

EUROPEAN COLLABORATIVE ACTION
INDOOR AIR QUALITY & ITS IMPACT ON MAN

Environment and Quality of Life

Report No 19

**Total Volatile Organic Compounds (TVOC)
in Indoor Air Quality Investigations**



EUROPEAN COMMISSION
JOINT RESEARCH CENTRE - ENVIRONMENT INSTITUTE

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Total Volatile Organic Compounds (TVOC) in Indoor Air Quality Investigations

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The amount of volatile organic compounds in indoor air, often called TVOC (total volatile organic compounds), has been measured for various purposes using different definitions and techniques which yield different results.

This report recommends a definition of TVOC and a method for sampling and analysis. It also specifies the application of the TVOC concept in indoor air quality investigations.

Following the recommended procedure will improve the comparability of TVOC data from different laboratories and buildings. It will also help avoid potentially misleading uses of the TVOC concept.

There was a consensus in the WG that TVOC is important for indoor air quality and that the likelihood of unwanted effects increases with increasing TVOC. However, at present the available data do not allow establishing of thresholds for TVOC.

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Abstract

ECA-IAQ (European Collaborative Action 'Indoor Air Quality and Its Impact on Man'), 1997. Total volatile organic compounds (TVOC) in indoor air quality investigations. Report No 19. EUR 17675 EN. Luxembourg: Office for Official Publications of the European Community

The amount of volatile organic compounds (VOCs) in indoor air, usually called TVOC (total volatile organic compounds), has been measured using different definitions and techniques which yield different results. This report recommends a definition of TVOC referring to a specified range of VOCs and it proposes a method for the measurement of this TVOC entity. Within the specified range, the measured concentrations of identified VOCs (including 64 target compounds) are summed up, concentrations of non-identified compounds in toluene equivalents are added and, together with the identified VOCs, they give the TVOC value.

The report reviews the TVOC concept with respect to its usefulness for exposure assessment and control and for the prediction of health or comfort effects. Although the report concludes that presently it is not possible to use TVOC as an effect predictor it affirms the usefulness of TVOC for characterizing indoor pollution and for improving source control as required from the points of view of health, comfort, energy efficiency and sustainability.

TABLE OF CONTENTS

<i>SUMMARY</i>	1
1. <i>INTRODUCTION</i>	3
2. <i>TVOC - REVIEW OF ANALYTICAL METHODS</i>	5
2.1 Introduction	5
2.2 Direct-reading instruments for VOCs	6
2.2.1 Principles of measurement	6
2.2.2 Advantages and limitations	6
2.3 VOC separation methods	6
2.3.1 General analytical steps	7
2.3.2 Methods without identification of individual compounds	8
2.3.3 Methods based on identification of individual compounds	8
2.4 Comparison of analytical methods	8
2.5 Special organic compounds in indoor air	9
3. <i>TVOC - PROPOSAL FOR A NEW DEFINITION</i>	11
3.1 Rationales for the proposed procedure to determine TVOC	11
3.2 Recommended procedure	11
3.3 Quality assurance	12
4. <i>VOCs AND HEALTH EFFECTS: EXPOSURE - RESPONSE RELATIONSHIPS</i>	13
4.1 Single compounds and interactions	13
4.2 Specific complex mixtures	13
4.3 Complex mixtures from materials and buildings	15
4.4 Previous approaches for evaluation	16
5. <i>USES OF TVOC AS AN INDICATOR</i>	17
6. <i>CONCLUSIONS AND RECOMMENDATIONS</i>	19
6.1 Conclusion	19
6.1.1 General aspects	19
6.1.2 For what can TVOC be used?	19
6.1.3 How the TVOC indicator should not be used	20
6.2 Future research	20
6.2.1 Analytical procedures	20
6.2.2 Health and comfort data	21
7. <i>REFERENCES</i>	23
Appendix 1: Minimum number of compounds to include in TVOC-analysis	31
Appendix 2: Indicators and their use	35
Appendix 3: Effect measures in relation to TVOC	39
Appendix 4: Members of the ECA-IAQ Steering Committee	45

SUMMARY

In this report, the literature on the previous usage of indicators for assessing the effects of volatile organic compounds (VOCs) in indoor air on comfort and health is reviewed. Advantages and disadvantages of a TVOC (Total Volatile Organic Compounds) concept are evaluated with respect to exposure assessment and prediction of health effects.

