INTERNATIONAL
STANDARD

ISO
16000-8

First edition
2007-06-15

Indoor air —

Part 8:
Determination of local mean ages of air in buildings for characterizing ventilation conditions

Air intérieur —

Partie 8: Détermination des âges moyens locaux de l'air dans des bâtiments pour caractériser les conditions de ventilation

Reference number
ISO 16000-8:2007(E)

PDF disclaimer

This PDF file may contain embedded typefaces. In accordance with Adobe's licensing policy, this file may be printed or viewed but shall not be edited unless the typefaces which are embedded are licensed to and installed on the computer performing the editing. In downloading this file, parties accept therein the responsibility of not infringing Adobe's licensing policy. The ISO Central Secretariat accepts no liability in this area.

Adobe is a trademark of Adobe Systems Incorporated.

Details of the software products used to create this PDF file can be found in the General Info relative to the file; the PDF-creation parameters were optimized for printing. Every care has been taken to ensure that the file is suitable for use by ISO member bodies. In the unlikely event that a problem relating to it is found, please inform the Central Secretariat at the address given below.

COPYRIGHT PROTECTED DOCUMENT

© ISO 2007

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either ISO at the address below or ISO's member body in the country of the requester.

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
Web www.iso.org

Published in Switzerland

--`,,```,,,,````-`-`,,`,,`,`,,`---

Copyright International Organization for Standardization
Provided by IHS under license with ISO
No reproduction or networking permitted without license from IHS
Not for Resale

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 16000-8 was prepared by Technical Committee ISO/TC 146, *Air quality*, Subcommittee SC 6, *Indoor air*.

ISO 16000 consists of the following parts, under the general title *Indoor air* :

- *Part 1: General aspects of sampling strategy*
- *Part 2: Sampling strategy for formaldehyde*
- *Part 3: Determination of formaldehyde and other carbonyl compounds — Active sampling method*
- *Part 4: Determination of formaldehyde — Diffusive sampling method*
- *Part 5: Sampling strategy for volatile organic compounds (VOCs)*
- *Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA$^{®}$ sorbent, thermal desorption and gas chromatography using MS/FID*
- *Part 7: Sampling strategy for determination of airborne asbestos fibre concentrations*
- *Part 8: Determination of local mean ages of air in buildings for characterizing ventilation conditions*
- *Part 9: Determination of the emission of volatile organic compounds from building products and furnishing — Emission test chamber method*
- *Part 10: Determination of the emission of volatile organic compounds from building products and furnishing — Emission test cell method*
- *Part 11: Determination of the emission of volatile organic compounds from building products and furnishing — Sampling, storage of samples and preparation of test specimens*
- *Part 12: Sampling strategy for polychlorinated biphenyls (PCBs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs) and polycyclic aromatic hydrocarbons (PAHs)*
- *Part 13: Determination of total (gas and particle-phase) polychlorinated dioxin-like biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDDs/PCDFs) — Collection on sorbent-backed filters*

- *Part 15: Sampling strategy for nitrogen dioxide* (NO_2)

- *Part 16: Detection and enumeration of moulds — Sampling by filtration*

- *Part 17: Detection and enumeration of moulds — Culture-based method*

The following parts are under preparation:

- *Part 14: Determination of total (gas and particle-phase) polychlorinated dioxin-like biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins/dibenzofurans (PCDDs/PCDFs) — Extraction, clean-up and analysis by high-resolution gas chromatography/mass spectrometry*

- *Part 18: Detection and enumeration of moulds — Sampling of moulds by impaction*

- *Part 23: Performance test for evaluating the reduction of formaldehyde concentrations by sorptive building materials*

- *Part 24: Performance test for evaluating the concentration reduction of volatile organic compounds and carbonyl compounds except formaldehyde by sorptive building materials*

- *Part 25: Determination of the emission of semi volatile organic compounds for building products — Micro chamber method*

Furthermore, the two International Standards, ISO 16017-1 on pumped sampling and ISO 16017-2 on diffusive sampling, focus on volatile organic compound (VOC) measurements.

Introduction

An adequate air change is of fundamental importance for indoor air quality. Proper ventilation of all buildings is necessary for the health and comfort of the occupants as well as to protect against damage (e.g. due to excessive atmospheric humidity). However, the present-day use of tightly sealed windows, for example in residential and office buildings, can lead to insufficient ventilation. This situation in turn may lead to an increase in the concentration of substances emitted indoors. Manual ventilation by the occupants or the use of mechanical ventilation systems is thus required. However, excessive ventilation can lead to discomfort and increased energy consumption.

Building regulations make provision for ventilation to control moisture and other pollutants. Measurements of the ventilation conditions allow confirmation of whether these requirements are met in practice. Knowledge of the ventilation conditions is important in order to be able to analyse the possible causes of poor indoor air quality. Thus, ideally, sampling and analysis of contaminants indoors should be accompanied by ventilation measurement, making it possible to estimate the strengths of contaminant sources.

This part of ISO 16000 describes the use of single tracer gas for determining the age of air in a building which is naturally or mechanically ventilated. The age of air is an important factor in assessing the adequacy of ventilation. The concept local mean age of air (and its inverse the local effective air change rate) is used for assessing the ventilation conditions in the building. The mean age of air in a building zone indicates the average time the air in a zone has spent in the building accumulating contaminants. It is closely connected to the time it takes to exchange the air within a zone. The concentration of a contaminant released from continuous indoor sources increases with the length of time the air has spent indoors. The lower the age of air in a space, the lower the concentration. Normally, the ventilation air is supplied at selected parts of the building envelope, and seeks its way to the different building spaces. Thus, before the ventilation air reaches a specific room, a significant portion of the air may have spent time in other rooms, accumulating contaminants. Therefore, the local mean age of air, which describes how long the air in a particular space has spent indoors, needs to be considered in relation to air quality.

The purpose of this part of ISO 16000 is to describe the use of ventilation measurement techniques suitable for air quality studies. For this purpose, the ventilation rate and the air distribution patterns in the building should be measured for representative conditions of interest.

ISO 12569 describes the use of tracer gas dilution for determining the air change rate in a single zone. The procedures for tracer gas dilution include concentration decay, constant injection and constant concentration. ISO 12569 should be used when studying the thermal performance of buildings.

In the case where a zone exchanges air only with the outside (i.e. has no inflow of air from other parts of the building), the tracer gas concentration within the zone can be characterized with a single value, and the ventilation conditions are constant over the measurement period; this part of ISO 16000 and ISO 12569 should, in theory, provide identical results. The methods described in this part of ISO 16000 can, however, be used beyond these conditions, for example in spaces with several zones, which may exchange air with each other, and in cases where the ventilation conditions vary during the measurement period.

Indoor air —

Part 8:
Determination of local mean ages of air in buildings for characterizing ventilation conditions

1 Scope

This part of ISO 16000 describes the use of single tracer gas for determining the local mean age of air as an indicator of ventilation conditions in a building. The procedures include concentration decay and homogeneous constant emission.

The described methods are intended for air quality studies and can be used for

a) checking whether the building ventilation requirements are met,

b) estimating the adequacy of ventilation in buildings with indoor air quality problems, and

c) characterizing the strength and distribution of indoor emission sources.

In principle, the methods can be applied to all indoor spaces, regardless of the type of ventilation used and the state of mixing of air between zones. The prevailing ventilation conditions need not be disturbed by the measurement.

This part of ISO 16000 does not address the details of the analytical methods for tracer gases. The availability of such analysis services should be checked before planning actual field measurements.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 12569, *Thermal performance of buildings — Determination of air change in buildings — Tracer gas dilution method*

ISO/IEC Guide 98:1995, *Guide to the expression of uncertainty in measurement (GUM)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 12569 and the following apply.

3.1
homogeneous emission
strategy to inject tracer gas in such a way that the injection rate per unit volume is equal in all parts of ventilated system

3.2
local mean age of air
ventilation parameter, which describes the length of time the air at a specific location has on average spent within the building

NOTE See A.1 for a further explanation of this term.

3.3
ventilated system
the building space, which can exchange air directly or indirectly with the space of interest

NOTE At the border of the ventilated system, there is no other inflow of air than outdoor air.

3.4
zone
space within the building where air mixing is sufficient to create an essentially uniform concentration of a tracer gas released anywhere within that space

NOTE 1 To be considered a zone, the space should not exhibit concentration differences larger than 20 % of the mean.

NOTE 2 A zone can be part of a room, an entire room or even include several rooms.

3.5
zone mean age of air
ventilation parameter, which describes the length of time the air in a zone has on average spent within the building

NOTE In the case of complete mixing within a zone, this is equal to the local mean age of air at any point within the zone.

4 Principles of tracer gas measurements for determining of ventilation conditions

4.1 General principles

Tracer gas techniques for measuring ventilation rely on the possibility of differentiating between air that is already within a space of interest and new air coming into that space. This means that it shall be able either to mark the air already in the space and follow how the marked air is replaced by new ventilation air or, alternatively, to mark the incoming air and measure how this marked ventilation air is distributed through the space.

It should be observed that air flowing into a specified zone from other zones that have a lower or higher concentration of tracer gas would influence the result of the measurement. Therefore, it is important to keep to the prescribed boundary conditions that are different for different tracer gas methods.

If the ventilation condition is to be determined in a zone, which has no inflow of air from other parts of the building (single isolated zone), it is not necessary to inject tracer gas or mark the air in other parts of the building in order to obtain correct results. However, if the zone can exchange air with other parts of the building, which is usually the case, special strategies for tracer gas injection in those connected zones shall be followed in order to avoid ambiguous results. It should also be noted that the closing of doors to a room does not necessarily lead to zero inflow of air from other parts of the building. Such means of restricting a normally occurring airflow will also change the ventilation of a room from that which would otherwise prevail.

4.2 Selected tracer gas methods

4.2.1 General

This part of ISO 16000 describes the strategies for tracer gas injection and measurement in spaces that cannot be regarded as single isolated zones. ISO 12569 presents the tracer gas dilution methods for spaces that can be characterized as a single zone. If the ventilation conditions are constant over the measurement period, and the space of interest can be regarded as a single isolated zone, the methods presented in this part of ISO 16000 and ISO 12569 are, in theory, identical. Under these conditions, the local mean age of air would be the same as the inverse of the air change rate determined using ISO 12569.

4.2.2 Decay method

The principle of the decay method is to mark the air in the ventilated system with tracer gas and determine the rate at which the marked air is replaced with unmarked air.

The zone to be measured and all other zones in the building with which the zone of interest can exchange air directly or indirectly shall be marked with a common initial tracer gas concentration. Such a strategy will prevent air coming from other parts of the building from being regarded as “clean ventilation air” to a greater extent than its actual delivered ventilation power.

The concentration history is recorded as a function of time. The local mean age of air is obtained from the quotient of the integral of the concentration versus time and the initial concentration.

The decay method can generally be used without problems up to air change rate $n = 10\ \text{h}^{-1}$.

4.2.3 Active homogeneous emission method

In the active homogeneous emission method, tracer gas is fed at measured constant rates into the zones by a suitable adjustable flow injection device. The injection rates shall be proportional to the zone volumes. The steady state tracer gas concentration of room air is measured using a suitable gas analyser. The local mean age of air is obtained from the quotient of the steady state concentration and the injection rate per unit volume.

The zone to be measured and all other zones in the building with which the pertinent zone can exchange air directly or indirectly shall be equipped with constant homogenous emission of tracer gas.

4.2.4 Passive homogeneous emission method

In the passive homogeneous emission method, tracer gas is emitted at known constant rates into the zones using diffusion sources. The emission rates shall be proportional to the zone volumes. The steady state tracer gas concentration of room air is measured by collecting an integrating sample in a sorbent tube (actively using an air sampling pump or passively using diffusion sampling) and analysing this sample afterwards in an especially equipped laboratory. The local mean age of air is obtained from the quotient of the steady state concentration and the emission rate per unit volume.

The zone to be measured and all other zones in the building with which the zone of interest can exchange air directly or indirectly shall be equipped with constant homogenous emission of tracer gas.

The use of this method requires a special analysis service able to analyse the sample from the sorbent tube in order to determine the amount of the tracer gas in the sample.

5 Measurement planning

5.1 General

Before measurement of the local mean ages of air in a building space, the purpose of the measurement shall be clearly defined. Also, knowledge of the type of building and the particular characteristics of that part of the building that is to be investigated are essential for the choice of tracer gas technique and the detailed planning of the test.

The ventilation rate and the air distribution patterns in the building should be measured at representative conditions of interest. These conditions should not be disturbed by the measurement, unless it is the purpose of experiment to test the effect of different conditions, of for example door opening, window opening, etc.

The homogenous emission method using sampling on adsorbent tubes is especially suitable for determining the ventilation conditions in the context of air quality studies. Depending on the requirement, short-term (pumped sampling of a few litres of air) or long-term measurements (passive sampling during days to several weeks) can be carried out. In the investigation of indoor air quality (IAQ) problems, the ventilation measurements usually accompany the actual measurement of pollutant. An advantage of this measurement method is the possibility to simultaneously determine the local mean ages of air and the pollutant concentration.

In determination of “air change” (“airflow rate” or “air change rate”), for example using the methods described in ISO 12569, only the total airflow rate to the ventilated system is of concern. Such measurements are therefore restricted to buildings or other enclosures that can be treated as a single zone. In those methods, it shall therefore be ensured that there is complete mixing of air between all spaces within the ventilated system during the measurement.

