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# Ventilation Criteria, Effectiveness, Measurement

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**ABSTRACT**

*Ventilation for healthy buildings requires a holistic approach. Most important is source control. The penalty for not undertaking adequate and rational source control is high ventilation flow rates and high energy consumption. Source control is essential from the beginning, in planning, through all phases in the building process, and throughout the life of the building.*

*Ideally, ventilation requirements should be assessed based on residual emissions of pollutants and air quality criteria. Different approaches to ventilation criteria are discussed here. The rationale behind the discussion is* NKB 41E, Indoor Climate—Air Quality, *recently published by the Nordic Committee for Building Regulations (NKB). Unambiguous air quality criteria apparently still belong to the future.*

## INTRODUCTION

Apart from protecting us from nature, a modern building has to meet a range of requirements. The most important ones are functional, aesthetic, and environmental. Indoor air quality has a tremendous impact on the well-being of people and on work capacity, which, in turn, constitutes a substantial economic factor in our societies. Regarding the indoor environment, a building is healthy if the occupants (children as well as adults, including hypersensitive individuals) feel comfortable physically, emotionally, and socially. Because of these many aspects, creating a healthy building requires a holistic approach, not merely eliminating bad smells and harmful compounds, although this is one of the most important issues.

The history of buildings is thousands of years old. In spite of this, we still apparently cannot make and maintain healthy buildings.

The evidence and documentation regarding indoor air quality problems are in numerous reports in the international scientific literature. Apart from small local variations, the problems seem to be identical in the western industrialized part of the world. Sick building syndrome (SBS), building-related illness (BRI), building-related symptoms (BRS), multiple chemical sensitivity (MCS), radon, too low ventilation flow rates, and improper functioning of HVAC installations are common manifestations.

Regarding complaints, many investigations show that a range of factors not building related, such as sex, psychosocial conditions, social status, work content, and different forms of stress, influence the frequency of complaints among individuals. Ruling out such factors, however, does not rule out differences between buildings, meaning that buildings play a substantial role as the cause of human discomfort and sickness.

There is substantial literature regarding the characterization of indoor air quality. However, discussions about strategies or societal requirements to improve indoor air quality are more limited. One contribution to such discussions is *Indoor Climate—Air Quality*, recently published by the Nordic Committee on Building Regulation (NKB). This document,[1] based on the present state of the art, forms the background for this paper.

The ever-increasing frequency of problems is assumed to be related to a range of circumstances, such as switching to year-round building construction, industrialized building processes involving short times for drying out between the different construction phases, insufficient development of quality assurance in construction, and new technology and synthetic materials, which, for technical and/or economic reasons, achieved ready acceptance without proper prior testing/control regarding building hygiene.

To this must be added a tendency to reduce ventilation and tighten the building envelope as a consequence of the need for energy management and reduced energy consumption and other factors. NKB especially draws attention to:

- Materials, furnishings, and furniture that emit pollutants of different kinds are used in buildings.
- Materials and construction sensitive to moisture are used while at the same time insufficient remedial action is taken to prevent moisture loading.
- Ventilation and air-conditioning installations in some cases provide insufficient outdoor airflow rates, either because they have been designed incorrectly or are not used properly, or because the supply air on its way through the ventilation plant becomes contaminated because of the use of materials and components that emit pollutants or because maintenance and cleaning are neglected.
- Coordination (quality assurance) in the building process is unsatisfactory with regard to the indoor climate. Buildings are constructed, operated, cleaned, and maintained in an unsatisfactory or faulty manner.

In addition to the above list, attention should be drawn to the contamination given off by people, cooking, smoking, and office processes and the introduction of new, improperly tested and approved chemicals in the cleaning process. There is also a tendency in our society to neglect housekeeping and cleaning.

Ventilation is only one of several factors to be considered in creating healthy buildings. Nevertheless, it is, by its nature, the most essential one and should not be underestimated. The main

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reason for this is that the building itself prevents the necessary fresh air exchange. The amount of supply air and its quality are crucial for the well-being of the people occupying a building and their capacity to work, a substantial economic factor in our society. On the other hand, it is of primary importance that the building itself not be a polluter, as the many SBS manifestations in our day frequently demonstrate. However, sick buildings are not a new occurrence. In the book of Moses in the Old Testament, we find both a description of a sick building and a cure for it. In the worst cases, the cure was to demolish and remove the whole building. We should learn from that. Obviously, their sick buildings were caused by mold, fungi, and microbial growth caused by moisture, which evidently is also a most important factor in the modern sick building mystery.