TVOC values reported in the literature are mostly not comparable. To increase comparability, TVOC must be defined clearly. Such a definition is given for a specified range of VOCs. The measured concentrations expressed as mass per air volume of identified VOCs within that range are added. Non-identified compounds in toluene equivalents are included and, together with the identified VOCs, they give the TVOC value.

Most reported TVOC-concentrations in non-industrial indoor environments are below 1 mg/m^3 and few exceed 25 mg/m^3 . Over this range the likelihood of sensory effects increases. The sensory effects include sensory irritation, dryness, weak inflammatory irritation in eyes, nose, air ways and skin. At TVOC concentrations above 25 mg/m^3 other types of health effects become of greater concern.

In view of the fact that there are few controlled human exposure studies and the results are not confirmed, and that the results of epidemiological studies are inconsistent, it is today not possible to conclude that sensory irritation is associated with the sum of mass concentrations of VOCs at the low exposure levels typically encountered in non-industrial indoor air. Therefore, although the likelihood of sensory effects will increase with increasing TVOC concentration, at present no precise guidance can be given on which levels of TVOC are of concern from a health and comfort point of view, and the magnitude of protection margins needed cannot be estimated.

Nevertheless, the general need for improved source control to diminish the pollution load on the indoor environments from health, comfort, energy efficiency and sustainability points of view leads to the recommendation that VOC levels in indoor air should be kept as low as reasonably achievable (ALARA). Such an ALARA-principle will require that TVOC concentrations in indoor environments - when determined with the proposed procedure on representative samples of buildings and spaces - do not exceed the typical levels encountered in the building stock of today, unless there are very good and explicit reasons.

It cannot be excluded that specific VOCs may turn up in the future to be much more potent in causing effects on humans than the average VOCs. In that case, they should be evaluated individually, and a list of such compounds should be established.

TVOC, or other measures of volatile organic compounds, may be used for a number of other applications. Examples are: Testing of materials, indication of insufficient or poorly designed ventilation in a building, and identification of high polluting activities.

1 INTRODUCTION

In Western Europe people may be exposed to indoor air for more than 20 hours per day. The quality of indoor air has a non-negligible impact on human comfort and even health. These two facts explain the growing interest in making available simple yet effective ways for the characterisation of the air indoors.

In the past, when human bioeffluents were considered to be the most important pollutants of indoor air, carbon dioxide (CO₂) was generally accepted as an indicator for indoor air quality (IAQ). CO₂ has lost this function partly because today many more sources than human beings emit pollutants into indoor air. In fact the widespread use of new products and materials in our days has resulted in increased concentrations of indoor pollutants, especially of volatile organic compounds (VOCs), that pollute indoor air and maybe affect human health. As a result, the air of all kinds of indoor spaces is frequently analysed for VOCs (Brown et al., 1994).

In many scientific publications dealing with VOCs a tendency can be observed not to report the concentrations of all analysed VOCs individually but rather to indicate the total concentration of VOCs under the term "Total Volatile Organic Compounds" (TVOC). One of the reasons is that the interpretation of one single parameter is simpler and faster than the interpretation of the concentrations of several dozens of VOCs typically detected indoors. In addition, editors of scientific journals tend to avoid printing long lists of compounds.

Unfortunately, this common practice suffers from the lack of a standardised procedure to calculate the TVOC value from the results of the analysis. Literature shows that there is a large variety of ways to calculate a TVOC value from the results of an analysis (e.g., De Bortoli et al., 1986; Gammage et al., 1986; Krause et al., 1987; Mølhave, 1992; Rothweiler et al., 1992; Seifert, 1990; Wallace et al., 1991). In addition to the mere calculation procedure, differences may arise from the influence of the analytical system including the adsorbent used for sampling, the sampling rate and volume, and the separation and detection system. For all these reasons, published TVOC data are often not comparable and, consequently, there is a need for an agreement on what "TVOC" means from the standpoint of the analyst.

As many VOCs are known to have short-term and long-term adverse effects on human health and comfort, VOCs are frequently determined if occupants report complaints about bad indoor air quality. On the comfort side VOCs are associated with the perception of odours. Adverse health reactions include irritation of mucous membranes, mostly of the eyes, nose and throat, and long-term toxic reactions of various kinds (ECA-IAQ, 1991). As VOCs belong to different chemical classes the severity of these effects at one and the same concentration level may differ by orders of magnitude.

