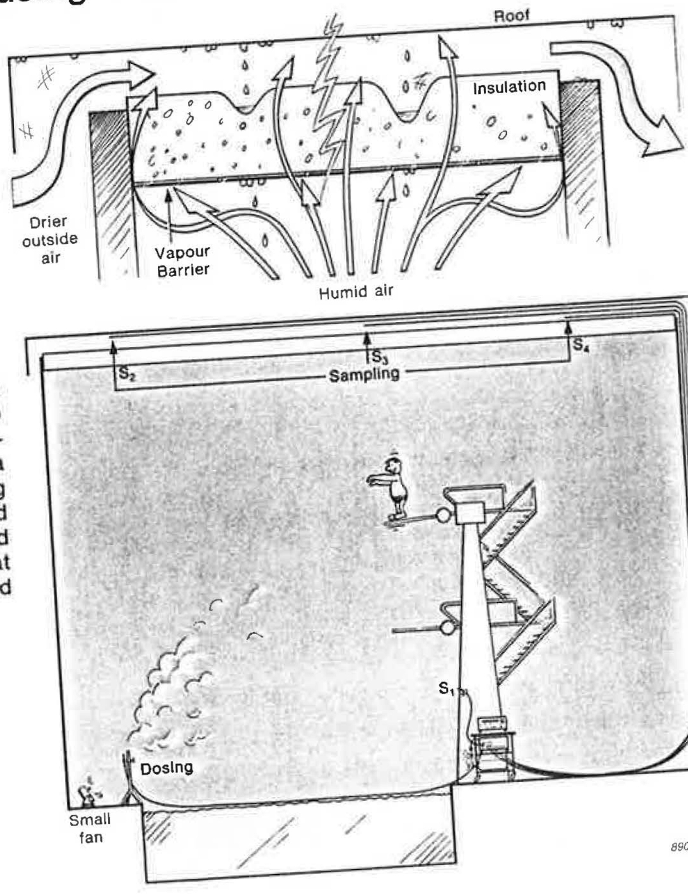


Measuring the spread of pollutants using 1 tracer-gas

Condensation of moisture onto a surface occurs when moist air comes into contact with a relatively cold surface. The problem of condensation is encountered in all sorts of buildings and is particularly common and damaging in roof spaces.

Condensation on the underside of the roof is often encountered in the roof space above swimming halls. When this happens, the condensed water often not only causes mouldy and rotting roof timbers, but drips down onto the roof insulation (thus ruining it) and eventually, back through the ceiling into the swimming hall.

Damp patches on the ceiling of the swimming hall are often the first noticeable signs of a problem. It is often difficult to find out the cause of the problem — is it due to condensation up in the roof-space or a leak in the roof? This is a typical situation in which tracer-gas pollution spreading techniques can be very useful. Tracer-gas is dosed to and kept at a constant concentration in the swimming hall, and a gas monitor measures the concentration of tracer-gas at one or more sampling points (S) in the swimming hall and in the roof-space over a period of time.