We have at present a contradictory situation. On the one hand, there is great knowledge today of indoor pollution. On the other hand, because most of the research has been of a survey character and not the kind that permits conclusions to be drawn as to which factors have significance for what regarding the incidence of ill health, it is not possible at present, other than in exceptional cases, to pinpoint "guilty" substances or factors.

In light of this uncertain state of knowledge, philosophy must be of a general nature. That is to say, we must not only avoid certain substances/factors but generally keep the number and intensity of pollution sources at a level low enough to secure a reasonable ventilation standard and adequate indoor air quality.

Ventilation for healthy buildings requires the following steps: (1) employing an adequate source control procedure, (2) quantifying the resultant "worst case" of contaminant generation, and (3) specifying the ventilation flow rate necessary to obtain acceptable indoor air quality in a worst-case situation. A strategic approach may be:

- Select the building location.
- Plan the building.
- Select construction materials, processes, etc., for the lowest possible contaminant exposures from the building and its use.
- Select a proper HVAC system.
- Predict its performance based on current criteria.
- Construct the building, including all HVAC installations.
- Commission and start to use the building.
- Verify its performance through experiments.

## VENTILATION

The main subject in building ventilation is source control. The penalties for not undertaking adequate and feasible measures to reduce emissions to a practical minimum are high ventilation flow rates and high energy consumption. Source control is essential from the beginning, in planning, through all phases in the building process, and throughout the life of the building.

### Building Requirements in Planning, Design, and Construction

Regarding the building site and ground conditions, special attention should be paid to moisture and radon exposure, waste deposits, and deposits from industrial activities that may create a substantial air quality problem if remedial action is not taken to prevent them. A recommended action is to prevent the substances from leaking into the building by sealing.

Outdoor air quality is considered because pollutants from the outside air may be a significant risk factor in town centers, near industrial sites, or near traffic routes. Guideline values for outdoor air quality have been set up by WHO. The trouble with these guidelines is that they do not consider the fact that there are also indoor sources of pollutants, which means that the outdoor air, complying with the guideline values, has no ventilation potential for these substances.

In construction, the risk of moisture damage is specifically underlined, especially with regard to its harmful influence on building materials with the risk of emission of contaminants to the indoor air. Moisture and temperature may cause microbial growth and chemical degradation of the materials with great risk of impaired air quality.

### Building Materials and Surface Finishes, Fixtures, and Fittings

Ideally, building materials should not contribute to the ventilation demand. However, this is not a realistic assumption, neither today nor for the near future. Building materials pollute, either more or less, and there is a great variety of materials in the market that have not been through a realistic emission, health risk, or building hygiene test.

The client should demand an indoor-climate-related product description of the material. Such declarations currently are not common. Testing techniques and standards are in the process of being developed and harmonized between different countries. It will take time both to establish control/certification procedures that are internationally agreed on and practiced and to rule out low-quality materials. Particleboard is a good example of such a process. From being a primary polluter 10 years ago, this material has been developed in Scandinavia to emit less formaldehyde than pine wood when properly handled, stored, and used. But there are still low-quality products in the international market, and faulty handling and use, especially with regard to moisture and cleaning chemicals, can degrade any material.

### Processes and Activities

When processes and activities that pollute the air are necessary, they should be encapsulated as much as possible, provided with a local external air supply, and/or limited to times when few people are exposed. When smoking occurs, special measures should be taken to prevent the risk of passive smoking. In many office environments, copy machines and laser printers may cause problems of ozone emission and dust generation.

### HVAC Pollution

HVAC systems can be a major source of indoor pollutants. It is important that these systems be clean and cleanable with proper filtration of the outdoor air and that they consist of nonpolluting materials and be designed to prevent accumulation and condensation of water.

### Cleaning of the Building

Cleaning of buildings is important. It is especially important that the building be prepared for cleaning, i.e., all surfaces that are in contact with room air or supply air are easily accessible and possible to clean. One should bear in mind that cleaning itself, through methods and agents, can deteriorate materials and air quality. Methods and agents need documentation showing both hygienic properties and suitability.