5.2 Identification of the ventilated system

In planning the test, the “ventilated system” to which the space of interest belongs shall first be identified, because all spaces within the ventilated system shall be tagged with tracer gas. The ventilated system is defined as the building space, which can exchange air directly or indirectly with the space of interest. At the border of the ventilated system, there shall not be any inflow of air other than outdoor air. Thus, a part of a building should only be considered a ventilated system if it has negligible inflow of air from other parts of the building (for example via doorways, air leakage or return air ducts). The location of pollutant sources should also be taken into account to ensure that polluted air is not misinterpreted as outdoor air. In practice, this means, for example that

- for a single family house, all rooms including the cellar (unless there is an airtight door) should be included in the ventilated system, and
- for a flat in an apartment building, all rooms in the studied apartment (and in some cases also the staircase) should be included in the ventilated system.

5.3 Identification of zones

A zone is a space within the ventilated system where it can be assumed that the air mixing is sufficient to ensure a uniform concentration of air tracer gas. Within the ventilated system, there may be several spaces that can be regarded as zones. All such zones should be identified and their volumes measured. The zone-volumes are needed in order to calculate the amount of tracer gas to be injected in the different zones. Small closed spaces with only extract air (e.g. bathrooms), or without any supply of outdoor air (e.g. closets) do not need any tracer gas injection. The volume of small closed spaces, which may receive some supply of outside air should be added to the volume of any connected zone. Large rooms and long corridors may be subdivided into two or more zones.

5.4 Choice of measurement method

5.4.1 General

The choice of the measurement method depends on the type and size of the building, the intended measurement time, the purpose of the measurement, and the availability of equipment and analysis service.

5.4.2 Type of building

5.4.2.1 Simple buildings (e.g. small to moderate-sized dwellings that can be characterized with one to four zones)

When the number of zones is small, it is relatively easy to achieve an initial homogeneous tracer gas concentration within the whole ventilated system. For short-term measurements, the decay method is therefore best suited.

5.4.2.2 Complex buildings (e.g. office buildings and other structures in which the ventilated system comprises several zones)

In this case, it may be very difficult to achieve the necessary condition for the decay method of equal initial tracer gas concentration in all zones. The homogeneous emission method may therefore be better suited than the decay method in this case.

5.4.3 Measurement period

5.4.3.1 Short-term conditions of interest

The decay method is the most practical method to monitor short-term ventilation conditions in simple buildings, while the passive homogeneous emission method with pumped sampling is better suited for complex buildings.

5.4.3.2 Long-term time variation of interest

Though repeated use of the decay method is feasible in buildings with few zones, the most appropriate choice for long-term measurement in all types of buildings is the homogeneous emission method. The purpose may be to monitor the change of ventilation conditions as a function of time, for example in order to investigate the effect of weather conditions or to test the effect of different ventilation strategies. This requires active air sampling using continuous monitoring of tracer gas concentration or repeated sampling using syringes, bags, evacuated gas tubes or pumped collection tubes. The active homogeneous emission method is suitable for measuring time-varying conditions in simple buildings, while passive homogeneous emission with active sampling is better suited for complex buildings.

5.4.3.3 Long-term average conditions of interest

The purpose may be to investigate only the time average of the mean ages of air in different parts of a building. Advantages of this monitoring strategy are that short-term variations in ventilation are levelled out and that the result is directly coupled to the average exposure to contaminants (or dose) generated indoors. The most appropriate choice for monitoring average conditions is the passive homogeneous emission method using passive sampling or integrating sampling using pumps.

5.5 Determination of measurement points

The suitable number and distribution of measurement points are determined from the purpose of the measurement. Air sampling is necessary only in those zones where it is of interest to determine the local mean age of air. If the purpose is to map the distribution patterns of ventilation air within the building, measurements should be performed in several zones, while sampling in only one or a few zones is necessary to get information on local ventilation conditions. Sampling shall be performed at places which are thought to be representative of the zones. It shall not be attempted close to the tracer gas sources (minimum 1 m distance) or close to an air supply terminal. Irrespective of the purpose of the measurement, at minimum of three measurement points should be used in order to gain information of the range of variation. When performing a manual sampling, the sample can advantageously be taken at different positions in the zone. If the purpose is to gain information on the total ventilation flow rate or air exchange efficiency in the building (see E.2), sampling should also be performed close to identifiable air exhaust points.

6 Tracer gases and equipment for determining ventilation conditions

6.1 Choice of tracer gas

Apart from being able to analyse at low concentration with available measurement equipment, tracer gases shall be harmless to health and should fulfil other requirements.

Annex B (informative) provides information on choosing tracer gases based on accepted practice.

6.2 Tracer gas concentration standard

The tracer gas should be used within safe limits for concentration. If the source is pure tracer gas, avoid gas volumes that could create inadvertent hazards. An extremely large pressurized cylinder of pure gas, for example, could momentarily create unsafe concentrations in a small room. Avoid conditions where the amount of tracer gas that may be absorbed onto surfaces and into subordinate enclosures is significant.

Avoid the use of radioactive tracer gases.

The required amount of tracer gas depends on the sensitivity of the detection method, the ventilation rate and the size of the rooms.

6.3 Equipment for feeding the tracer gas

6.3.1 Decay technique

The purpose of tracer gas feeding for the decay technique is to achieve a uniform concentration of tracer gas throughout the ventilated system.

Choose one of the following apparatus for injecting tracer gas.

— **Graduated syringe**, or other container of known volume with a means for controlled release of its content.

— **Compressed tracer gas supply**, with a flow rate measurement and control device.

Choose a technique for creating a uniform initial concentration in the ventilated system from one or more of the following.

a) **Fans** that permit good mixing within and between zones.

b) **Injection lines** that dispense tracer gas via manifolds or switches. All parts of the injection lines shall be clearly labelled “Tracer Gas Only” and shall be keyed to the location that receives the tracer gas.

c) **Swinging doors**. After tracer gas injection in all zones, the doors between zones may be swung back and forth to increase interzonal mixing.

Injection lines should be purged to ensure delivery of known tracer gas volume to a given zone.

All artificial mixing shall be turned off and doors reset to their desired state (open/closed) at the moment of the start of the decay measurement.

NOTE Leaks in injection lines can release tracer gas at unwanted locations and in uncontrolled unwanted concentrations.

6.3.2 Active homogeneous emission technique

The purpose of feeding the tracer gas is to achieve a homogeneous emission rate of the tracer gas within the ventilated system. This means that the constant tracer gas injection rate in each zone of the ventilated system shall be proportional to the zone volume. The following steps are necessary for this:

a) metering the tracer gas emission rate in each zone (This can be performed directly using a pressurized cylinder that is brought into the zone and controlling the gas emission rate via pressure regulator and flow meter, or by using injection lines connecting a remotely located tracer gas source to the zone.);

b) ensuring complete mixing within zones may be necessary in large zones. (This can be achieved by operating one or more fans or by distributing the injection to several points throughout the zone.)

6.3.3 Passive homogeneous emission technique

The purpose of feeding the tracer gas is to achieve a homogeneous emission rate of the tracer gas within the ventilated system. This means that the constant tracer gas injection rate in each zone of the ventilated system is proportional to the zone volume. The following steps are necessary for this:

a) emitting the tracer gas in each zone using diffusion sources with known emission rates;

b) ensuring complete mixing within zones may be necessary in large zones. (This can be achieved by using one or more fans. Multiple diffusion vials with known emission rates may be required for larger zones.)

The fact that the tracer gas emission rate from diffusion sources is strongly temperature dependant, shall be taken into consideration when distributing passive tracer gas sources. The temperature should also be logged at representative locations throughout the measurement period.

6.4 Sampling the tracer gas

6.4.1 Sampling methods

The sampling methods described below are suitable for both decay and homogeneous emission methods, depending on the analytical method used for the tracer gas.

Sampling should be carried out at representative points, and should never be located close to air supplies and windows.

6.4.2 Continuous automatic sampling

The gas analyser is usually connected to the measurement points by one or more inert gas sample tubes through which air is drawn with a pump to the gas analyser. When sampling from several locations, the sampling locations can be chosen via automatically or manually operated multi-port valves. It is important that a sampling tube is flushed with new sample just before introduction into the analysing instrument.

6.4.3 Manual sample collection

With manual sample collection methods, a sample is first collected using a suitable container (syringe, bag or evacuated gas container). The sample is then analysed in the laboratory.

Materials used in manual sample collectors shall be non-absorbent, non-reactive and impermeable for the tracer gas in use. Depending on the tracer gas, the list of suitable materials may include, for example, glass, copper, stainless steel, polypropylene, polyethylene and polyamide.

Care should be taken when collecting manual samples in rooms with a normally closed door. Opening the door and entering the room may introduce a large unwanted amount of air exchange between the two connected zones. An easy and often used practice is to install a tube from the room to the adjacent room through the keyhole, draw one or two syringe samples for purging the tube and take the next sample for analysis.

6.4.4 Solid sorbent samplers

In the active solid sorbent sampling method, room air is drawn (continuously or intermittently) through a solid sorbent suited to the tracer gas in use for the sampling period. After sampling, which shall be performed using a calibrated sampling pump, the loaded samplers are desorbed (using thermal desorption or solvent extraction) to determine the sorbed amount of tracer gas and hence the tracer gas concentration in the sampled air. Pumped sampling using solid sorbent tubes is appropriate for continuous sampling periods of up to a few hours and for intermittent sampling for several days. When using intermittent pumped sampling, measures should be taken to minimize diffusion of air into the sorbent in between pump periods, e.g. using a capillary restriction.

For long-term sampling, which can extend over one to several weeks, passive sampling using diffusive solid sorption samplers can advantageously be used. The sampling rate of passive samplers shall be carefully calibrated for the type of tracer gas use.

When using the homogeneous emission technique, sample collection points should always be at least 1 m from the nearest tracer gas injection point.

6.5 Determination of tracer gas concentration

From the continuous sample collection system, the tracer gas/air mixture under test is passed directly, or via sample tubes, into a gas analyser to determine its tracer gas content. Manually taken air samples and solid sorbent tubes are usually analysed afterwards in a laboratory. If solid sorbent sample collectors are used, thermal desorption or solvent extraction is necessary in order to introduce the tracer gas sample into the gas analyser.

The gas analyser shall be suitable for the measuring task (sample gas volume, analytical period, cross-sensitivities), the tracer gas used and the tracer gas concentration. The gas analyser accuracy should be known.

For the tracer gases listed in Table B.1, infrared (IR) gas analysers or gas chromatography (GC) are suitable for determination of concentration. GC with an appropriate detector, e.g. ECD (electron capture detector) or MS (mass spectrometry), enables particularly sensitive tracer gas analysis.

7 Measurement methods

7.1 Decay method

7.1.1 Principles of the measurement technique

In the decay method, the tracer gas is injected into the zones and uniformly distributed throughout the whole ventilated system. The local mean age of air, $\bar{\tau}$, is calculated from the decay of tracer gas concentration.

$$\bar{\tau} = \frac{\int_{t_0}^{\infty} \varphi \mathrm{d}t}{\varphi_{t=t_0}} \tag{1}$$

where

t is the time, in hours (h);

$\varphi_{t=t_0}$ is the initial tracer gas concentration (e.g. in $\mathrm{cm}^3/\mathrm{m}^3$) at time $t = t_0$ (start of decay). This should be equal in all zones.

The initial tracer gas concentration, $\varphi_{t=t_0}$, should be chosen to be at least 100 times the detection limit of the analysis system.

The volume v_p of (pure) tracer gas to be injected into a zone (zone volume V_p) is given by Equation (2):

$$v_\mathrm{p} = \varphi_{t=t_0} \cdot V_\mathrm{p} \tag{2}$$

7.1.2 Preparations and planning of the test

The planning steps described in Clause 5 are advantageously performed in advance using a plan or sketch of the building space to be investigated.

7.1.3 Measurement procedure

After tracer gas is injected in all zones and mixed to ensure a uniform tracer gas concentration in the ventilated system, sample collection is started using one of the methods mentioned in 6.4. Sample collection is advantageously performed at equal time intervals in each zone of interest. Sample collection should proceed for at least twice the assumed mean age of air (e.g. for a period of 4 h for a normally ventilated dwelling). In order to get satisfactory data for analysis of the decay course, at least seven samples should be collected in each zone of interest during that time. When performing manual sample collection, care should be taken to minimize unnecessary disturbance of air distribution when entering rooms through a normally closed door.

The purpose of the tracer gas injection is to achieve an initial homogeneous concentration of the tracer gas within the ventilated system. In a building with multiple zones, this is best achieved if the injected amounts are proportional to the zone volumes and well distributed into the zone volumes by some mixing devices. Refer to the equipment for tracer gas distribution and mixing described in 6.3.1.

All artificial mixing shall be turned off and doors reset to their desired state (open/close) at the moment of the start of the decay measurement.

Before decay measurement starts, field personnel should, if possible, verify that the tracer gas concentration is equal in all zones of the ventilated system. In the case of a large zone (e.g. room volume greater than 500 m^3 or ceiling heights greater than 4 m), or if it is suspected that there may be pronounced air paths in the room, a uniform initial concentration should be verified by determining the concentration at various points in that room. In such rooms, where incomplete mixing may be suspected, decay measurements at different positions may also be appropriate.