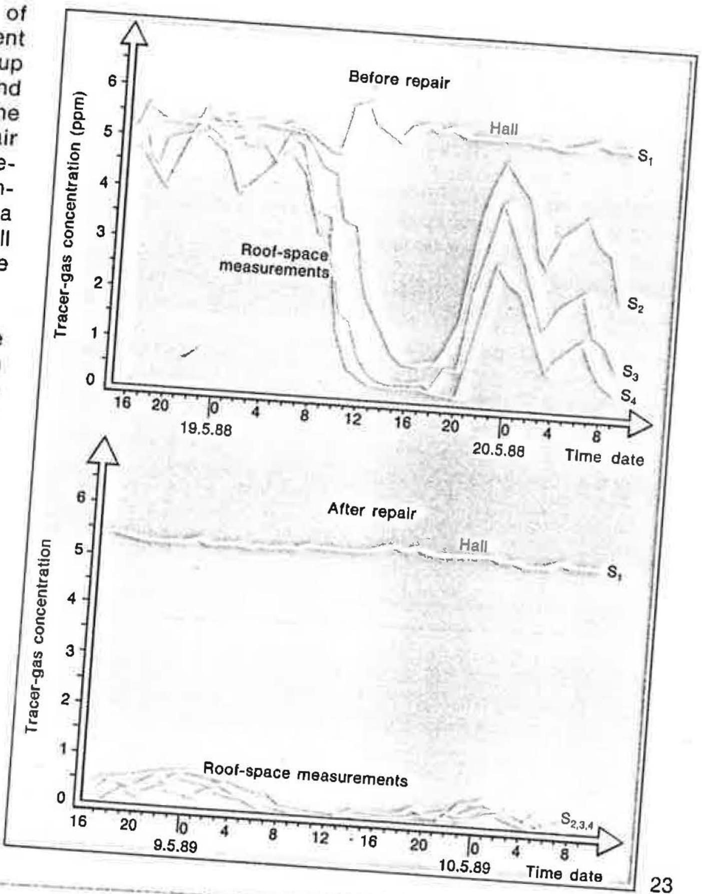


Measuring the spread of pollutants using 1 tracer-gas

In the example considered here a measurement period of 36 hours was considered suitable. From the measurement report we can see that the movement of moist air up through the swimming-hall ceiling is particularly serious and almost certainly the cause of the water dripping from the hall's ceiling. We can also see that more than 80% of the air entering the roof-space during the first night of measurements came from the hall. The large indoor-outdoor temperature difference at night is probably responsible for a strong rising air-current or "stack effect" inside the hall which is able to overcome the flow-inhibiting barriers of the ceiling.

The amount of leakage from the hall into the roof-space and the damage caused to the insulation was so serious in this case that the only real solution was to take down the ceiling and fit new insulation and a carefully-sealed vapour-barrier. In less serious cases, cheaper solutions to the problem may be possible such as increasing the outside air flow through the roof-space —thus lowering the humidity of air in the roof space to a level at which it would not condense.

As well as being a useful tool for the identification and analysis of problems, the tracer-gas techniques are very useful for checking that repairs have been successful.



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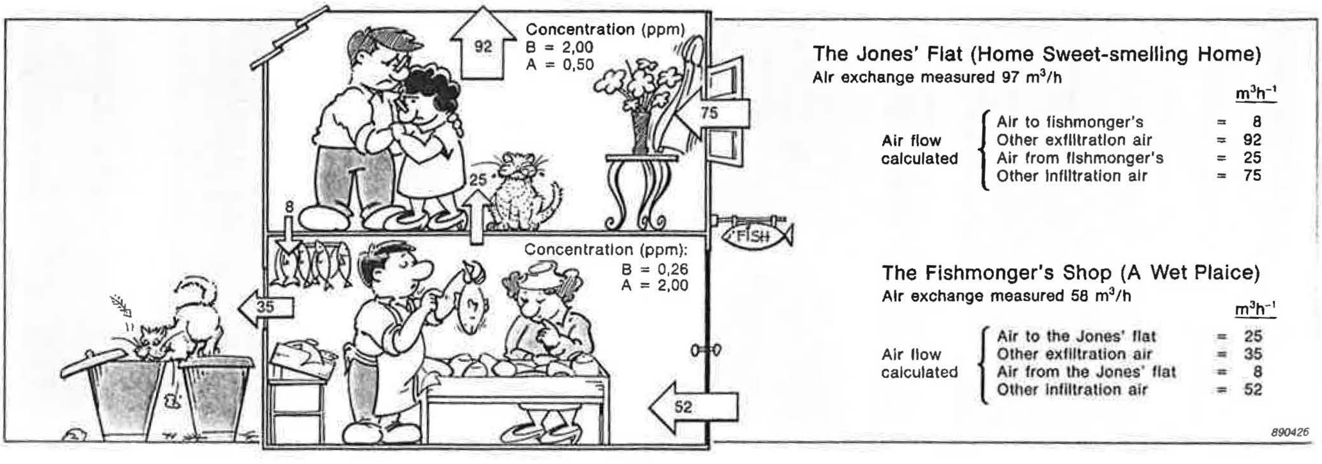
Measuring the spread of pollutants using 2 tracer-gases

Mr and Mrs. Jones live above a fishmonger and are very happy that they do not have far to walk if they want fresh fish for their breakfast. When the shop first opened, however, they were worried by a strange smell which penetrated everything in their home, and by a pride of cats which followed them around when they walked outside. The local ventilation expert was called in to solve the problem and, after a quick inspection, she decided to use the two-tracer constant-concentration technique for a spread-of-pollutants investigation.