## VENTILATION CRITERIA

Ideally, ventilation requirements should be assessed based on residual emissions of pollutants and air quality criteria. There is no doubt that in contrast to earlier ventilation codes, which regarded humans as the principal polluters, we have to consider other sources more carefully. Some codes have recognized the building itself as a polluter, but only to a minor extent. It was not suggested earlier to add together the different demands, although this has been common in the field of occupational hygiene.

However, much knowledge is still needed before a dose-response can be quantified in relation to a certain exposure or any specific pollution source in a normal building. It is only in exceptional cases that it has been possible to relate symptoms of ill health of the SBS type to the concentration of specific air pollutants or combinations of these.

Correlation between airflow rates and symptoms of the SBS type is, as can be expected, ambiguous. However, it has been found that, for a specific building, the frequency of complaints decreases as ventilation rates increase.

Humans are, of course, still an important pollution source. As early as the 1850s, Pettenkofer could give good criteria for ventilation rates for the control of human effluents based on the $CO_2$ content.

**Perceived Air Quality**

A classic measure of air quality is the extent to which odor and/or chemical irritation is perceived as acceptable by visitors directly on entry into the premises. The measure was used by Yaglou in his classic studies and has in recent years been developed by Fanger et al., manifested by the olf and decipol concepts. One olf is equivalent to the emission of the perceived air pollution (bioeffluents) by a standard person. One decipol is the perceived air quality due to one olf ventilated at 10 L/s of fresh (clean) air. The decipol is further geared to PPD (predicted percentage of dissatisfied persons). The new line is to quantify actual pollution sources in buildings, such as tobacco smoke, building materials, surface coverings, furnishings and furniture, processes, etc., in olfs. In theory, the ventilation criterion for comfort could be to specify the air quality in decipols. The ventilation requirement is then calculated from the olf load. Fanger has shown that there is a considerable variation in pollution load in olfs between buildings. The variation was on the order of 1:50 with an average of 0.3 olf/$m^2$, equivalent to approximately four persons per 10 $m^2$ floor area. Most remarkably, he found in some cases that the ventilation system contributed most to the olf load. It is believed that the load can readily be lowered to 0.05 to 0.1 olf/$m^2$ in new buildings by careful selection of materials and HVAC systems.

There are a few questions. One is how to mathematically treat olfs from different sources (should it be simple, hypo, or hyper addition). Fanger, based on his findings, suggests as a best choice, until we know more, that olfs be added arithmetically ($1 + 1 = 2$). The other question concerns adaptation. Some adaptation of occupants will take place after a while, especially in the case of human bioeffluents, although it is less pronounced for typical building materials. On the one hand, adaptation with regard to perceived air quality does not guarantee there will not be other health effects, such as fatigue, headache, heavy-headedness, lack of concentration, sore eyes, irritation of the mucous membranes, etc. On the other hand, the adaptation effect will quickly disappear when the exposure stops, as in leaving the premises. In a typical office environment, people are quite mobile, so it seems right to use the visitor concept when criteria are assessed. Last but not least, we have the question of to what extent dissatisfaction with regard to perceived air quality upon entry can be connected to health effects and discomfort during occupation. More knowledge is needed in this field.

A working group under COST 613, convened by Fanger,[4] is preparing a document on ventilation requirements based on perceived air quality.

**Chemical Air Quality**

The odor and chemical senses react when exposed to chemicals although not to all substances that may be harmful to human health. In theory the best criterion is to express air quality in safe concentration levels for the different contaminants when the health risk criteria and source intensities are known. For a few substances, guidelines are given by WHO (Air Quality Guidelines for Europe), but for the great majority of substances and for a number of interacting substances, knowledge is insufficient, and very little is known about the source intensities. To this must be added allergens and mycotoxins related to microorganisms and fungi.