7.1.4 Evaluation and calculation of the results

The integral in Equation (1) is usually evaluated numerically from the measured tracer gas concentration history using a suitable numerical integration technique (e.g. the trapezoid method). When a zone exchanges air with another connected zone, the first part of concentration decay is usually not purely exponential. However, after some time the decay will always approach an exponential decay. It is therefore sufficient to perform the numerical integration to the time t_e when an exponential decay has been ascertained (linear logarithmic plot) and add the area under the "tail" of the decay assuming exponential behaviour.

$$\int_0^\infty \varphi_t \mathrm{d}t = \int_{t_0}^{t_\mathrm{e}} \varphi_t \mathrm{d}t + \int_{t_\mathrm{e}}^{\infty} \varphi_{t=t_\mathrm{e}} \cdot \mathrm{e}^{-\lambda_\mathrm{tail}(t-t_\mathrm{e})} \mathrm{d}t = \Delta t \left(\frac{\varphi_{t_0}}{2} + \varphi_{t_0+1\Delta t} + ... + \varphi_{t_0+(n-1)\Delta t} + \frac{\varphi_{t_\mathrm{e}}}{2} \right) + \frac{\varphi_{t=t_\mathrm{e}}}{\lambda_\mathrm{tail}} \qquad (3)$$

where λ_tail is the absolute value of the slope from a plot of the logarithm of concentration as a function of time in the last exponential part of the decay according to Equation (4).

$$\ln \varphi_t = \ln \varphi_{t=t_\mathrm{e}} - \lambda_\mathrm{tail}(t - t_\mathrm{e}) \qquad (4)$$

First, the logarithm of the tracer gas concentration versus time should be plotted and inspected. If the plot is linear from $t = t_0$, the local mean age of air can be directly evaluated from the inverse of the absolute value of the slope:

$$\bar{\tau} = \frac{1}{\lambda_\mathrm{linear}} \qquad (5)$$

If the logarithmic plot shows curvature, the plot should be inspected for the beginning of the linear segment of the plot. The slope of the linear segment is evaluated and λ_tail is set equal to the absolute value of the slope.

Next, choose one of the measurements within the linear part of the plot as the endpoint for the numerical integration (concentration = φ_e at time t_e). Perform the numerical integration from $t = t_0$ to $t = t_\mathrm{e}$ and add $\varphi_\mathrm{e}/\lambda_{tail}$ according to Equation (3) to get an approximation of the concentration integral from $t = t_0$ to $t = \infty$.

Finally, the local mean age of air is calculated from the integral through division by the concentration at the beginning of the decay ($\varphi_{t=t_0}$) according to Equation (1).

7.1.5 Uncertainty

Any calculated value of the local mean age of air determined using the decay technique shall be accompanied by an estimate of its uncertainty. Uncertainty shall be estimated and expressed in harmony with the ISO/IEC Guide 98:1995.

Information on how to estimate the uncertainty of measured local mean ages of air according to this part of ISO 16000 can be found in Annexes C and D.

7.2 Active homogeneous emission method

7.2.1 Principles of the measuring technique

In the homogeneous emission method, a tracer gas stream is continuously injected into the zones in the ventilated system at constant rates that are proportional to the volume of each zone. This establishes a tracer gas concentration in each zone that is dependent on the local mean age of air in each zone.

Like the tracer decay technique, the homogeneous emission technique yields the local mean age of air, $\overline{\tau}$, in a zone as

$$\overline{\tau} = \frac{\varphi}{(q_V / V)} \tag{6}$$

where

φ is the measured tracer gas concentration (cm^3·m^{-3}) in a zone at steady state, in cm^3·m^{-3};

q_V / V is the constant injection rate (cm^3·h^{-1}) of pure tracer gas per cubic metre (m^3) of space — equal in all zones of the ventilated system (in for example, cm^3·h^{-1}·m^{-3}).

The desired proportionality constant between the injection rate of pure tracer gas q_V (cm^3·h^{-1}) in a zone with volume V is given by Equation (7).

$$q_V = k_V \cdot V \tag{7}$$

where k_V is a constant (cm^3·h^{-1}·m^{-3}) which can be estimated by the product of the anticipated air change rate (ACH in h^{-1}) and the desired tracer gas concentration (cm^3·m^{-3}) at steady state suitable for analysis.

7.2.2 Preparations and planning of the test

The planning steps described in Clause 5 are advantageously performed in advance using a plan or sketch of the building space to be investigated. The zone volumes shall be determined and tracer gas emission rates for each zone shall be calculated. The tracer gas shall be injected uniformly into the zones at a constant flow rate so that good mixing of the tracer gas is established (see 6.3.2). The locations of the injection points shall be planned and necessary equipment (e.g. injection and sample lines) shall be prepared.

7.2.3 Measurement procedure

Sample collection using one of the methods described in 6.4 is started when approaching the equilibrium (or steady state) tracer gas concentration, which requires approximately three to four times the mean age of air.

7.2.4 Evaluation and calculation of the results

The local mean age of air, $\bar{\tau}$, in a zone is determined from the measured tracer gas content at steady state and the tracer gas emission rate per volume unit using Equation (6).

7.2.5 Uncertainty

Any calculated value of the local mean age of air determined using the active homogeneous emission technique shall be accompanied by an estimate of its uncertainty. Uncertainty shall be estimated and expressed in harmony with the ISO/IEC Guide 98:1995.

Information on how to estimate the uncertainty of measured local mean ages of air according to this part of ISO 16000 can be found in Annexes C and D.

7.3 Passive homogeneous emission method

7.3.1 Principles of the measuring technique

The principle of the passive homogeneous emission technique is similar to that of the active homogeneous emission technique (see 7.2.1). However, the tracer gas is emitted from miniature passive tracer gas sources, which can be easily distributed within the ventilated system to yield a homogeneous emission. Due to low tracer gas concentrations, perfluorocarbon tracers (PFT) are used; these can be analysed with extremely high sensitivity.

7.3.2 Measurement procedure

Diffusion sources utilizing capillary diffusion or permeation membranes to control the emission rate of the tracer gas are distributed in the ventilated system in such a way that the tracer gas emission rates are proportional to the zone volumes as described in 6.3.3. After the equilibrium state is reached, the mass concentration of the tracer gas at the selected locations is determined by air sampling using solid sorbent samplers as described in 6.4.4 and subsequent laboratory analysis using gas chromatography.

In the case of short-term measurements, sampling is performed using a pump. For long-term measurements, diffusive sampling is advantageously used in order to obtain the local mean ages of air averaged over the sampling period.

7.3.3 Evaluation and calculation of result

The local mean age of air, $\bar{\tau}$, in a zone is determined from the measured average tracer gas concentration (as evaluated from the tracer gas contents in the sampling tubes) and the tracer gas emission rate per volume unit using Equation (8).

$$\bar{\tau} = \frac{\rho_a}{(q_m / V)} \tag{8}$$

where

$\bar{\tau}$ is the local mean age of air, in hours (h);

(q_m / V) is the constant emission rate of tracer per cubic metre (m^3) of space — equal to the constant k_m in all zones of the ventilated system (in for example, $\mu g \cdot h^{-1} \cdot m^{-3}$); a suitable value of k_m can be estimated from the desired collected amount of tracer;

ρ_a is the time average of the tracer gas concentration in the room air, in micrograms per cubic metre ($\mu g \cdot m^{-3}$).

7.3.4 Uncertainty

Any calculated value of the local mean age of air determined using the passive homogeneous emission technique shall be accompanied by an estimate of its uncertainty. Uncertainty shall be estimated and expressed in harmony with the ISO/IEC Guide 98:1995.

Information on how to estimate the uncertainty of measured local mean ages of air according to this part of ISO 16000 can be found in Annexes C and D.

8 Application of results

The methods described in this part of ISO 16000 can be used for the following purposes.

a) **Checking whether the ventilation requirements are met, both in individual buildings (commissioning) and in broad surveys**

The advantage of these methods is that they can be used while the building is in normal use. The decay method is suitable for short-term measurements of individual buildings. The passive homogeneous emissions method with its simple field equipment is suitable for long-term measurements in broad surveys with hundreds of measurement objects. It takes into account, for example, occupant behaviour and changes in weather conditions. The same method can also be used in **assessing the correlation of ventilation with health and comfort outcomes in epidemiological studies.**

In building regulations and the plans of the ventilation system, the ventilation conditions are usually expressed in ventilation flow rates or specific ventilation flow rates. The interpretation of the local mean age of air into other ventilation parameters requires fulfilment of certain assumptions. This is discussed in more detail in informative Annex E.

b) **Estimating the adequacy of ventilation in buildings with IAQ problems**

Ventilation controls moisture and concentrations of other pollutants and it may have significant role in IAQ problems. This role should be assessed in IAQ problem investigations. Sampling and analysis of contaminants indoors should be accompanied by ventilation measurement, making it possible to determine correct remedial actions. Both short-term and long-term measurements can be used here, and all methods in this part of ISO 16000 are suitable for this. Local mean age of air is the best indicator of ventilation conditions in this case.

c) **Characterizing the strengths and distribution of indoor emission sources**

This may also be needed in IAQ problem investigations. By measuring contaminant concentrations and local ages of air simultaneously, it is possible to identify differences in source strengths between zones. An example of this is given in Annex E. The choice of measurement method depends on the time-scale of the contaminant measurement.

9 Test report

The test report shall contain at least the following information:

a) all details necessary to identify the building tested, and fully characterize the ventilated system, zone divisions and description of the tested zones;

b) a reference to this part of ISO 16000;

c) a summary of test technique, test conditions and apparatus used;

d) a summary of collected data and results including an estimation of the accuracy;

e) the date of the test.

Details for each item can be reported taking into consideration the information in Annexes A to D.

Annex A
(informative)

Explanation of some terms and definitions

NOTE For terms and definitions, see Clause 3.

A.1 Local mean age of air

The local mean age of air is a ventilation parameter, which describes the length of time the air in a specific building space has on average spent within the building.

The concept “local mean age of air” (and its inverse “the local air change rate”) is used for assessing the ventilation condition in the building. The local mean age of air indicates the average time the air in a specific space has spent in the building accumulating contaminants. It is closely connected to the time it takes to exchange the air in that space. The concentration of a contaminant released from continuous indoor sources increases with the length of time the air has spent indoors. The lower the age of air in a space is, the lower the concentration. Normally, the ventilation air is supplied at selected parts of the building envelope, and seeks its way to the different building spaces. Thus, before the ventilation air reaches a specific room, a significant portion of the air may have spent time in other rooms, accumulating contaminants. Therefore, the local mean age of air, which describes the length of time the air in a particular space has spent indoors needs to be considered in relation to air quality.

A.2 Purging flow rate

A pollutant (or a tracer gas) that is injected within one zone (and not any other) will attain a steady state concentration in that zone equal to the quotient of the injection rate and the purging flow rate. For contaminants which are emitted in several zones, or outdoors, the purging flow rate is not a good indicator of air quality. The purging flow rate is a measure of how much outside air is transferred (directly or indirectly) per hour to the zone in question. Its maximum value is equal to the total airflow rate, this occurs for example when there is complete mixing between zones. In most cases, however, some of the air supplied to a building is extracted before it has a possibility to enter a certain zone, a fact that diminishes the purging flow rate in that zone from the maximum possible.

Annex B
(informative)

General requirements of tracer gases, background contents and methods of detection of the most important ones

B.1 General requirements

Apart from being able to be analysed at low concentrations with the available measurement equipment, tracer gases should have the following properties:

a) be non-toxic and non-hazardous to health in the concentration range used;

b) be chemically inert, stable, odourless and tasteless;

c) as far as possible, not be adsorbable by walls, furniture or other surfaces;

d) be non-flammable and non-explosive;

e) not be ordinarily present in the indoor air or outdoor ambient air;

f) if present in ambient air, have concentrations which are significantly lower than those used for tracer gas analysis;

g) be easily transported and handled;

h) be readily miscible with air;

i) have no disadvantageous environmental effects;

j) be inexpensive and readily available from commercial sources.

B.2 Background content and methods of detection

Table B.1 — Background content and methods of detection of the most important tracer gases

Tracer gas	Background volume fraction in air	Method of detection	Measuring range volume fraction in air
Sulfur hexafluoride, SF_6	$(0,85 \text{ to } 1,5)\cdot 10^{-12}$	Gas chromatograph with electron capture detector or mass spectrometer[d]	$5\cdot 10^{-12}$ to $200\cdot 10^{-9}$
Perfluorocarbons e.g. Hexafluorobenzene (C_6F_6)	$< 1\cdot 10^{-12}$	Gas chromatograph with electron capture detector or mass spectrometer [d]	$50\cdot 10^{-12}$ to $10\cdot 10^{-9}$
Nitrous oxide (laughing gas), N_2O[a]	$315\cdot 10^{-9}$	Infrared gas analyser	$1\cdot 10^{-6}$ to $200\cdot 10^{-6}$
Carbon dioxide, CO_2[b]	$360\cdot 10^{-6}$		$1\cdot 10^{-6}$ to $5\cdot 10^{-3}$
Sulfur hexafluoride, SF_6	$(0,85 \text{ to } 1,5)\cdot 10^{-12}$		$1\cdot 10^{-7}$ to $100\cdot 10^{-6}$
Nitrous oxide (laughing gas), N_2O[a]	$315\cdot 10^{-9}$	Photoacoustic detector	$50\cdot 10^{-9}$ [c]
Carbon dioxide, CO_2 [b]	$360\cdot 10^{-6}$		$3\cdot 10^{-6}$ [c]
Sulfur hexafluoride, SF_6	$(0,85 \text{ to } 1,5)\cdot 10^{-12}$		$5\cdot 10^{-9}$ [c]

[a] Use of N_2O requires that water solubility and adsorption effects be taken into account.

[b] CO_2 is suitable only with qualification. The following factors shall be taken into account: the varying content in feed air and exhaust air; and, under some circumstances, the uncertainty of human-related CO_2 release and other possible internal sources. If CO_2 is used as a tracer gas, the CO_2 content of the surrounding air shall be subtracted from the measured CO_2 content.

[c] The upper measuring range is dependent on the calibration.

[d] The instructions of the manufacturers of electron capture detectors shall be considered with respect to radioactivity.

Although radioactive noble gases comply with many of the desired properties of tracer gases, the use of these previously employed tracer gases is now no longer advisable because of radiation-protection reasons.

The tracer gas most frequently used to determine the air change rate is sulfur hexafluoride. When used in buildings, this tracer gas best meets the properties of an ideal tracer gas of the gases listed in Table B.1. However, for sampling on solid sorbents (e.g. for passive tracer gas methods), perfluorocarbons are better suited.