By dosing gas A to a constant-concentration in the fishmonger's, and gas B to a constant-concentration in the Jones' home, and recording the emission rates of the gases and the concentration of both gases in both zones a lot of very useful information was obtained.

If we regard the study as two ordinary constant-concentration air-exchange rate measurements it is easy to see how the individual air-exchange rates for the fishmonger's and the Jones' were obtained. Performing both measurements at the same time means that we can also calculate the airflow from the fishmongers to the Jones' and/or vice versa. If the airflow or mixing between the two premises is significant, then we can use the results to help deduce the cause and, thereby, the best solution to the problem. The results of the initial investigation are shown in the drawing below.



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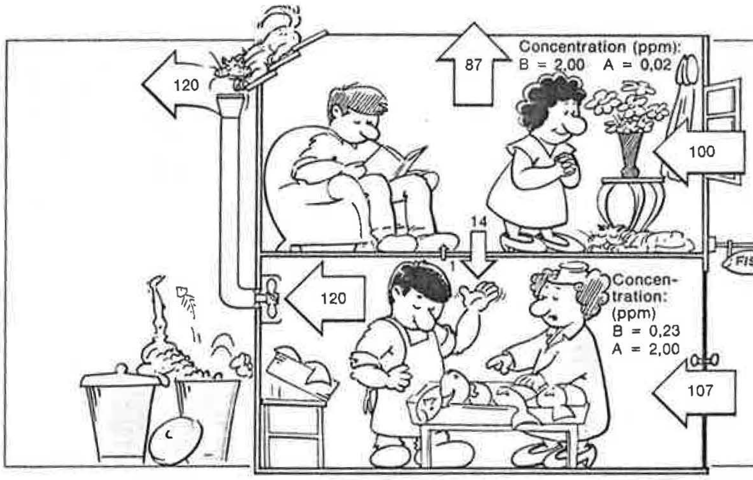
Measuring the spread of pollutants using 2 tracer-gases

Pollution spreading between two zones is caused by either general mixing between the zones, or due to a pressure-difference induced flow from one zone to the other. The solution to a pollution problem depends on the type and cause of pollution and the mode of spreading. If the problem is one of general mixing between zones and reducing the pollution at source is not a practical consideration, then the solution is to seal the two zones off from one another.

If, as was found to be the case in the fishmonger case-study, the problem is one of a flow from one zone to another, then the best solution may be to alter the pressure differential between the two zones.

The original measurements also showed that ventilation of the fishmongers' was insufficient and the ventilation expert therefore concluded that the best way to solve the problem was for the fishmonger to install an air-extraction unit with a chimney. This solution should both have reduced the pollution at source and altered the pressure differential between the two spaces. Sometime after the extraction-unit had been installed the spread-of-pollutants study was repeated and, from the results obtained, appeared to be a great success.



The Jones' Flat (Home Sweet-smelling Home)
Air exchange measured 101 m^3/h

		m^3h^{-1}
Air flow calculated	Air to fishmonger's	= 14
	Other exfiltration air	= 87
	Air from fishmonger's	= 1
	Other infiltration air	= 100

The Fishmonger's Shop (A Wet Plaice)
Air exchange measured 121 m^3/h

		m^3h^{-1}
Air flow calculated	Air to the Jones' flat	= 1
	Other exfiltration air	= 120
	Air from the Jones' flat	= 14
	Other infiltration air	= 107