The evaluation of health effects caused by complex VOC mixtures is difficult. According to basic toxicological knowledge the effects of pollutants may be additive ($\text{Effect}_{\text{MIX}} = \text{Effect}_A + \text{Effect}_B + \dots$), synergistic ($\text{Effect}_{\text{MIX}} > \text{Effect}_A + \text{Effect}_B + \dots$), antagonistic ($\text{Effect}_{\text{MIX}} < \text{Effect}_A + \text{Effect}_B + \dots$), or even independent from each other. When many pollutants are present at low concentrations, their possible combined human health effects are hardly predictable based on present toxicological knowledge. For sensory reactions, the interaction mechanisms are known only for a small group of VOCs with strong odours for which hypoadditive behaviour has been demonstrated (Berglund and Olsson, 1993).

Although there is not an agreed definition for TVOC, this entity is often used in the literature to describe indoor air exposures and to estimate health consequences and risks. The justification for this is mostly derived from the work of Mølhave (Mølhave, 1986; Mølhave et al., 1986; 1993) who studied the health and comfort effects of a mixture of 22 VOCs, and the subsequent complementing work carried out at the laboratories of the US-EPA using almost the same mixture

(Otto et al., 1990; Hudnell et al., 1992; Koren et al. 1992). However, given the relatively small number of VOCs used in these studies and the specific composition of the mixture used, it cannot be anticipated that the observed increased subjective ratings of general discomfort and CNS mediated symptoms would also occur with another mixture even if the TVOC levels of the two mixtures were very close to each other.

It has recently been suggested that improved correlation between Sick Building Syndrome (SBS) effects and other metrics of the VOC content in air can be found. In a new approach, Ten Brinke (1995) takes into account the differences in irritation potency of individual VOCs by weighing the concentration of individual compounds with a constructed relative irritation value based on data from mouse assays, and by adjusting the highly correlated nature of VOC mixtures by means of principal component analysis. A somewhat similar approach for constructing a perceptually weighted level of VOCs (PWVOC) has been suggested by Cometto-Muniz and Cain (1995). An evaluation of the usefulness of these refined indices of VOC exposure is beyond the scope set out for the working group, and is therefore not included in the present report.

It is the first objective of this report to discuss the background of VOC analyses and to investigate the possibilities of recommending a meaningful definition of the term TVOC. The second objective is to discuss thoroughly the association between VOCs and specific effects like sensory, neurotoxic and behavioural effects, and irritation of mucous membranes with the question of the potential of TVOC to serve as an effects indicator in mind.

2 TVOC - REVIEW OF ANALYTICAL METHODS

2.1 Introduction

In view of the large number of known organic chemicals in indoor air there is a tendency to divide them into several classes for easier handling. The division can be made according to, e.g., their chemical character (alkanes, aromatic hydrocarbons, aldehydes, etc.), their physical properties (boiling point, vapour pressure, carbon number, etc.), or their potential health effects (irritants, neurotoxics, carcinogens, etc.). Following the classification given by a WHO working group on organic indoor air pollutants (WHO, 1989), it has become common practice to divide organic chemicals according to boiling point ranges and to discriminate between VVOC, VOC, SVOC and POM (see Table 1 below).

Table 1. Classification of indoor organic pollutants (WHO, 1989)

Category	Description	Abbreviation	Boiling-point range*	Sampling media typically used in field studies
1	Very volatile (gaseous) organic compounds	VVOC	< 0 to 50-100	Batch sampling; adsorption on charcoal
2	Volatile organic compounds	VOC	50-100 to 240-260	Adsorption on Tenax, graphitized carbon black or charcoal
3	Semivolatile organic compounds	SVOC	240-260 to 380-400	Adsorption on polyurethane foam or XAD-2
4	Organic compounds associated with particulate matter or particulate organic matter	POM	> 380	Collection on filters

* Polar compounds appear at the higher end of the range

If a VOC mixture is analysed in indoor air, the result is often expressed as TVOC (total volatile organic compounds). This means that one single value is taken to represent the VOC mixture. It is important to note that although the TVOC value is mostly determined by the content of VOC in the air, the analytical conditions are often such that it may include part of what belongs to the classes of VVOC, and SVOC (see Table 1).