B.3 Health criteria in the use of tracer gases

The use of tracer gases can have adverse effects on the health of the room occupants, depending on the type and chosen concentration of the tracer gas. Health guide values for the indoor air concentration of the most frequently used tracer gases, sulfur hexafluoride and nitrous oxide, have not yet been established. Since, in the detection range, nitrous oxide is close to the MAK value (maximum permissible workplace concentration 1); see Tables B.1 and B.2), when air change rate has been determined, all persons not directly participating in the measurements shall leave the room.

---

1) MAK values are published by the “Senatorial commission for the examination of hazardous working materials (Senatskommission zur Prüfung gesundheitsschädlicher Arbeitsstoffe)” of the German Science Foundation (DFG). The list of MAK values is checked annually and enlarged.

The MAK values tolerated at the workplace apply to the personnel carrying out the measurement. These are intended as 8-h mean values.

Table B.2 — Permissible tracer gas concentrations for the test personnel

Tracer gas	MAK value mg·m^{-3}
CO_2	9 100
N_2O	180
SF_6	6 100

Annex C
(informative)

Estimation of uncertainty of measured local mean ages of air

C.1 General

C.1.1 Criteria

The determined values of local mean ages of air shall be given together with estimates of their uncertainty. The uncertainty in a measured quantity is made up of contributions from uncertainties and errors in the factors used to evaluate the quantity. As described in this annex and in the ISO/IEC Guide 98:1995, the uncertainties in the contributing factors can either be obtained from the measurement (type A) or from other existing sources (type B). In Annex D, it is demonstrated how the uncertainty of the determination of the local mean ages of air can be evaluated for some given examples.

The local mean ages of air cannot be measured directly. The determination of the mean age of air relies on tagging the air with tracer gas and measuring the rate of which tagged air is replaced with unmarked air.

In the decay technique, the volume fraction ($\varphi(t)/\varphi_0$) of the initially tagged air (φ_0), which is left after different times t, is measured. It can be shown theoretically that the integral of this fraction from $t = 0$ to $t = \infty$ yields the local mean age of air.

In the homogeneous emission technique, the tracer gas concentration is measured when the removal rate of tracer gas is equal to the injection rate. It can be shown theoretically that this steady state concentration is the product of the local mean age of air and the tracer gas injection rate per volume unit, provided that the tracer gas emission is homogeneously distributed throughout the space.

The uncertainty of the determination of local mean ages of air is therefore connected to the uncertainty of tracer gas concentration, the uncertainty of the calculation of the integral and the uncertainty of tracer gas emission rates and its distribution.

This annex describes how the uncertainty of a measurement can be estimated from individual estimates of uncertainties in the different contributing factors.

These contributing factors can be divided into two groups: one group with the characteristics of the equipment used; and the other which is specific to the measurement situation and its evaluation.

It is here assumed that the characteristics of the used equipment are fully known and documented for use in the particular application.

C.1.2 Examples of necessary knowledge about the equipment performance

C.1.2.1 Analysis instruments

a) Calibrated for the concentrations of concern

b) Standard deviation of analysis investigated at the concentrations of concern

c) Long- and short-term stability documented

C.1.2.2 Tracer gas injection equipment (active)

a) Calibrated flow control devices (e.g. rotameters, mass flow controllers, critical orifices)

b) Standard deviation of flow rate adjustment documented (including precision of pressure regulation)

c) Long- and short-term stability documented

C.1.2.3 Sampling devices (manual)

a) Documented long- and short-term inertness and tightness of sampling syringes, containers or canisters

b) Calibrated air sampling pump for solid sorbent tubes

c) Standard deviation of air sampling rate (volume) documented

d) Documented sorption capacity, suitable sampling flow rate and break-through volume

C.1.2.4 Sampling devices (passive)

a) Calibrated diffusive samplers

b) Standard deviation of equivalent air sampling rate for diffusive samplers

c) Documented performance of diffusive samplers as a function of concentration and exposure time

d) Documented desorption (extraction) efficiency of sorbent sampler

C.1.2.5 Tracer gas injection equipment (passive diffusion devices)

a) Calibrated tracer gas sources

b) Standard deviation of sources documented

c) Temperature dependence of emission rate investigated and documented within temperatures of concern

d) Long-term, short-term and transient behaviour of emission rates known

C.1.3 Examples of factors specific for the measurement situation

The factors influencing the measurement uncertainty that are specific for the measurement occasion shall be evaluated from the circumstances during the measurement and the recorded data.

Such factors are, for example,

a) inability to achieve a uniform initial tracer gas concentration throughout all zones before start of decay,

b) inability to record the initial concentration in all zones,

c) temporal and spatial variation of concentration due to bad mixing within zones, and

d) inability to achieve a homogeneous emission rate throughout all zones in the homogeneous emission technique.

C.2 Decay technique

The normal (relative) uncertainty s of a measurement of a local mean age using the decay technique is made up of contributions from the (relative) standard deviations of determination of the integrated area and the initial concentration

$$s^2 = s_{\text{area}}^2 + s_{\varphi_0}^2 \tag{C.1}$$

where

s_{area}^2 is the variance in calculating the true integral from $t = t_0$ to $t = t_\infty$;

$s_{\varphi_0}^2$ is the variance in estimating the initial concentration.

The relative uncertainty s_{area} of the integrated area can be estimated from the absolute uncertainties $s_{A_{\text{num}}}$ and $s_{A_{\text{rest}}}$ which belong to the numerically integrated part and the extrapolated part, respectively.

$$s_{\text{area}} = \frac{\sqrt{s_{A_{\text{num}}}^2 + s_{A_{\text{rest}}}^2}}{A_{\text{num}} + A_{\text{rest}}} \tag{C.2}$$

s_φ is the relative uncertainty in the initial concentration. It depends not only on the analysis uncertainty, but also on possible spatial variations within and between zones due to inability to achieve a homogeneous initial concentration in the whole ventilated system.

C.3 Homogeneous emission technique

In the homogeneous emission technique, the local mean age of air is computed from the steady state tracer concentration divided by the emission rate per volume unit. The standard relative uncertainty of the local mean age of air is therefore made up of contributions from uncertainties in measurement of concentration s_{meas} and uncertainties in the emission rate per volume s_{distr}.

$$s_\tau^2 = s_{\text{meas}}^2 + s_{\text{distr}}^2 \tag{C.3}$$

In the estimate of the uncertainty in concentration s_{meas}, both random errors of the analysis s_{anal} and uncertainty in the concentration of the calibration mixture s_{cal} should be taken into account.

$$s_{\text{meas}}^2 = s_{\text{cal}}^2 + s_{\text{anal}}^2 \tag{C.4}$$

s_{distr} has two main contributions which have to be accounted for, the uncertainty in the injection rate s_{inject} and the uncertainty due to any known inability to achieve a true homogenous emission rate s_{inhom}.

$$s_{\text{distr}}{}^2 = s_{\text{inject}}^2 + s_{\text{inhom}}^2 \tag{C.5}$$

Examples are given in Annex D of the way in which the different contributions can be estimated for the active and passive homogeneous techniques.

Annex D
(informative)

Examples of measurement procedure, calculation and estimation of uncertainty

D.1 General

In this annex, examples are given of the measurement procedure, calculation and estimation of uncertainty using four different techniques covered in this part of ISO 16000. The input data for the examples are obtained from simulations and measurements.

Examples are given for the following techniques:

a) decay technique using automatic tracer gas injection, sampling and analysis;

b) decay technique using manual tracer gas injection and sampling;

c) homogeneous emission technique using automatic tracer gas injection and analysis;

d) homogeneous emission technique using passive injection and sampling.

The determined values of local mean ages of air shall be given together with estimates of their uncertainty. The uncertainty in a measured quantity is made up of contributions from uncertainties and errors in the factors used to evaluate the quantity. As described in informative Annex C and in the ISO/IEC Guide 98:1995, the uncertainties in the contributing factors can either be obtained from the measurement (type A) or from other existing sources (type B). The examples demonstrate the way in which the uncertainty of the determination of the local mean ages of air can be evaluated.

First, it should be noted that the ventilation condition in a building is not a static matter. Ventilation and air distribution patterns change with wind pressure, outside temperature, window opening, door opening, inside temperature distribution, people's activity, etc., all of which are factors that vary with time. The local mean ages determined at one instant may be different if measured a second time. Such fluctuations are not included in the estimated uncertainty of the measurement. The estimate of uncertainty only indicates the limits within which it is plausible that the true ventilation conditions lie at the time of measurement.

In order to use a short-term measurement for predictive purposes, all factors that may influence the ventilation rate and air distribution shall be known at the instant of measurement. Additionally, a model is required, which describes how the ventilation rate and the air distribution is influenced by those factors. It is beyond the scope of this part of ISO 16000 to discuss ventilation measurements for predictive use.

D.2 Decay technique

D.2.1 Tracer gas injection

D.2.1.1 Automatic injection

For automatic tracer gas injection, there is commercially available doser/analyser equipment that can be programmed to inject tracer gas to a common concentration in up to 12 zones. In order to achieve a uniform distribution in all zones, the injection points should be behind mixing fans.

D.2.1.2 Manual injection

For manual injection, the injection is usually made while walking from zone to zone and injecting tracer gas from a gas cylinder or a syringe. The injected amounts should be proportional to the zone volumes and well distributed into the zone volumes by some mixing devices. After proper injection into all zones, a common initial concentration in all zones shall be secured, preferably using mixing fans that mix the air between zones.

It should be noted that it may be difficult to achieve the necessary equal initial tracer gas concentration in all zones, especially when the number of zones is larger than four to five. Tracer gas distribution should be made quickly enough to avoid decay by ventilation, which may result in significant deviation from the equal concentration distribution.

D.2.2 Tracer gas sampling and analysis

D.2.2.1 Automatic sampling

Automatic sampling is usually performed using a network of tubes through which air is drawn from the different sampling points using a pump. In order to get the correct timing of analysis, it is important to flush the tubes, just before performing the analysis. Sampler equipment is commercially available, which automatically performs flushing of the next sampling tube, while sampling from the preceding one.

The first sample(s) shall be taken at time $t = 0$, just after the mixing fans have been switched off. The subsequent samples should be taken as fast as the sampling and analyser equipment allows, preferably with equal time intervals between sampling at the same position.

With automatic sampling, the tracer gas analysis is usually performed on-line in real time, i.e. with an analysing instrument connected to the sampling device. The most common instruments for online analysis are based on infrared absorption (IR). However, gas chromatography (GC) or mass spectrometry (MS) for field use can also be used.

D.2.2.2 Manual sampling

Manual sampling is usually performed using a syringe, a bag or an evacuated gas container (canister).

As a typical example, medical syringes (e.g. 50 ml plastic syringes) are used for sampling, because they are easy to handle, seal tightly for months, are inexpensive and can be sent for analysis. Because of the relatively low sample volume, sampling with a syringe is especially suitable if SF_6 is used as the tracer gas and analysis is performed by a gas chromatograph (GC) with an electron capture detector (ECD).

In order to be able to evaluate the local mean age of air in buildings where the air is not completely mixed, at least seven samples should be taken during the decay in each zone. The first sample(s) shall be taken at time t = 0, just after the mixing fans have been switched off. The subsequent samples should be taken preferably with equal time intervals during a period that is at least equal to the expected mean age of air in the object (2 h to 3 h for a dwelling).

After sampling, the syringes are capped and sent to a laboratory for analysis using GC/ECD equipment. Tightness, inertness and non-permeation characteristics of the sampling syringes shall be certified before use.

D.2.3 Example of decay technique using on-line sampling and analysis

D.2.3.1 Simulated data

When performing automatic sampling with on-line analysis, the tracer gas concentration as a function of time is usually obtained in the form of a data file. An example is given below of how to evaluate such a file.

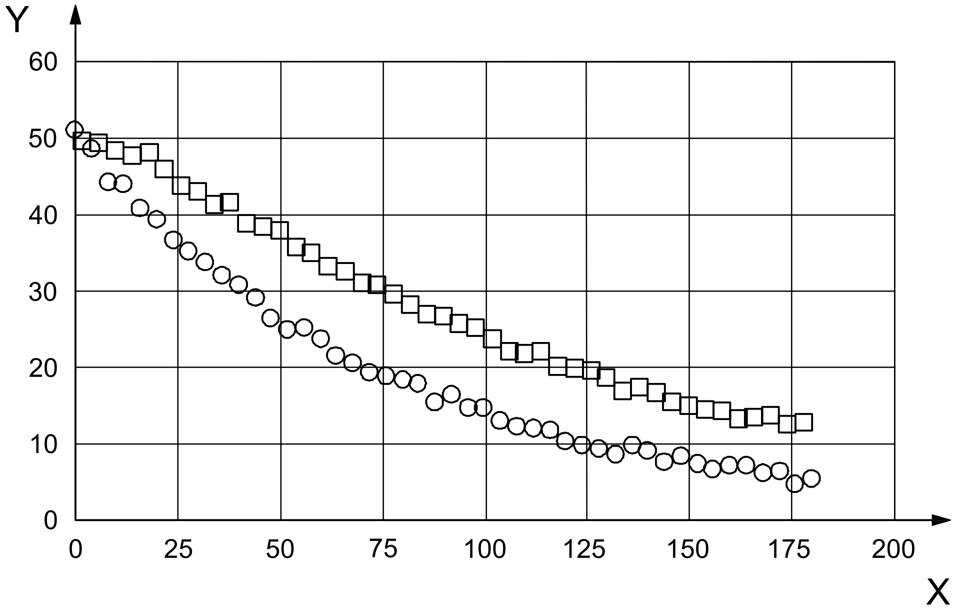
In the simulated example below (see Table D.1), samples were automatically taken and analysed during 3 h at 2-min intervals in the bedroom and the kitchen of a dwelling. The sampling in the bedroom began at time $t = 0$. The dwelling was ventilated with mechanical exhaust in the bathroom and kitchen, while the air inlets were situated in the living room and the bedroom. The bedroom door was closed at the start of the decay.