However, volatile organic compounds (VOC) as a mixture are not reflected in the WHO document. At concentrations that can occur indoors, reactions of irritability and hyperactivity can be expected to some of the substances. Such reactions and toxic effects can occur at very low concentrations of single substances, and it can be very difficult to identify the "guilty" substance. It is probably not the total level of indoor air pollution but the occurrence of certain substances or combinations of them that produces health effects. There is, however, very little information about the contribution of single and/or combinations of substances to health effects. Dose-effect/dose-response data are completely lacking. In spite of this lack of data, a working group under the Norwegian Public Health Department of the Ministry of Social Affairs has decided to give a guideline value of exposure to TVOC of 400 $\mu g/m^3$, formaldehyde and carcinogens excluded. This value was chosen partly because it is readily obtainable in practice by careful selection of source control measures, and partly because an elevated presence of symptoms is not generally found at such concentrations. Other suggestions are 300 $\mu g/m^3$ TVOC, proposed by Seifert.[3] Values here depend on how they are measured. Elevated concentrations are generally caused by specific contaminant sources for which specific remedial actions should be taken.

The Norwegian document further proposes:

- **Formaldehyde** should not exceed 60 $\mu g/m^3$.
- **Suspended particulate matter** in the indoor air is probably not a ventilation matter, but is related to certain remedial actions such as filtering, avoiding material-generating particles, avoiding conditions favorable for microbial growth, etc. A high content of certain particles will carry VOC into the respiratory system, intensify the feeling of dry air, or intensify symptoms such as irritation of the mucous membranes and dry skin. The suggestion here is **40 $\mu g/m^3$ for the fine fraction (<2.5 $\mu m$)** and **90 $\mu g/m^3$ for total dust (<10 mm).**
- **Asbestos fibers** should have a target value of zero.
- No level of health effects is documented for **MMF**, but these fibers should not be present indoors.
- **Tobacco smoking** should not occur indoors.
- **Mites** should have a target value of less than 50 mites/g dust.
- Regarding **microorganisms**, no pathogens should be present indoors. Others should be as low as possible, and there should be no smell of mold.
- **Radon** should not contribute to ventilation requirements but be subject to a source control such as sealing and/or subfloor ventilation.
- **Humidity** in the indoor air may directly or indirectly have an impact on the occupants. High humidity may stimulate the growth of fungi and microorganisms and may cause condensation and building damage. High humidity may also enhance the emission of chemicals from building materials. Low humidity per se seldom causes a problem. To suppress the growth of dust mites, it is important to avoid high relative humidity, especially in the bedrooms. Humidity may be a ventilation criterion, and relative humidity should not exceed 70%.

In theory, the different guideline values could be criteria for calculating ventilation flow rates. ASHRAE Standard 62-1989[6] proposes such an air quality procedure. The conclusion is, however, that at present too little is known about the sources for such procedures to be employed as a whole. The use of low-polluting materials is encouraged. Otherwise, ventilation requirements are given based on person load. ETS is not considered specifically (see table for comparison).

Scanvac recently published a guideline[2] for classifying indoor air quality, introducing a calculation model based on emission rates from building materials. This is a good model of current thought. However, lack of knowledge is a barrier, as mentioned previously, both with regard to quantifying emission rates and to relating and quantifying health risks with concentrations of contaminants. In spite of the lack of data, Scanvac introduces three different emission classes for building materials in the document and has tried to group building materials into these three classes. Instead of using exact emission data and threshold values, it gives formulas linking the amount of square meters used of the different material classes to ventilation flow rates. The document also gives restrictions in the use of the worst class if the aim is a high air quality level. The use of low-polluting materials is encouraged.

The IEA reported "minimum ventilation rates" in 1987.[5] The work behind the report was motivated mainly by energy conservation. Different aspects of air quality (pollution sources) were thoroughly discussed, such as smoking, radon, and formaldehyde. The conclusion for building-related contaminants, such as volatile organic compounds, microorganisms, and many particulates, was that current knowledge is limited, but there are, nevertheless, indications that they may be associated with significant health effects. Further research is required to characterize the sources and to investigate the effects of the pollutants, which may be particularly important for offices and similar buildings.

The report concludes, not unexpectedly, with relatively conservative ventilation requirements related mainly to persons and prescribes sealing, removal, and elimination as actions to control contaminants not covered by person-related requirements. ETS is considered to some extent (see table for comparison).

The Norwegian Directorate of Labour Inspection recently published a revised edition of *Guidelines for Indoor Climate and Air Quality in Work Environment.*[7] In the new edition, three categories of pollution sources are defined: person load, building fixtures and furnishings, and activity and processes. It suggests these different demands be added (see table for comparison).