890427

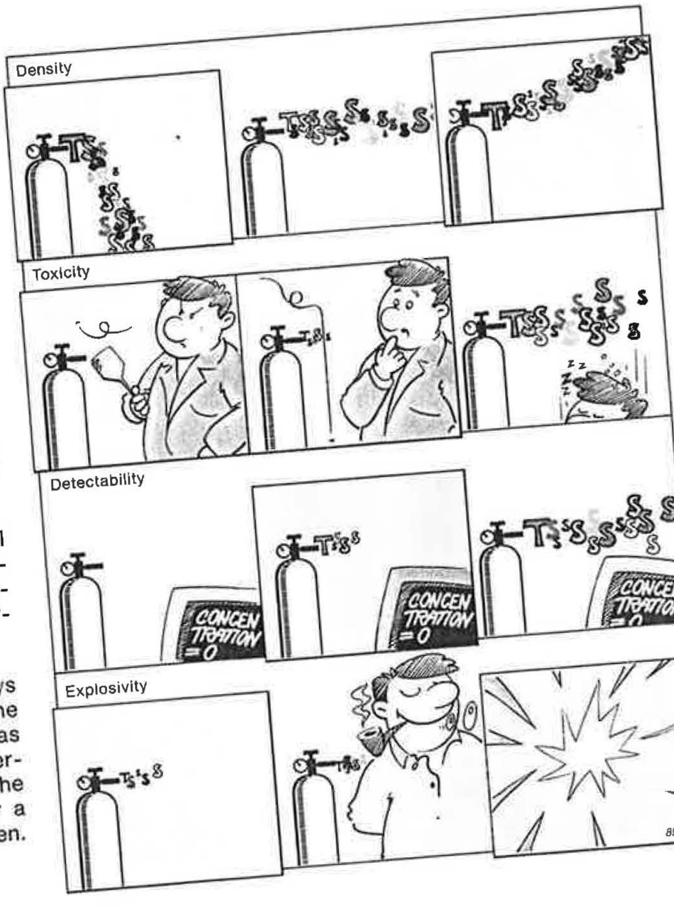
What makes a good tracer-gas ?

To be suitable as a tracer, a gas should have a similar density to air, should not normally be present in indoor or outdoor air, and its concentration must be measurable to a good order of accuracy, even when highly diluted. Perhaps the most important considerations when choosing a suitable tracer gas are, however, what it must not do!

For safety considerations, for example, the gas should be neither flammable nor explosive and, as measurements are often performed in occupied buildings, it should have no smell or any adverse health effects in the concentrations required for the tests. And finally, since tracer-gas analyses are based upon the mass-balance equation it is important to ensure that all the tracer leaving the enclosure does so by the process of ventilation. This means that the gas chosen must not be absorbed by walls or furnishings, and it must not react with building surfaces or the room air, nor decompose during the measurements.

No gas fulfils all the requirements given above, but several gases are used successfully as tracers. These include nitrous oxide, carbon dioxide, sulphur hexafluoride, and refrigerants. Appendix B gives a broad outline of the properties of some of the most commonly used tracer-gases.

Before starting tracer-gas analysis it is important to always check that the air in and around the building in which the analysis is to be performed contains none of the tracer gas you intend to use, or any other gas which is likely to interfere with the measurement of the intended tracer gas. If the air is found to contain either the intended tracer gas or a likely interferant an alternative tracer gas should be chosen.



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* The Air Infiltration and Ventilation Centre is Annex V of the International Energy Agency's "Energy Conservation in Buildings and Community Systems" project. Their address is: AIVC, University of Warwick Science Park, Coventry CV4 7EZ, Great Britain.

Appendix A: Age-of-air measurement equations

The table on the next page gives an overview of equations used for calculating age-of-air. An example of how the calculations are made in practice is shown below.

Using the tracer-gas concentration-decay method the room-average age-of-air, $\langle\bar{\tau}\rangle$, is given by:

$$\langle\bar{\tau}\rangle = \frac{\text{1st moment of measured area} + \text{1st moment of residual area}}{\text{Measured area} + \text{Residual area}}$$

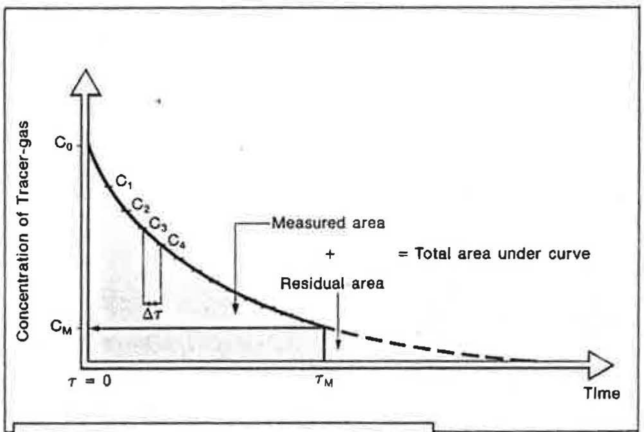
Measured area
$$= \tfrac{1}{2}\left(C_0 + C_M\right)\cdot\Delta\tau + \sum_{j=1}^{M-1} C_j\cdot\Delta\tau$$