From the logarithmic plot (see Figure D.2) , it can be seen that the curve for the kitchen is non-linear at the beginning and approaches a linear trend at 100 min. For the bedroom, the curve is linear from the beginning. The sampling could therefore have been interrupted after 100 min.

Table D.1 — Measured tracer gas concentration ($cm^3 \cdot m^{-3}$) during decay

Bedroom			Kitchen		
minute	$cm^3 \cdot m^{-3}$	ln [a]	minute	$cm^3 \cdot m^{-3}$	ln [a]
0	50,9	3,93	2	49,5	3,90
4	48,5	3,88	6	49,4	3,90
8	44,2	3,79	10	48,4	3,88
12	43,9	3,78	14	47,5	3,86
16	40,7	3,71	18	47,9	3,87
20	39,3	3,67	22	45,9	3,83
24	36,5	3,60	26	43,6	3,78
28	35,2	3,56	30	43,0	3,76
32	33,7	3,52	34	41,3	3,72
36	32,0	3,47	38	41,5	3,72
40	30,8	3,43	42	38,9	3,66
44	29,0	3,37	46	38,4	3,65
48	26,3	3,27	50	37,7	3,63
52	24,9	3,22	54	35,7	3,57
56	25,1	3,22	58	35,0	3,55
60	23,7	3,16	62	33,2	3,50
64	21,4	3,06	66	32,5	3,48
68	20,4	3,02	70	30,9	3,43
72	19,2	2,95	74	30,6	3,42
76	18,8	2,94	78	29,4	3,38
80	18,4	2,91	82	28,1	3,34
84	17,7	2,88	86	26,9	3,29
88	15,4	2,74	90	26,5	3,28
92	16,3	2,79	94	25,6	3,24
96	14,7	2,69	98	25,2	3,23

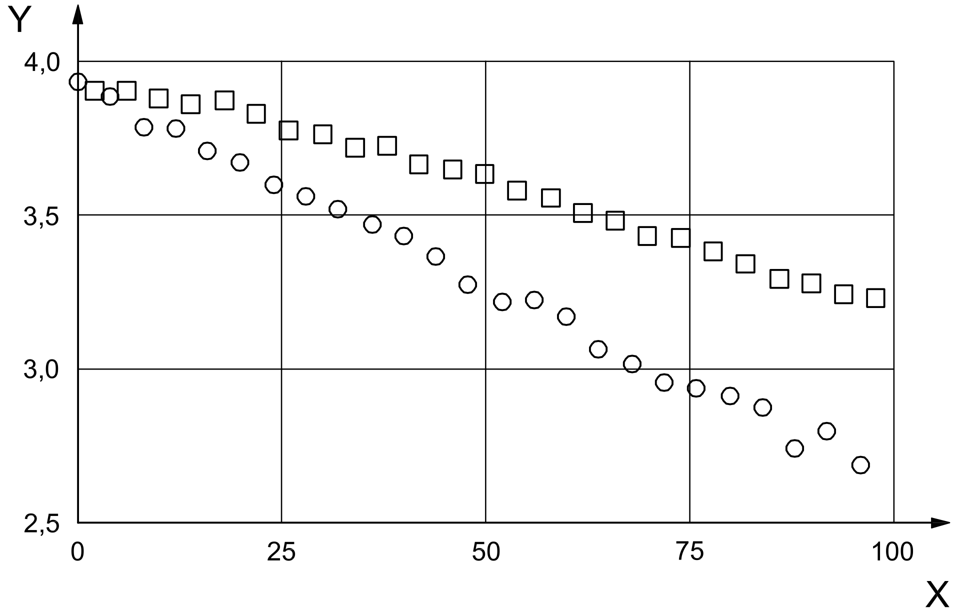
[a] ln denotes the natural logarithm.



Key

X	time, in minutes from the start of decay
Y	N_2O, in $cm^3 \cdot m^{-3}$
O	bedroom
□	kitchen

Figure D.1 — Plot of tracer gas concentration versus time



Key

X	time, in minutes from the start of decay
Y	$\ln(\varphi)$, in $cm^3 \cdot m^{-3}$
O	bedroom
□	kitchen

Figure D.2 — Plot of log of concentration versus time

D.2.3.2 Steps for calculating local mean ages of air

The calculation of the local mean age of air involves the following steps.

a) Plot the natural logarithm (ln) of tracer gas concentration as a function of time.

   It is advantageous if a logarithmic plot can be made in real time, because the sampling can be interrupted when a linear plot is ascertained at all sampling points.

b) Identify the beginning and end of the linear part in the logarithmic plot.

   Observe that low concentrations will show large scattering, due to measurement uncertainty and unstable air movements. Do not include the range of excessive scattering.

   Sometimes, a logarithmic plot is linear from the beginning of decay. This means that the decay is purely exponential, as in the case of complete mixing between zones. In this case, no numerical integration is needed. The local mean age of air can be calculated from the inverted value of the absolute value of the slope of the logarithmic plot.

c) Calculate the slope ($-\lambda$) of the linear part of the logarithmic plot.

   A spreadsheet calculation programme can be advantageously used to calculate the equation of the trend line. Use the absolute value of the correlation coefficient to obtain λ.

d) Make a numerical integration of tracer gas concentration $\varphi(t)$ (e.g. using the trapezoid method) from time $t = t_0$ to a time $t = t_\text{e}$ within the linear part of the logarithmic plot.

   Usually, sampling at different positions cannot be performed simultaneously. Therefore, only one position can be analysed at $t = t_0$. Samples from the other positions are then analysed with successive time delays. Care should therefore be taken when calculating the area of the first trapezoid from $t = t_0$ to $t = t_\text{p1}$, where t_p1 is the time for the first measurement at a position p.

   Best practice is to add an area equal to $(t_\text{p1} - t_0) \cdot [\varphi(t_\text{p1}) + \varphi(t_0)]/2$ to the calculated integral. $\varphi(t_0)$ is the initial tracer gas concentration at the beginning of decay. This initial concentration should be equal in the whole ventilated system and can be taken as the measured concentration at the location measured at $t = t_0$.

   The time t_e can be chosen freely within the linear part of the logarithmic decay.

e) Estimate the total time integral by adding the extrapolated integral $\dfrac{\varphi_{t=t_\text{e}}}{\lambda_\text{tail}}$ from $t = t_\text{e}$ to infinity to the numerically calculated integral.

   The value of $\varphi_{t=t_\text{e}}$ can be taken as the measured concentration at $t = t_\text{e}$. However, a better practice is to use the trend line equation calculated for the logarithmic decay.

   The expectation value $\varphi_{t=t_\text{e}}$ is obtained from $\varphi_{t=t_\text{e}} = \text{e}^{\ln\varphi(t_\text{e})}$, where $\ln\varphi(t_\text{e})$ is obtained from the correlation equation with $t = t_\text{e}$.

f) Finally, divide the estimated total integral(s) by the common initial tracer gas concentration $\varphi_{t=t_0}$ at time $t = t_0$ to get an estimate of the local mean age of air.

   Here, it is very important to get the correct initial concentration. Usually, the concentration measured at the beginning of decay can be used.

D.2.3.3 Evaluation of local mean ages of air in the given example

Below, the actions associated with steps a) to f) in D.2.3.2 are illustrated for the example in Table D.1.

a) The plot of the natural logarithm (ln) of tracer gas concentration as a function of time is shown in Figure D.2.

b) The beginning of the linear part in the logarithmic part plot is identified by inspection to be 40 min for the kitchen. For the bedroom, the curve is linear from the beginning. The end of the linear region is chosen as 100 min, where the scatter around the trend-line is still moderate.

c) With the help of a spreadsheet calculation programme, the least squares trend-line for the kitchen is calculated as $\ln(\varphi) = -0{,}008\,3\ t + 4{,}03$ (using data between 42 min and 98 min) which yields $\lambda = 0{,}008\,3\ \text{min}^{-1}$ or $0{,}498\ \text{h}^{-1}$. For the bedroom, the whole interval between 0 min and 96 min can be used, which yields the correlation equation, $\ln(\varphi) = -0{,}0129\ t + 3{,}92$. The λ-parameter for the bedroom is thus $0{,}012\,9\ \text{min}^{-1}$ ($0{,}774\ \text{h}^{-1}$).

d) Since the decay in the bedroom is exponential from the beginning of the decay, there is no need for a numerical integration. The local mean age of air is directly obtained from the inverted value of λ [Equation (5)], i.e. $\overline{\tau} = 1/\lambda = 1/0{,}774 = 1{,}29\ \text{h}$.

In the kitchen, a numerical integration from $t = 2$ min to $t = 78$ min (arbitrarily chosen within the linear part of the decay) yields

$$A_{(2\text{-}78)} = 4\left(\frac{\varphi_{t=2}}{2} + \sum_{t=6}^{t=74} \varphi(t) + \frac{\varphi_{t=78}}{2}\right) = 4(24{,}8 + 721{,}4 + 14{,}7) = 4 \times 760{,}8 = 3\,043\ \text{cm}^3 \cdot \text{m}^{-3} \cdot \text{min}.$$

Because the analysis did not start at $t = 0$, the missing area from $t = 0$ to $t = 2$ min shall be added.

$$A_{(0\text{-}2)} = 2\left(\frac{\varphi_{t=0}}{2} + \frac{\varphi_{t=2}}{2}\right) = 2\left(\frac{50{,}9}{2} + \frac{49{,}5}{2}\right) = 100\ \text{cm}^3 \cdot \text{m}^{-3} \cdot \text{min}$$

e) As the last contribution to the area under the decay curve, the extrapolated area from $t = 78$ to $t = \infty$ is computed,

$$A_\text{rest} = \frac{\varphi_{t=t_\text{e}}}{\lambda} = \frac{29{,}3}{0{,}008\,3} = 3\,531\ \text{cm}^3 \cdot \text{m}^{-3} \cdot \text{min},$$

where $\varphi_{t=t_\text{e}} = \text{e}^{\ln\varphi(t_\text{e})}$ and $\ln\varphi(t_\text{e})$ are obtained by inserting $t = 78$ min in the correlation equation [see step c)].

The total integrated area, $A_\text{tot} = A_{(0\text{-}2)} + A_{(2\text{-}78)} + A_\text{rest} = 6\,675\ \text{cm}^3 \cdot \text{m}^{-3} \cdot \text{min}$.

f) The local mean age of air in the kitchen is calculated from the total integrated area divided by the initial concentration [Equation (1)].

$$\overline{\tau} = \frac{A_\text{tot}}{\varphi_{t=t0}} = \frac{6\,674}{50{,}9} = 131\ \text{min} = 2{,}19\ \text{h}$$

D.2.3.4 Estimates of uncertainty

D.2.3.4.1 General

The uncertainty of a local mean age of air obtained using the decay technique with automatic sampling is composed of contributions from uncertainties in the influencing factors.

$$s^2 = s_{\mathrm{area}}^2 + s_{\varphi_0}^2 \tag{D.1}$$

where

s_{area}^2	is the (relative) variance in calculating the true integral from $t = t_0$ to $t = t_\infty$;
$s_{\varphi_0}^2$	is the (relative) variance in estimating the initial concentration.

It is assumed here that the analysing instrument yields a linear response as a function of concentration from $\varphi = 0$ to the highest measured concentration. Due to the fact that the integral is divided by the measured concentration at $t = t_0$, the instrument does not need to be calibrated in absolute terms.

D.2.3.4.2 Uncertainty of the integral

The integral from $t = t_0$ to $t = t_e$ is approximately $(n - 1)/n$ times the sum of the n concentration measurements during that time, multiplied by the time interval Δt between measurements. The uncertainty of measurement probably depends to a certain extent on the concentration range. If it is assumed here that all measurements have equal absolute uncertainties, the absolute uncertainty of the numerical integration will be equal to the uncertainty $\sqrt{n} s_{\mathrm{meas}}$ in the estimated sum, multiplied by $\Delta t (n-1)/n$. Therefore,

$$s_{A_{\mathrm{num}}} = \Delta t (n-1)/n \cdot = \Delta t (n-1)/\sqrt{n} s_{\mathrm{meas}} \tag{D.2}$$

where

$s_{A_{\mathrm{num}}}$	is the absolute standard deviation of the numerical integration;
s_{meas}	is the absolute standard deviation of a single measurement;
n	is the number of points used in the calculation.

It should be noted that there is an additional error involved when using the trapezoid integration. Due to the fact that the decay curve is concave upwards, the numerical integration will yield an overestimate of the true integral. Depending on the extent of decay between measurements, the overestimate can range from negligible to several tens of percent. If a substantial decay has taken place between measurements, a better approximation of the area between two adjacent measurement points is to assume an exponential decay between them and approximate the area between points i and j according to Equation (D.3) below instead of using the trapezoid rule:

$$A_{ij} = \Delta t_{ij} \frac{(\varphi_i - \varphi_j)}{\ln(\varphi_i) - \ln(\varphi_j)} \tag{D.3}$$

The uncertainty in the rest area A_{rest} depends on the accuracy of determining φ_{e} and the exponential decay parameter λ. The λ value is best estimated using a linear least squares fit of $\ln(\varphi)$ as a function of time. The relative standard deviation s_λ of the correlation coefficient $(-\lambda)$ and of the estimate $s_{\varphi_{\mathrm{e}}}$ can be computed using a spreadsheet programme. The absolute standard deviation of the estimate of the tail-area, A_{rest}, can be written

$$s_{\mathrm{rest}} = A_{\mathrm{rest}} \sqrt{s_\lambda^2 + s_{\varphi_{\mathrm{e}}}^2} \tag{D.4}$$

Observe, that the estimate has its smallest standard deviation $s_{\varphi_{\mathrm{e}}}$ at the time corresponding to the mean of the time values used in the linear correlation.