In the new Nordic air quality guideline, NKB61E,[1] neither the perceived air quality comfort equation of Fanger nor an air quality procedure is employed in full, simply because too little is known at present about the characteristics and intensities of sources indoors, measured in any quantity for such procedures to be applied. However, these theories as a whole have formed the background for professional judgment regarding proposed ventilation requirements. NKB61 has adopted the addition principle, not as normal addition but as hypo addition, where the building materials and other sources unrelated to persons have a weighting factor of 1 and the person load a weighting factor of 0.5. Effective source control is the prerequisite for the specified flow rates (see table for comparison).

One should bear in mind that total ventilation flow rates in practice may differ significantly from the requirements discussed regarding air quality. In the case of many buildings, other factors,

**Comparison of Different Guidelines for Ventilation Requirements**

| Source Room | Notations | NKB61 | ASHRAE Standard 62 - 1989 | IEA | The Norw. Direct. for Lab. Insp. | |
|---|---|---|---|---|---|---|
| Person non smoking | l/sp | 7 | 10 | 5.5 - 8 | 7 - 10 | |
| Person smoking | .l/s p | sep.room. 20 | sep.room. 30 | 8 - 20 | Not allowed | |
| Building-material. | l/s m² | 0,7 1) 3) | | | 0,7 1)<br>2,8 3) | |
| Buildingrel Office | l/s m² | > 0,7 2) | | | >1.7 2) | |
| Polluting activity | l/s | Consid. | Include | Consid. | Calc. and add | |
| Kitcen | .l/s Exhaust | 20 | 50 mech<br>25 nat | | | |
| Bathroom | l/s Exhaust | 15 | 25/10 | | | |
| Dwellings | l/s m²<br>ach | 0,35 | 7,5 l/s p<br>0,35 | <br>0,5 | | |
| Toilet priv<br>" public | l/s Exhaust | 10<br>15 | 10<br>25 | | | |

1) After one year, low-emitting materials
2) New building/redecorated building
3) Lack of documentation of low-emitting materials

such as the need for maintaining thermal comfort by cooling, may call for much higher flow rates.

Energy consumption may be lowered and comfort even improved when employing demand-controlled ventilation. Such a strategy should be based on air quality sensors. In many circumstances, it can be based on user patterns or individual requirements. The need for developing air quality sensors and other sensors and/or control devices in this field is great. The IEA has an annex working with this issue.

## EFFICIENCY

The ventilation flow rates discussed presuppose complete mixing between contaminants generated in the space and the room air. The air quality is generally not the same throughout a ventilated space. What really counts is the air quality in the breathing zone. The objective for an efficient ventilation process is to aim at the lowest possible contaminant concentrations in the breathing zone compared with the concentrations in the return air terminal, which, in contrast to the concentrations in the occupied space, are indifferent to how ventilation is accomplished. Inhomogeneity in air quality is connected to ventilation efficiency and has an impact on the ventilation requirements.

The air quality may be poorer in the breathing zone than in the return air terminal for two reasons:

1. Inefficient air distribution, causing an inefficient purging of ventilation air through the breathing zone, meaning that some of the ventilation air is short-circuiting to the exhaust.
2. Ineffective removal of contaminants, causing an accumulation of contaminants in the breathing zone.

The penalty is increased flow rates.

The efficiency of an air distribution system and the purging flow rate are connected to the age of the air in the breathing zone. This age is taken as the time elapsed since the air at a point entered the space.

The overall effectiveness of the contaminant removal is connected to the age of the contaminant at the return air terminal. This age is taken as the time elapsed from the moment the contaminant was released at the source. The younger the air and the younger the contaminants are in this context, the more efficient the ventilation process is.

However, the breathing zone conditions regarding pollutants cannot be characterized by the local age of the contaminants. The procedure is simply to compare local concentrations with the return air concentration.

The air quality in the breathing zone may be better than in the return air terminal when efficient ventilation has been a design goal. This introduces a potential for lowering the ventilation flow rates.

In general, any ventilation system can be regarded roughly as a two-zone flow pattern. One zone is the air supply zone and the other zone comprises the rest of the room. In mixing ventilation, the supply zone is usually above the breathing zone. The best efficiency is achieved when the mixing is so effective that the two zones are transformed into one zone. In displacement ventilation,[8] there is generally a supply zone occupied by people and an exhaust zone above. The best efficiency (and higher than for complete mixing) is achieved when there is minimal mixing between exhaust and supply zones.