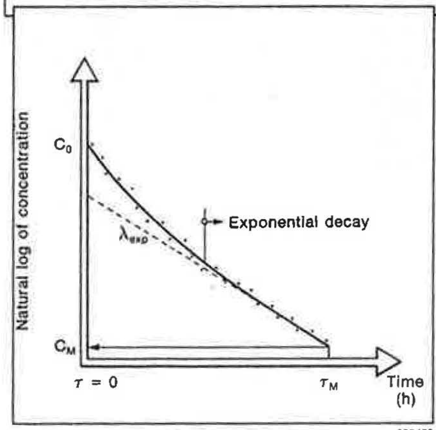
1st moment of measured area
$$= \tfrac{1}{8}C_0\cdot\Delta\tau + \tfrac{1}{2}C_M\cdot\Delta\tau\cdot\tau_M + \sum_{j=1}^{M-1} C_j\cdot\tau_j\cdot\Delta\tau$$

Residual area
$$= \frac{C_M}{\lambda_{exp}}$$

1st moment of residual area
$$= \frac{C_M}{\lambda_{exp}}\left(\tau_M + \frac{1}{\lambda_{exp}}\right)$$

where
C_j = concentration measurement j
C_M = final concentration measured
M = number of measurements
$\Delta\tau$ = sampling interval
λ_{exp} = slope in the exponential decay region
τ_j = time of measurement j
τ_M = total measuring time, $\tau_M = M\cdot\Delta\tau$





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Appendix A: Age-of-air measurement equations (Cont'd)

Tracer-gas measurement method	Measurement Equation	
	Local mean air-of-air $\overline{\tau_p}$ (Arbitrary measurement point)	Room-average age $<\bar{\tau}>$ (Measured in exhaust)
Concentration decay method	$\dfrac{\int_0^\infty C(\tau)\,d\tau}{C(0)}$	$\dfrac{\int_0^\infty \tau\, C_{exh}(\tau)\,d\tau}{\int_0^\infty C_{exh}(\tau)\,d\tau}$
Concentration growth method	$\int_0^\infty \left(1 - \dfrac{C(\tau)}{C(\infty)}\right) d\tau$	$\dfrac{\int_0^\infty \tau \left(1 - \dfrac{C_{exh}(\tau)}{C(\infty)}\right) d\tau}{\int_0^\infty \left(1 - \dfrac{C_{exh}(\tau)}{C(\infty)}\right) d\tau}$
Pulsed injection	$\dfrac{\int_0^\infty \tau \cdot C(\tau)\,d\tau}{\int_0^\infty C(\tau)\,d\tau}$	$\dfrac{1}{2} \cdot \dfrac{\int_0^\infty \tau^2\, C_{exh}(\tau)\,d\tau}{\int_0^\infty \tau\, C_{exh}(\tau)\,d\tau}$

where $C(0)$ = concentration at $\tau = 0$; $C(\infty)$ = concentration at $\tau = \infty$; $C_{exh}(\tau)$ = concentration in exhaust; $C(\tau)$ = concentration at time τ; τ = time

T02114GB0

Appendix B: Properties of a selection of tracer gases

Tracer	Formula	Density Compared to air	Max Concentration		Comments
			For Density[1] ppm	For Safety[2] ppm	
Nitrous oxide	N_2O	1,53	640	25	Anaesthetic gas. Widely used as a tracer
Carbon dioxide	CO_2	1,53	640	5000	High background concentration variation due to occupants. Readily available
Sulphur hexafluoride	SF_6	5,11	83	1000	Detection affected by other halogenated compounds in air. Decomposes to toxic components at 550°C. Widely used as a tracer
R–12	CF_2Cl_2	4,18	107	1000	Detection affected by other halogenated compounds in air. Possible background levels. Used in multi-tracer work. Decompose to toxic components at high temperatures
R–13B1	CF_3Br	5,13	83	1000	
R–115	$CClF_2CF_3$	5,31	80	1000	

T01979GB0

1) In terms of density the maximum concentration has been set at a level of tracer concentration above which the air/tracer mixture would differ by 0,03%. Such a density difference (equivalent to a temperature difference of ~0,1°C) is very unlikely to have a significant effect on the airflow or air-exchange rate of a space.

2) These safety limits often vary with time and from country to country. You should always check what the local exposure limits are and stay within these limits when using any tracer gas within an occupied building.