Lastly, in the computation of the uncertainty of the local mean age of air, one has to consider the uncertainty in the initial concentration. This uncertainty is not only due to uncertainty in analysis, but also due to possible spatial variations of tracer gas distribution at the start of decay. The latter uncertainty has to be based on an informed guess using information based on the concentration recordings. The injection of tracer gas and mixing before the start of the decay should be performed so that the spatial concentration differences do not exceed 5 %.

D.2.3.4.3 Evaluation of uncertainty in the given example

The uncertainty of the computed area is

$$s_{A_{\text{num}}} = \Delta t(n-1)/\sqrt{ns_{\text{meas}}} \tag{D.5}$$

s_{meas} is the uncertainty of measuring a concentration. It can be obtained from known performance of sampling and analysis or be calculated from repeated measurement of the same tracer gas concentration. In the present example, s_{meas} is estimated to be 1 cm^3·m^{-3}. Δt is equal to 4 min and the number of measurements $n = 20$. Therefore, $s_{A_{\text{num}}}$ is estimated to approximately 17 cm^3·m^{-3}·min or 0,5 %, which is quite negligible. The underestimate due to using the trapezoid method can also be shown to yield a negligible error by a simple comparison between the two methods of calculation of areas. The small uncertainty in the computed area is, due to the fact that errors cancel each other when calculating the sum.

The uncertainty in the interpolated area A_{rest} is

$$s_{\text{rest}} = \sqrt{s_{\lambda}^2 + s_{\varphi_{\text{e}}}^2} \tag{D.6}$$

where the relative standard deviation s_{λ} is computed as 2,2 % using a least squares technique in the range from 42 min to 98 min. $s_{\varphi_{\text{e}}}$ is only 0,6 %. Therefore, s_{rest} is 2,3 % of A_{rest} or 80 cm^3·m^{-3}·min.

The relative uncertainty of the area under the curve is computed as

$$s_{\text{area}} = \frac{\sqrt{s_{A_{\text{num}}}^2 + s_{A_{\text{rest}}}^2}}{A_{\text{num}} + A_{\text{rest}}} = \frac{\sqrt{17^2 + 80^2}}{6\,674} = 1{,}2\ \% \tag{D.7}$$

The dominating component contributing to the uncertainty in determination of the local mean age of air in this case may be the uncertainty in the initial concentration s_{φ_0}. Assuming this to be 3 %, it is calculated according to Equation D.8.

$$s_{\text{total}} = \sqrt{0{,}012^2 + 0{,}03^2} = 3{,}2\ \% \tag{D.8}$$

D.2.4 Example of decay technique using manual injection and manual sampling

D.2.4.1 Experimental

In this example, tracer gas is distributed to the different zones of the ventilated system using a graduated syringe filled with SF_6 (sulfur hexafluoride) gas or SF_6/inert gas mixture. In each zone, a portion of the tracer gas that is proportional to the volume of the zone is injected. The injections are made while walking around in the zone in order to distribute the tracer gas evenly. In order to avoid unequal tracer gas concentrations between the zones due to decay during injection, the injections shall be performed as quickly as possible.

After injection in all zones, the air is mixed within and between the zones as described above to secure a homogeneous tracer gas distribution. Immediately after mixing, all internal doors are set to their desired positions and the first sample is taken, using a 50 ml plastic syringe, at a representative location or while walking around between zones. Six subsequent samples are thereafter taken in each zone of interest, with equal time intervals using clean and labelled 50 ml syringes, which are capped after filling. The preferred sampling interval is determined so that the samplings are distributed evenly within a time period, which is equal to the anticipated mean age of air, which in the present case is 2 h.

The capped syringes are delivered to a laboratory, which can perform GC/ECD analysis of the SF_6 concentration in the samples.

D.2.4.2 Simulated data

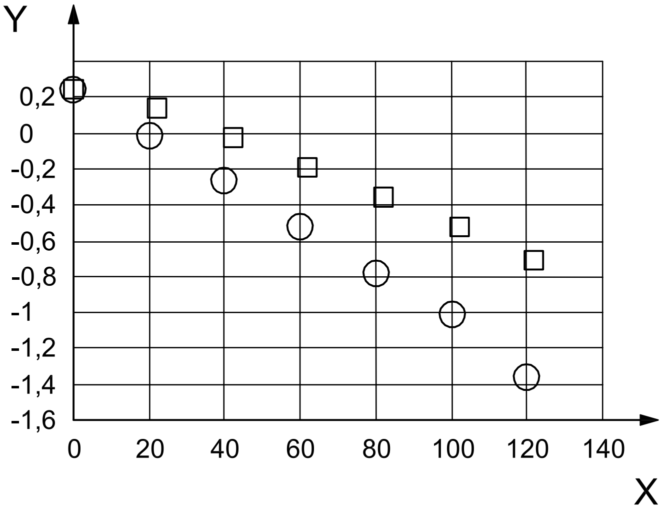
The result in this simulated experiment is shown in Table D.2 together with area calculations as in the example of automatic sampling. The result is plotted in Figures D.3 and D.4.

Table D.2 — Analysed concentration of tracer gas in manually taken air samples

Bedroom						Kitchen					
Time min	φ $cm^3 \cdot m^{-3}$	$\ln(\varphi)$ $cm^3 \cdot m^{-3}$	A_{trap} $cm^3 \cdot m^{-3}$ min	A_{exp} $cm^3 \cdot m^{-3}$ min	$A_{trap} - A_{exp}$ $cm^3 \cdot m^{-3}$ min	Time min	φ $cm^3 \cdot m^{-3}$	$\ln(\varphi)$ $cm^3 \cdot m^{-3}$	A_{trap} $cm^3 \cdot m^{-3}$ min	A_{exp} $cm^3 \cdot m^{-3}$ min	$A_{trap} - A_{exp}$ $cm^3 \cdot m^{-3}$ min
0	1,27	0,24				0	(1,27)[a]	(0,24)			
20	0,98	−0,02	22,6	22,4	0,6 %	22	1,15	0,14	26,6	26,6	0,1 %
40	0,77	−0,26	17,5	17,4	0,5 %	42	0,97	−0,03	21,2	21,1	0,2 %
60	0,59	−0,52	13,6	13,5	0,6 %	62	0,83	−0,19	18,0	18,0	0,2 %
80	0,46	−0,78	10,5	10,5	0,5 %	82	0,70	−0,35	15,3	15,3	0,2 %
100	0,36	−1,01	8,2	8,2	0,5 %	102	0,59	−0,52	13,0	12,9	0,2 %
120	0,25	−1,37	6,2	6,1	1,0 %	122	0,49	−0,71	10,9	10,8	0,3 %

NOTE A_{trap} is the interval area calculated using linear interpolation; A_{exp} is the interval area calculated using exponential interpolation.

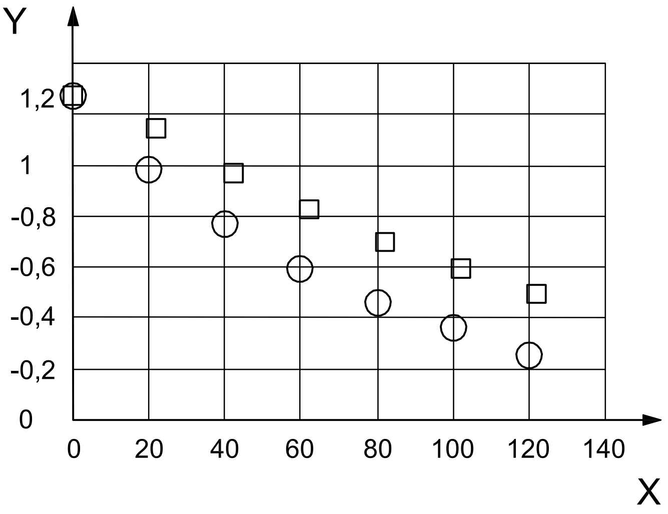
[a] The parentheses indicate the assumed initial concentration (that should be the same in all rooms).



Key

X time, in minutes
Y $\ln(\varphi)$, in $cm^3 \cdot m^{-3}$
O bedroom
□ kitchen

Figure D.3 — Logarithmic plot during decay



Key

X time, in minutes
Y φ, in $cm^3 \cdot m^{-3}$
O bedroom
□ kitchen

Figure D.4 — Linear plot during decay

D.2.4.3 Calculation of local mean ages of air

From an inspection of the logarithmic plot (Figure D.3), it is decided to use the samples taken between 40 min and 120 min as the range of exponential decay for the kitchen. For the bedroom, the decay is assumed to be exponential from the beginning.

The calculation is performed similarly to the one in the preceding example with automatic sampling.

a) The plot of the natural logarithm (ln) of tracer gas concentration as a function of time is shown in Figure D.3.

b) The beginning of the linear part in the logarithmic plot is identified by inspection to be 60 min for the kitchen. For the bedroom, the curve is linear from the beginning. The end of the linear region is chosen to 120 min.

c) With the help of a spreadsheet programme, the least squares trend-line for the kitchen is calculated as $\ln(\varphi) = -0{,}0087\ t + 0{,}35$ (using data between 62 min and 122 min) which yields $\lambda = 0{,}008\,7$ min^{-1} or 0,52 h^{-1}. For the bedroom, the whole interval between 0 min and 120 min can be used, which yields the correlation equation $\ln(\varphi) = -0{,}013\,1\ t + 0{,}25$. The λ-parameter for the bedroom is thus 0,013 min^{-1} or 0,79 h^{-1}.

d) Since the decay in the bedroom is exponential from the beginning of the measurement, there is no need for a numerical integration. The local mean age of air is directly obtained from the inverted value of λ, i.e. the $\bar{\tau} = 1/\lambda = 1/0{,}79 = 1{,}27$ h. In the kitchen, a numerical integration from $t = 0$ min to $t = 102$ min (arbitrarily chosen within the linear part of the decay) yields $A_{(0\text{-}102)} = 26{,}6 + 21{,}2 + 18{,}0 + 15{,}3 + 13{,}0 = 94{,}1\,\text{cm}^3 \cdot \text{m}^{-3} \cdot \text{min}$

e) As the last contribution to the area, the extrapolated area from $t = 102$ to $t = \infty$ is computed.

$$A_{\text{rest}} = \frac{\varphi_{\text{e}}}{\lambda} = \frac{0{,}58}{0{,}008\,7} = 67{,}2\ \text{cm}^3 \cdot \text{m}^{-3} \cdot \text{min} \tag{D.9}$$

where $\varphi_{\text{e}} = \text{e}^{\ln\varphi(t_{\text{e}})}$ and $\ln\varphi(t_{\text{e}})$ are obtained by inserting $t = 102$ min in the correlation equation [see step c)].

The total integrated area $A_{\text{tot}} = A_{(0\text{-}102)} + A_{\text{rest}} = 161{,}3$ cm^3·m^{-3}·min

f) The local mean age of air in the kitchen is calculated from the total integrated area divided by the initial concentration [Equation (1)].

$$\bar{\tau} = \frac{A_{\text{tot}}}{\varphi_{t=t0}} = \frac{161{,}3}{1{,}27} = 127\,\text{min} = 2{,}12\ \text{h} \tag{D.10}$$

D.2.4.4 Evaluation of uncertainty in the given example

The estimate of uncertainties is calculated similarly to the case of automatic sampling.

$$s_{A_{\text{num}}} = \Delta t(n-1)/\sqrt{ns_{\text{meas}}} \tag{D.11}$$

yields

$$s_{A_{\text{num}}} = 20 \times 5\frac{0{,}02}{\sqrt{6}} = 0{,}82\,\text{cm}^3 \cdot \text{m}^{-3} \cdot \text{min}$$

where it is assumed that the absolute uncertainty of concentration determination is 0,02 cm^3/m^3 and the six first samples are used for the numerical integration.

$$s_{\text{rest}} = A_{\text{rest}}\sqrt{s_{\lambda}^{2} + s_{\ln\varphi,t_{\text{e}}}^{2}} \qquad \text{(D.12)}$$

yields

$$s_{\text{rest}} = 67{,}2 \times \sqrt{0{,}028^{2} + 0{,}012^{2}} = 67{,}2 \times 0{,}030 = 2{,}03\ \text{cm}^{3} \cdot \text{m}^{-3} \cdot \text{min}$$

where the relative uncertainty of the slope s_{λ} and the relative uncertainty of the expectation value of concentration at $t = 102$ min are calculated using conventional least squares technique.

The relative uncertainty of the area under the curve is computed as

$$s_{\text{area}} = \frac{\sqrt{s_{A\text{num}}^{2} + s_{A\text{rest}}^{2}}}{A_{\text{num}} + A_{\text{rest}}} = \frac{\sqrt{0{,}82^{2} + 2{,}03^{2}}}{161{,}3} = 1{,}4\ \% \qquad \text{(D.13)}$$

s_{φ_0} shall be estimated using an informed guess based on recorded data. In the present case, it can be estimated using the uncertainty of the least squares equation for the bedroom, where the decay seems to be purely exponential from the outset. Using conventional least squares calculation of the uncertainty of the intercept at $t = 0$ yields $s_{\varphi_0} = 2{,}2\ \%$.

Adding together the contribution of uncertainties [Equation (D.1)], the following is obtained

$$s_{\tau} = \sqrt{0{,}014^{2} + 0{,}022^{2}} = 2{,}6\ \%$$

D.3 Homogeneous emission method

D.3.1 Tracer gas injection

The purpose of tracer gas injection in the homogeneous emission technique is to establish constant and equal injection rates per volume unit in all parts of the ventilated system. The tracer gas injection can either be active or passive.

D.3.2 Tracer gas sampling

The sampling can either be passive (diffusive) or active. The passive sampling yields an average value of the local mean ages of air during an extended time, while active sampling yields instantaneous values. Active sampling can be automatic, yielding information on ventilation conditions as a function of time, or manual, yielding information on selected instants.