A unidirectional flow pattern for both air and contaminant is the most efficient. An example of this is a unidirectional flow from floor to ceiling, as can be accomplished in a clean room because of the high flow rates. In spaces such as office rooms, the efficiency is a function of the location and characteristics of the terminal devices and of the pollution sources. It is further a function of the temperature and flow rates of supply air. Ceiling-mounted terminal devices in combination with supply air heated above room temperature may be very inefficient. In displacement ventilation, the aim is to create a flow pattern with a tendency to unidirectional flow. These systems are generally more efficient than systems aiming at complete mixing. In most of these applications, the main flow direction is from floor to ceiling, relying upon upward convective currents to carry contaminants out of the breathing zone.

The efficiency can be calculated by numerical simulation, measured experimentally, or determined from experience. The first two methods are not widely used in the design phase, mostly for economic reasons. IEA Annex 20 is dealing with this topic.

The air exchange between rooms and time-varying flow rates also have an impact on ventilation effectiveness. Multiroom and temporal ventilation effectiveness are also dealt with in IEA Annex 20.

## MEASUREMENT

Generally, apart from ventilation flow rates, not many parameters are specified in design documentation. However, this is in the process of being changed. Builders and clients are now encouraged to require, and are also more conscious of, specification of rational air quality parameters connected to present guidelines.

The process of verifying the performance of the ventilation system then is to measure the parameters specified in the design and compare measurements with specified values. Such specifications include ventilation flow rates, ventilation efficiency, and air quality parameters.

### Ventilation Measurements

Total ventilation flow rates delivered by the mechanical ventilation system and the distribution of it through the ducting system and the terminals can readily be measured using well-known and well-described methods. However, an important prerequisite for a meaningful outcome is that the ventilation system be designed and constructed for such measurements. If there is no mechanical system, one has to rely upon certain tracer gas methods, such as PFT passive sampling,[9] the active constant-concentration method, or the classic tracer gas decay method. The $CO_2$ from people can also be used as a tracer in these contexts.

What counts next are the purging flow rates and the ventilation efficiency in the different spaces. Building infiltration will also be encountered in these measurements. Such measurements can most readily be accomplished by applying one or more tracer gas methods that measure the age of the air in the occupied zones and at the return air terminal. Practical measurements involve either injecting tracer gas in the main ventilation system at a constant rate or injecting a certain amount of tracer gas in the occupied spaces and mixing it well with the room air before starting measurements. The tracer gas concentration is measured as a function of time. From this, the different quantities can be calculated.[10]

For contaminants generally, the local contaminant-removal effectiveness or the local ventilation index, defined as the ratio between the contaminant concentration in the return air terminal and the concentration at a local point, is readily measured directly by measuring the concentrations of the different contaminants. Methods are given by Nordtest[13,14] and AIVC.

### Air Quality

As already stated, there are a large number of agents in the indoor air that can be measured. What is meaningful to measure is, first of all, all parameters that have been used as design criteria or guidelines. The most important factors that should be determined are the perceived air quality, TVOC, suspended particulate matter such as dust and fibers, and, in special cases, radon and microorganisms.

Perceived air quality can be measured in different ways. The method most widely used presently is probably the one developed by Fanger et al. using trained panels judging the air quality in decipols or untrained panels also resulting in a decipol estimation.

Regarding measurements of chemical substances, there are many situations and pollutants in the different types of indoor spaces that call for quite a large set of sampling procedures to be established. However, there are general considerations that apply in most circumstances. These general considerations cover the dynamics of the indoor environment (which is very important) and the questions of why, when, how long, how often, and where sampling should be carried out. The publication of COST 613 Report No. 6,[11] *Strategy for Sampling Chemical Substances in Indoor Air*, covers all these questions.

There is currently no strong rationale for measuring chemical substances other than TVOC and specific irritants, including particulate matter. Perceived air quality and questionnaires currently constitute the most meaningful measurements.

All measurements should be preceded by a standardized questionnaire, such as the one described in COST 613 Report No. 4,[12] *Sick Building Syndrome—A Practical Guide*. Air quality measurements should be carried out the first time soon after the building is in use, the second time after one year, and later every third or fifth year.

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