Unfortunately, there is no general agreement on which compounds should be included in the procedure to generate the TVOC value. Hence, the number and the nature of VOCs on which the TVOC value is based varies between studies reported in the literature. This is also one of the problems if the TVOC value is used as an indicator of health effects.

There are three basic approaches for analysis and determination of VOCs in indoor air. These differ with regard to the amount of work involved and the degree of information they provide. The most simple way is to use a chemical or biological detection system which does not separate the mixture into its individual components. This principle is used in **direct-reading instruments**. In a more elaborate procedure the components of a chemical mixture are separated, and the approach is then to sum the instrumental responses for the individual compounds, although **no identification** is accomplished. Following the third approach, the constituents of the mixture are separated to permit an **identification of individual compounds**. In the following, the three approaches will be described in more detail.

2.2 Direct-reading instruments for VOCs

The detectors that are used in gas chromatography to detect individual compounds after separation can also be used to provide information on a given mixture without a prior separation step. VOC-detectors that can be used for this purpose are, for example, the flame-ionisation detector (FID) and the photo-ionisation detector (PID). A further direct-reading instrument for VOCs is the photo-acoustic sensor (PAS). Other types of sensors may become important in the future; most of these are still under development (e.g. "electronic noses").

2.2.1 Principles of measurement

In the FID, an organic compound is burned in a hydrogen flame giving rise to ions which are attracted to a collector electrode. The resulting electric current is amplified and recorded. The intensity of the signal depends primarily on the number of carbon atoms of the molecule, but to some extent it is also influenced by the character or structure of the chemical. Therefore, the same amount of molecules of two different VOCs with the same number of carbon atoms can give rise to two different signals. The FID is very stable. It is the most common detector used for VOCs because it detects a very large number of VOCs.

In the PID the VOCs are ionized by UV radiation. The energy from the UV lamp is sufficient to ionize most VOCs, but not all. For example, some chlorinated compounds are not ionized. For many VOCs, the PID is more sensitive than the FID by about an order of magnitude. However, the PID may be less stable than the FID and again, the response can only be viewed as an indicator of TVOC.

The PAS combines the pressure variation of organic vapours caused by absorption of infrared radiation and the resulting temperature increase with acoustic detection. This is achieved by modulating the intensity of the infrared light (by chopping the light beam) with an acoustic frequency. The response of the PAS depends on the wavelength(s) of the infrared light used for detection and interference with water vapour and methane require special attention.

Direct-reading detectors are generally calibrated with one single compound, e.g. a hydrocarbon such as n-hexane or toluene. Consequently, the signal obtained from a mixture of VOCs is always expressed in terms of concentration equivalents of this compound regardless of the composition of the mixture.

Since the TVOC values measured by all direct-reading instruments differ from one another and also from the new TVOC value defined in chapter 3 of this report, it is here proposed that in future, in order to avoid confusion, these measurements are marked with a suffix indicating the type of direct reading instrument used such as 'TVOC', 'TVOC_{PID}' or 'TVOC_{PAS}'.

2.2.2 Advantages and limitations

Direct-reading instruments are easy to use. They are portable and provide a real-time signal which makes it possible to detect rapid concentration changes.

Direct-reading instruments do not only respond to VOCs but also to other organic compounds, especially to VVOCs. As the instruments are calibrated with only one compound, the signal represents all compounds of the mixture as an equivalent of this compound. The output signal gives no information about the qualitative composition of the mixture.

2.3 VOC separation methods

In many cases the information obtained from direct-reading instruments is insufficient because details are needed on individual organic compounds. To fulfil this need, the chemical mixture has to be separated into its constituents. Most VOC analyses of indoor air are carried out using sampling on a sorbent and subsequent separation by gas chromatography (GC). However, if special attention is paid to

specific classes of VOCs, analytical techniques other than GC may be used. As an example, aldehydes are frequently determined using high-performance liquid chromatography following derivatisation with 2,4-dinitrophenyl hydrazine. The number of GC procedures used to analyse VOCs in indoor air is large (Otson and Fellin, 1992) and no single procedure can be recommended as the only possible. In a compilation of analytical procedures for indoor air analysis (Seifert et al., 1993), examples of GC procedures including short-term and long-term sampling are given.