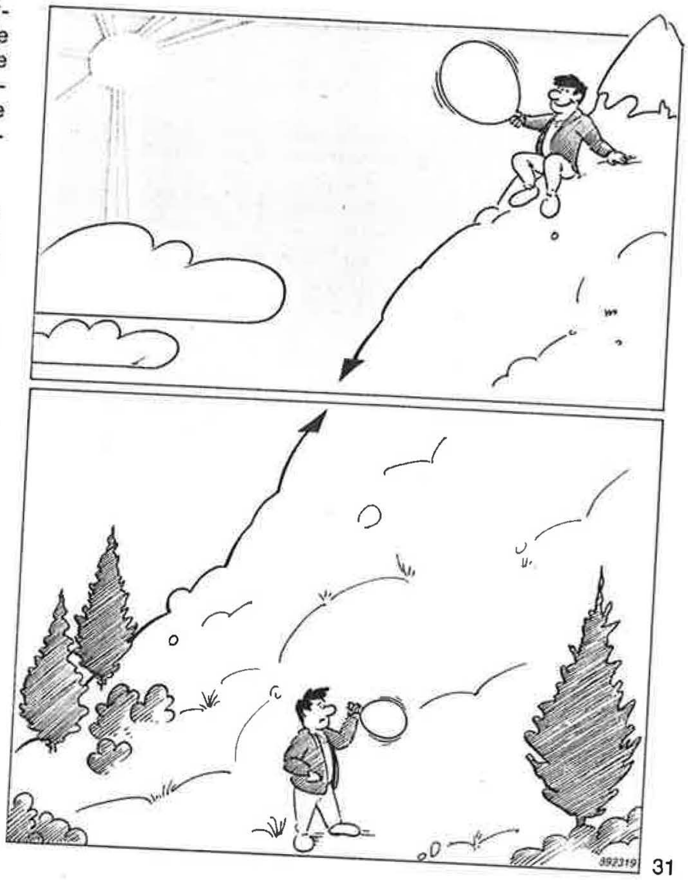
Appendix C: Reference temperature and pressure

Measurements of air quality parameters are made at different temperatures and pressures. In order to make a reliable comparison of results obtained at different places, then, the results must be expressed with respect to a reference temperature and pressure. It is also important to quote the temperature, pressure, and humidity at which the measurements took place.

At present no single set of reference values of temperature and pressure are available. The recommended values expected in the forthcoming ISO 8756 standard are 273 K and 103,3 kPa respectively.

Air exchange results made at temperature T_1 and pressure P_1 can be converted to reference conditions T_{ref} and P_{ref} using the following equation:

$$q_{v(ref)} = q_{v(1)} \times \frac{P_1}{P_{ref}} \times \frac{T_{ref}}{T_1}$$



Glossary

air-exchange rate	the ratio of the volume of air entering an enclosure per hour to the effective volume of the enclosure
air infiltration	the uncontrolled inward air-leakage through cracks and interstices. Infiltration is caused by the interaction between the building's leakage characteristics and external driving forces caused by the weather
capture efficiency	the percent of a pollutant gas an extraction device can extract directly from a specified point in a room
displacement ventilation	a ventilation method that pushes air into a space over a large surface area so as to avoid high air velocities and turbulence. The overall effect is one of piston flow from the supply to the exhaust
economiser	a device in a ventilation unit which recirculates air from the extract duct into the supply air duct
effective volume	the volume of air in a room excluding that unmixed air in, for example, built-in cupboards, and including the volume of connected spaces with which the room air mixes freely
local mean age-of-air	the mean age of air-"molecules" passing an arbitrary point. The age of the molecule being defined as the time elapsed since it entered the room
room-average age-of-air	the mean-age of all air present in the room. The age of the molecule being defined as the time elapsed since it entered the room
measured zone	the space or enclosure in which the measurements are made, normally a room
mechanical ventilation	ventilation by means of one or more fans
natural ventilation	ventilation using only purpose-provided openings and the natural forces of wind and temperature difference
pitot tube	a detector for transmitting the static and dynamic pressure of a moving fluid stream. The difference in the measured pressures is used to determine the velocity of the fluid
ventilation	the process of supplying and removing air by natural or mechanical means to and from any space
ventilator	appliance or aperture for ventilating room, compartment, or mine, etc

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Printed in Denmark: K.Larsen & Søn A/S · DK-2600 Glostrup

English BR 0608-11