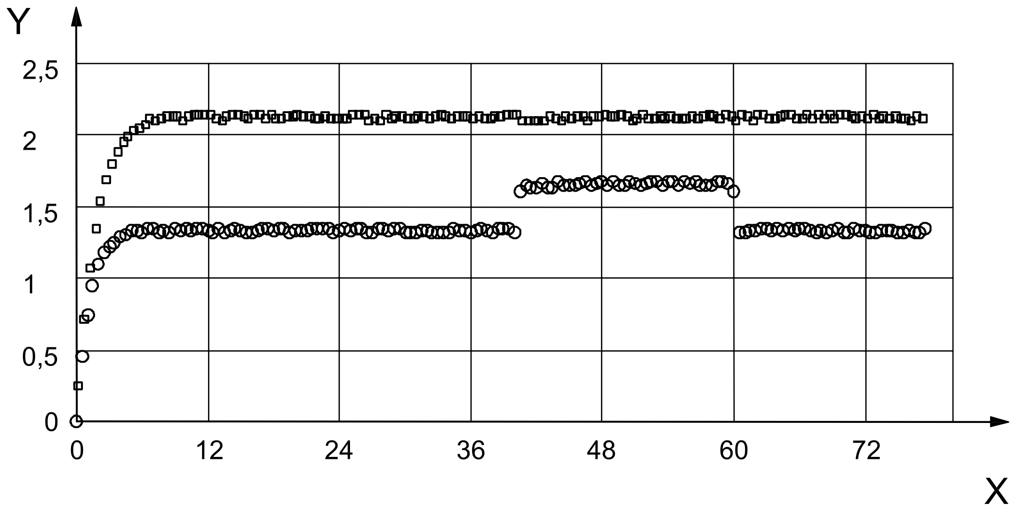
D.3.3 Example of homogeneous emission using active injection and active sampling

D.3.3.1 Simulated experiment

In this example, tracer gas SF_6 is injected into the three zones of the dwelling using a commercially available doser. This equipment can be programmed to inject the tracer gas at up to six different ports. Programming the fraction of time that the different ports are open regulates the amount injected. The tracer gas is mixed with air before dispensing to the different ports in order to avoid excessive concentration and density. Polyethylene tubes (4 mm inner diameters) are used to distribute the tracer gas to the three different zones. The tracer gas/air mixture is released behind a low-capacity fan in each room, in order to improve the tracer gas distribution in the rooms. Other equipment for controlled release and distribution of tracer gas can also be used, but in all cases, the release rate shall be carefully calibrated to match the zone volumes.

Sampling is performed during 80 h at 15 min intervals in the bedroom and in the kitchen. Analysis is performed with multi-gas monitor, which uses infrared absorption with a photoacoustic detector to analyse the tracer gas concentration.

Tracer gas SF_6 is injected at a rate of 1 $cm^3 \cdot m^{-3} \cdot h^{-1}$. Altogether, 122,4 ml per hour is distributed in the dwelling. In order to illustrate the effect of changing the air distribution pattern, the door between the bedroom and the living room is simulated to be open from 40 h to 60 h after beginning the injection. The simulated result is shown in the diagram in Figure D.5.



Key

X hours from the start of injection

Y tracer gas SF_6, $cm^3 \cdot m^{-3}$

O bedroom

□ kitchen

Figure D.5 — Result of tracer gas concentration measurement using homogeneous emission technique with active injection and sampling — From 40 h to 60 h, the door to the bedroom is open (simulated data)

D.3.3.2 Calculation of local mean ages of air

The local mean age of air is computed from the quotient of the steady state concentration and the tracer gas emission rate per volume unit.

$$\bar{\tau} = \frac{\varphi}{\left(q_V / V\right)} \qquad \text{(D.14)}$$

After 10 h of injection, a steady state is approached. Table D.3 below shows the result of the average value of the concentration measurements and the averages of the calculated local mean ages during different periods.

Table D.3 — Average steady state concentrations during decay — From 40 min to 60 min, the bedroom door is open

	Bedroom		Kitchen	
	cm^3/m^3	$\bar{\tau}$ h	cm^3/m^3	$\bar{\tau}$ h
10 h to 40 h	1,33 ± 0,01	1,33	2,13 ± 0,01	2,13
40 h to 60 h	1,65 ± 0,15	1,65	2,12 ± 0,01	2,12
60 h to 80 h	1,34 ± 0,01	1,34	2,12 ± 0,01	2,12

D.3.3.3 Estimates of uncertainty:

The relative uncertainty of the local mean ages of air using the homogeneous emission technique is determined from the standard deviation of the contributing factors:

$$s_{\tau}^{2} = s_{\text{meas}}^{2} + s_{\text{distr}}^{2} \tag{D.15}$$

The relative standard deviation of the measured concentration is made up of the uncertainty of the analysis instrument, which depends on the calibration of the instrument, its drift and instability. It is assumed here that the instrument is calibrated against a standard SF_6/air mixture which is known within limits $\pm s_{\text{cal}}$ and that the instrument yields a standard deviation around the mean of s_{anal}. The total concentration measurement variance is therefore

$$s_{\text{meas}}^{2} = s_{\text{cal}}^{2} + s_{\text{anal}}^{2} \tag{D.16}$$

It is assumed that any deviation between the nominal concentration of the calibration standard and the mean of measured values on this standard (systematic error), is accounted for using a correction constant.

The uncertainty in the homogeneous emission rate depends on how well the emission rates into the different zones can be measured and kept constant. The relative uncertainty in the regulation of the injection rate should be known from calibration and is designated s_{inject}.

There is a further factor in the homogeneous emission rate that shall be accounted for when computing the uncertainty. This error is due to any known inability to achieve a homogeneous distribution. This uncertainty is different in different zones and should be calculated the following way:

Set (q_V/V) as the average injection rate of tracer per volume in the ventilated system and $(q_V{}^{p}/V^{p})$ as the injection rate in a specific zone p divided by the volume of this zone.

$$s_{\text{inhom}} = \frac{\left| q_V/V - q_V{}^{p}/V^{p} \right|}{q_V/V + q_V{}^{p}/V^{p}} \tag{D.17}$$

The total variance is therefore computed by

$$s_{\tau}{}^{2} = s_{\text{cal}}^{2} + s_{\text{anal}}^{2} + s_{\text{inject}}^{2} + s_{\text{inhom}}^{2} \tag{D.18}$$

There is an additional uncertainty in the measurement due to incomplete mixing of tracer gas within the zone. This uncertainty in determining the zone average of the local mean age can only be evaluated by measuring at different positions within a zone.

Variations due to changes in the ventilation rate and air distribution with time can be evaluated by analysing the time variations of the concentration measurement. It should be noted that such variation can be much larger than the method uncertainty calculated by the technique mentioned above.

D.3.3.4 Evaluation of uncertainty in the given example

$$s_{\tau} = \sqrt{s_{\text{meas}}^{2} + s_{\text{inject}}^{2} + s_{\text{inhom}}^{2}} \tag{D.19}$$

The uncertainty in analysis s_{meas} can be estimated from the standard deviation of the sampling and analysis system as determined from repeated analysis of a calibration gas with similar concentration. Such standard deviation is typically $s_{\text{meas}} = 3\ \%$.

The relative uncertainty in the regulation of the injection rate s_{inject} should be known from calibration. A typical value is $s_{\text{inject}} = 3\ \%$.

s_{inhom} is the uncertainty due to any known inability to achieve a homogeneous distribution of tracer gas. The reason for such inhomogenity of tracer gas distribution may be that the regulation equipment does not allow the user to make an exact match to a desired injection rate. The matching between desired and regulated injection rate may be different in different zones (refer to D.3.3.2 estimates of uncertainty above for calculating s_{inhom} in different zones).

If s_{inhom} is neglected in the given example, the relative uncertainty in measurement of the local mean age of air using the homogeneous emission technique with active injection and sampling, applying Equation (D.19), is

$$s_{\tau} = \sqrt{0{,}03^2 + 0{,}03^2} = 4{,}2\ \%$$

It should be noted that the estimate of uncertainty only refers to a single measurement. If the uncertainty of an average of several measurements is to be estimated, the standard deviation of the mean should be determined using conventional techniques. Observe that random errors in single measurements tend to cancel each other when computing an average. However, uncertainties due to systematic errors remain. Therefore, it is advisable to estimate the uncertainty of an average value from Equation (D.20).

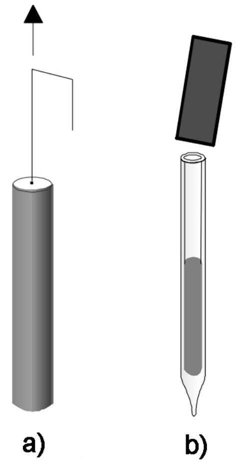
$$s_{\text{average}} = \sqrt{\frac{s_{\text{series}}^2}{n-1} + s_{\text{cal}}^2 + s_{\text{distr}}^2} \tag{D.20}$$

where s_{series} is the relative standard deviation in the time series with the n measurements on which the average is computed.

D.3.4 Example of homogeneous emission using passive injection and passive sampling

D.3.4.1 General

The homogeneous emission technique with passive injection and passive sampling is usually used in order to determine the time average of the local mean ages of air during an extended time period. In this example, passive tracer gas sources of the adjustable capillary type and passive diffusive sampler tubes with activated carbon sorbent are used (see Figure D.6).



Key

a capillary tracer gas source, with emission adjustment device

b passive sampler with charcoal sorbent

Adjustment of the emission rate from a capillary source can be provided by a metal wire extending to different depths into the capillary tube.

Figure D.6 — Example of source and sampler capsules

In the literature, several types of passive sources and samplers have been described. Some of these are commercially available from companies that also perform tracer gas analysis. The emission rate of passive sources shall be carefully calibrated before use. They exhibit a strong temperature dependency and this shall be accurately known. The diffusive sampling rate of the passive samplers shall also be carefully measured before use. Commercially available sources and samplers have undergone careful calibration and testing.

D.3.4.2 Planning of test

It is decided that the local mean ages of air shall be determined in a one-family house as averages during one week. A sketch of the house is prepared and the room volumes calculated (Figure D.7). The house also has a cellar. The total volume of the living space is 248 m^3 and the volume of the cellar connected via the staircase 140 m^3. On the ground floor, 33 m^3 is identified as small enclosed spaces with only exhaust air or without supply air (bathroom, laundry and wardrobes). These small spaces need not be equipped with tracer gas sources.

Information on the calculated room volumes is sent to a company, which delivers twelve adjusted and labelled tracer gas sources, eight of which are to be distributed on the ground floor and four in the cellar.

D.3.4.3 Performance of test

The twelve labelled tracer gas sources and the five passive tracer gas samplers are distributed on the walls of the rooms according to the instruction from the delivering company. After positioning the sources, the passive samplers are distributed and de-capped (kitchen, hall, children's bedroom, office and cellar). Sources, samplers and temperature loggers are positioned at such a height that they are out of reach of small children. The occupants are informed about the purpose of the measurement and instructed not to remove the equipment. A protocol and a return box is left, so that the occupants can stop the measurement themselves after a week by capping the samplers and send them together with the temperature loggers by mail to the laboratory for analysis. The sources are sent in a separate package the next day in order to avoid contamination.

D.3.4.4 Results

Table D.4 below shows the zone volumes, the emission rates, the amount of tracer gas in the samplers and the calculated local mean ages of air in the different rooms. The total exposure time T is 164 h. The (equivalent) air sampling rate of the passive samplers κ is 16 ml/h.

Table D.4 — Analysed tracer gas amount, emission rates and computed mean ages of air in rooms using a passive tracer gas technique

Room	Volume V m^3	Emission rate q_m µg/h	Tracer amount M ng	Mean age of air $\bar{\tau}$ h
Living room	68	35		
Kitchen	31	16	3,6	2,7
Hall	38	19	3,7	2,8
Play room	24	12		
Children's bedroom	24	12	4,5	3,4
Parents' bedroom	41	21		
Office	22	11	3,4	2,5
Cellar	140	70	1,9	1,4

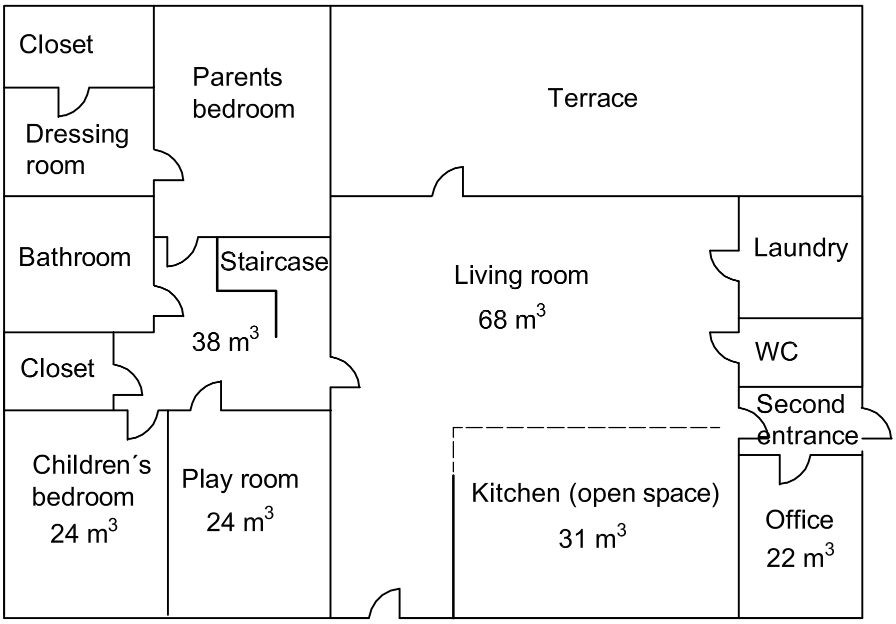


Figure D.7 — Plan sketch for use in the calculation of tracer gas distribution and for use as a complement to the protocol to indicate the positions of sources and samplers

The average tracer gas concentration ρ_a at a sampler position is evaluated from the analysed tracer gas amount M.

$$M = \kappa \cdot T \cdot \rho_a \tag{D.21}$$

The local mean age of air $\bar{\tau}$ is calculated from

$$\bar{\tau} = \frac{\rho_a}{q_m / V} \tag{D.22}$$

where q_m / V is the average emission rate per volume unit (in for example, µg·h^{-1}·m^{-3}).

D.3.4.5 Estimates of uncertainty of local mean ages of air

The estimate of the total inaccuracy s of a determined local mean age of air is calculated as follows:

$$s = \sqrt{s_{\text{source}}^2 + s_{\text{sampl}}^2 + s_{\text{meas}}^2 + s_{\text{inhom}}^2} \tag{D.23}$$

where

s_{source} is the uncertainty of the overall emission rate. It is composed of the uncertainty of the total emission rate in the ventilated system which should be computed from the relative standard deviation of individual sources (as determined by calibration) divided by the square root of the number of sources in the system + uncertainty due to inadequate temperature compensation;

s_{sampl} is the relative uncertainty of sampling. It should be estimated as the relative standard deviation of sampling rate as determined by calibration + uncertainty due to non-representative sampling because of insufficient mixing in the zone;

s_{meas} is the relative uncertainty due to analysis (reproducibility + drift + uncertainty of calibration). (max. 0,08);

s_{inhom} is the relative uncertainty due to any deviation from the homogeneous tracer gas emission rate occur in individual zones. The error due to such deviations is dependent on the actual coupling (in the airflow sense) between the particular zone and the rest of the ventilated system. Since the magnitude of this coupling is usually unknown the estimate of the local mean age of air will be associated with an uncertainty (refer to the example in D.3.3.3 for how to calculate s_{inhom}).

D.3.4.6 Evaluation of uncertainty in the given example

With twelve sources, each with a relative uncertainty of emission rate of 5 % and with relative uncertainty of 3 % due to uncertain temperature compensation, the uncertainty of sources becomes

$$s_{\mathrm{source}} = \sqrt{0{,}05^2/12 + 0{,}03^2} \qquad \text{(D.24)}$$

The uncertainty of sampling can be calculated from

$$s_{\mathrm{sampl}} = \sqrt{0{,}05^2 + s_{\mathrm{mix}}^2/(n-1)} \qquad \text{(D.25)}$$

where the uncertainty in the calibration of the sampling rate is assumed to be 5 %.

s_{mix}^2 denotes the mixed variance due to variation of individual sampling tubes and non-representative sampling in the zone, which should be determined from the relative standard deviation of n samplers in the zone. If only one sampler is used (for example in a small zone), $s_{\mathrm{mix}}^2/(n-1)$ should be replaced by $0{,}05^2$ for a normally mixed zone.

$s_{\mathrm{meas}} = 0{,}03$ (3 %) is a typical value for the relative uncertainty of tracer gas analysis using liquid extraction and GC/ECD analysis. However, the relative uncertainty grows rapidly as the tracer gas amount decreases.

If a deviation from homogeneous distribution of emission rates is neglected, a typical total uncertainty of local mean age estimation amounts to 11 % in this example.

$$s = \sqrt{s_{\mathrm{source}}^2 + s_{\mathrm{sampl}}^2 + s_{\mathrm{meas}}^2 + s_{\mathrm{inhom}}^2} = \sqrt{(0{,}05^2/12 + 0{,}03^2) + (0{,}05^2 + 0{,}05^2) + 0{,}08^2 + 0} = 0{,}11$$

A typical total uncertainty of local mean age estimation amounts to 11 % in this example.

It should be noted that the estimate of uncertainty only refers to the average of the local mean ages of air during the measurement period. Any variations due to changes in the ventilation rate and air distribution with time are not included. This can only be evaluated by analysing the time variations of the concentration.

Annex E
(informative)

Air quality relevance of local mean age of air and expression of results

E.1 Air quality relevance of the local mean age of air

E.1.1 Mean age of air and air quality

The “local mean age of air” indicates the length of time the air surrounding a particular point in space has spent on average within the ventilated system. The longer the air has spent indoors, the greater the likelihood that the air has accumulated contaminants from indoor sources. The local mean age of air could be therefore an air quality indicator. The air surrounding the point may however have spent different times in different zones of the ventilated system.

The pattern of distribution of mean ages of air in a building describes how the ventilation air is distributed within the building. The local mean age of air is closely connected to the time it takes to renew the air at the particular location.

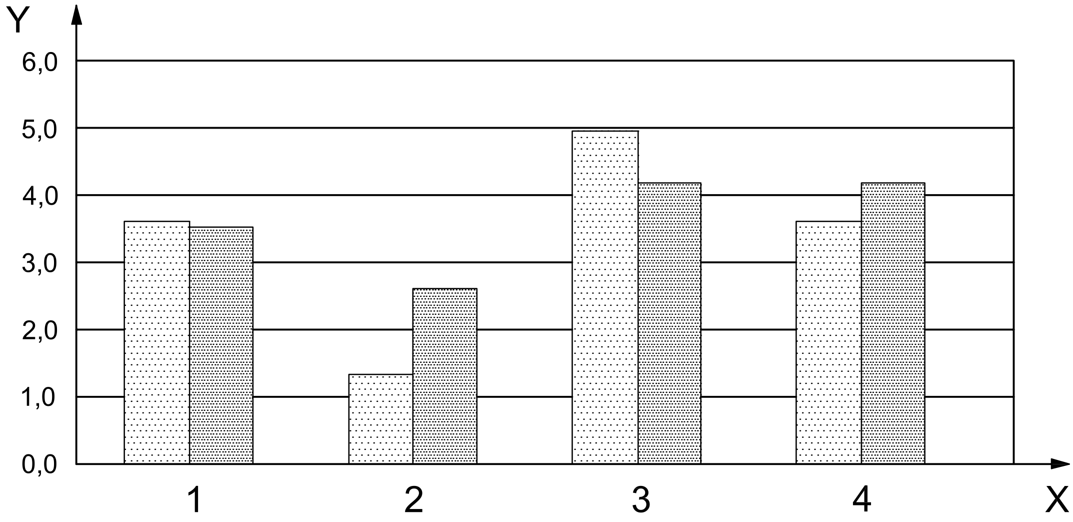
E.1.2 Example: Estimation of contaminant emission rates

An approximate value of the overall emission rate of a contaminant C per cubic metre of space $\left\langle q_w{}^{\mathrm{C}} / V \right\rangle$, whose concentration is measured simultaneously with the mean age of air, can be obtained using the following procedure.

First, calculate the average concentration $\left\langle \rho^{\mathrm{C}} \right\rangle$ of the contaminant C in the ventilated system by computing the volume-weighted concentrations. Then, divide this by the average mean age of air in the system $\langle \bar{\tau} \rangle$, which is computed from the volume-weighted local mean ages of air.

$$\left\langle q_w{}^{\mathrm{C}} / V \right\rangle \approx \frac{\left\langle \rho^{\mathrm{C}} \right\rangle}{\langle \bar{\tau} \rangle} \qquad \text{(E.1)}$$

It is not possible to say how this contaminant emission rate is distributed between the zones, without having additional information on the airflow patterns within the system. It is however possible to compare the distribution of expected concentration with the actual concentration distribution. The expected zone concentrations with a homogenous distribution of contaminant emission rates can be estimated by multiplying the computed $\left\langle q_w{}^{\mathrm{C}} / V \right\rangle$ value by the local mean ages of air in the different zones.



Key

X room
Y concentration ρ^{C}, mg· m^{-3}

⊡ measured concentration
▦ expected concentration

1 living room
2 bedroom
3 kitchen
4 bathroom

Figure E.1 — A comparison between measured contaminant concentration and the calculated expected concentration assuming a homogeneous emission yields information on the distribution of contaminant sources

Rooms that show higher concentration than expected have a higher emission rate per cubic metre (m^3) than calculated $\left\langle q_w{}^{\mathrm{C}} / V \right\rangle$, while rooms with lower values have a smaller emission rate per cubic metre (m^3) than calculated.

E.2 Expression of results

The local mean ages of air in the different zones are the primary results of the measurements according to this part of ISO 16000. However, there are a number of secondary or deduced quantities of the ventilation condition in a building that also might be recorded as test results:

a) the room-specific ventilation flow rate (h^{-1});

b) the average mean age of air (h);

c) the nominal time constant (h);

d) the air exchange efficiency;

e) the local air exchange indices;

f) the specific ventilation flow rate (ACH) (h^{-1});

g) the total ventilation flow rate ($m^3 \cdot h^{-1}$).

Under special circumstances, these parameters can be calculated from the known volumes and local mean ages of air in the different zones, into which the ventilated system is divided.

The definitions and calculation of those additional quantities are given below.

The room-specific ventilation flow rate (h^{-1}) is the inverse of the local mean age of air in a zone. This quantity has formerly often been referred to as “local air change rate” (local ACH). The advantage of this parameter lies in its close resemblance to the well-known specific ventilation flow rate (ACH), which is defined only for the ventilated system as a whole.

The average mean age of air in the ventilated system indicates how old, on average, the air is in the ventilated system. It is calculated from the volume-weighted average of local mean ages of air in the different zones.

$$<\tau> = \Sigma(V_i \tau_i)/\Sigma V_i$$

where

V_i is the zone volume;

τ_i is the local mean age of air.

In this calculation, only those zones are included for which the local mean age has been determined (i.e. those zones equipped with both tracer gas sources and samplers).

The air exchange time is defined as twice the average mean age of air in the ventilated system.

The nominal time constant is defined from the total volume of the ventilated system divided by the total ventilation flow rate. It is also equal to the mean age of air leaving the system. It should if possible be computed from the extract-flow-weighted average mean ages of air measured by samplers located close to identified air extract points. If the extract flows are not known, a simple arithmetic mean of measured mean ages of air at the extract points should be taken. If air extract points are not identifiable the average mean age of the system may be taken as an approximation of the nominal time constant. However, when one of these approximate methods is used, an uncertainty value should be given which is equal to the standard deviation of the individual mean ages from the average.

The air exchange efficiency is defined as the ratio of the nominal time constant to the air exchange time in the system. This parameter describes how well the ventilation air is utilized compared with the ventilation with an ideal “piston flow” through the ventilated system, with the same ventilation flow rate. For a fully mixed system, the air exchange efficiency is 50 %.

The air exchange index is the ratio of the nominal time constant to the local mean age of air. This index describes how well a local space is ventilated compared with the ventilation in a fully mixed system with the same total ventilation flow rate.

The specific ventilation flow rate is defined as the total flow rate of outside air entering into a ventilated system, divided by the volume of the ventilated system. This quantity is equivalent to the formerly used quantity “air change rate” (ACH). The specific ventilation flow rate is not locally defined for a zone (also see: “room-specific flow rate”). It should be calculated from the reciprocal value of the nominal time constant.

The total ventilation flow rate is computed from the ratio of the total volume of the ventilated system to the determined nominal time constant. The total volume shall include all spaces of the ventilated system and not only the volume of the investigated zones.

E.3 Note on measurement and interpretation of "purging flow rate"

E.3.1 Definition

The "purging flow rate" U is a ventilation concept which indicates how effective the ventilation is in removing locally emitted contaminants from a zone. It is defined from the following equation:

$$\rho^{\mathrm{C}} = \frac{q_w{}^{\mathrm{C}}}{U} \tag{E.2}$$

where

ρ^{C} is the steady state concentration in the zone;

$q_w{}^{\mathrm{C}}$ is the emission rate of the contaminant within that zone.

Note that this equation only holds if the same contaminant is not emitted anywhere else in the ventilated system.

If the same contaminant is also emitted in other zones j of the ventilated system, the following equation should be used for the steady state concentration of the contaminant in zone i:

$$\rho_i{}^{\mathrm{C}} = \frac{\left(q_w{}^{\mathrm{C}}\right)_i + \sum\limits_{j \neq i} P_{ij} \left(q_w{}^{\mathrm{C}}\right)_j}{U_i} \tag{E.3}$$

where

P_{ij} is the transfer probability of contaminants emitted with emission rates $\left(q_w{}^{\mathrm{C}}\right)_j$ in other zones j into zone i.

The purging flow rate in a zone can easily be measured using a tracer gas with a known constant emission rate in a zone (and no other zone) and measuring the steady state concentration within that zone. When using the homogeneous emission technique for measuring the local mean ages of air, the purging flow rate in a zone can be determined simultaneously by using a tracer gas of a different type in that zone.

E.3.2 Interpretation of the purging flow rate

The purging flow rate U can be interpreted as the flow rate of outside air to the ventilated system, which is available in a specific zone to dilute contaminants. The maximum value of U is the total ventilation flow rate to the system, and occurs for example when there is good mixing between zones.

According to multi-zone theory, the purging flow rate can be interpreted as composed of ventilation flow rates q_i directly from outside into the different zones:

$$U_i = q_i + \sum_{j \neq i} P_{ij} q_j \tag{E.4}$$

where

P_{ij} is the transfer probability of air from zone j into zone i;

q_i is the flow rate of outside air directly to zone i.

Bibliography

[1] ISO 16000-1, *Indoor air — Part 1: General aspects of sampling strategy*

[2] ISO 16017-1, *Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography — Part 1: Pumped sampling*

[3] ISO 16017-2, *Indoor, ambient and workplace air — Sampling and analysis of volatile organic compounds by sorbent tube/thermal desorption/capillary gas chromatography — Part 2: Diffusive sampling*

ICS 13.040.20

Price based on 41 pages