In the following sections, information is given on the general steps that are needed in separation procedures, and on the different ways used to generate the TVOC value from the results of the analysis.

2.3.1 General analytical steps

If separation of individual compounds is required, the complete procedure to analyse VOCs in indoor air generally includes the following steps: (a) sampling, (b) sample storage, (c) sample transfer to the analytical system, (d) separation, and (e) detection and quantification of individual VOCs. If laboratories report contradicting results this may be due to different ways of generating the TVOC value, or it may be due to differences in sampling and sample transfer techniques or in the separation step.

Sampling can be done either passively or actively. Depending on which alternative is chosen, the sampling time will differ: whereas active sampling generally extends over periods of minutes to hours, passive sampling is mostly covering hours or days, although there may be exceptions from this rule. Typically, the sorbents used for sampling are identical for the two methods.

The type of sorbent used for sampling depends on the nature of the VOC mixture studied. Primarily, porous polymers or charcoal-type sorbents are used. It should be emphasized that not all VOCs can be determined with the currently used sorbents. Comparisons of sorbents for sampling VOCs in indoor air have been made recently (De Bortoli et al., 1992; ECA, 1995; Tirkkonen et al., 1995). Tenax TA is the most often used and best evaluated sorbent for VOC sampling.

Once the VOCs are collected on the sorbent, the sample is transported to the laboratory for analysis.

The procedure for transferring the pollutants from the sorbent to the separation and identification instruments has a strong influence on the sensitivity of the overall analytical method. There are essentially two methods for the sample transfer: (i) solvent extraction of the trapped VOCs from the sorbent and injection of an aliquot of the extract into a gas chromatograph (GC) and (ii) thermal elution of adsorbed VOCs from the sorbent by means of a pure carrier gas, usually helium. In this latter case the desorbed compounds are re-concentrated in a cryotrap from which they are flash heated directly into a GC column. Using thermal elution all compounds collected from an air sample are available for one analysis. Therefore, thermal elution is the most sensitive method and most often applied.

A GC column is used to separate the collected VOCs. The proper selection of the column as well as the temperature program are crucial as they influence the number of VOCs that can be identified by retention times or subsequent mass spectrometric analysis.

To detect the individual VOCs, different instruments may be used such as an FID, an electron capture detector (ECD) or a mass spectrometer (MS). Most FID procedures that have been described in studies of VOCs in indoor air typically quantify only about 50 VOCs out of the many more present. The use of a combination of two GC columns of different polarity and/or the use of both an FID and an ECD permit a more reliable identification of a broader spectrum of individual VOCs (Mattinen et al., 1995).

Although an MS has the advantage of providing more specific information on individual VOCs, even with a GC/MS combination not usually all compounds detected in a sample can be identified, and hence, quantified.

2.3.2 *Methods without identification of individual compounds*

The result of the separation step is usually a chromatogram containing a large number of peaks. In most systems the integration of the peak areas is obtained automatically by a computer. However, as has been mentioned before, not all peaks can be identified. To obtain a TVOC value, even if individual compounds have not been identified, one approach is to combine the total area under the chromatographic curve with the response factor of one single compound, e.g. n-hexane or toluene.

In another procedure, Wallace et al. (1991) considered the variability of the response factors for different VOCs. Rather than taking one single response factor, the authors combined the area under the chromatogram with the average of the response factors of 17 target VOCs.

2.3.3 *Methods based on identification of individual compounds*

Ideally, the best way to generate a TVOC value would be first to identify all VOCs in the mixture, then to determine their amount by using their own response factor and finally to sum the masses of the individually calibrated VOCs. Although tedious, this approach has been used in practice (Krause et al., 1987). However, in most indoor situations the VOC mixture encompasses many more individual VOCs than the 54 compounds as determined by Krause and co-workers.

Taking into account that usually a certain percentage of VOCs cannot be identified, Clausen et al. (1991) have combined the "individual calibration" and the "one response factor" approaches. They defined the TVOC value as the sum of the identified VOCs plus the amount obtained by applying to the non-identified peaks in the chromatogram the response factor of toluene.

2.4 Comparison of analytical methods

Little information is available on the difference between TVOC concentrations resulting from the use of different methods. Comparing the TVOC values obtained with a PID instrument and Tenax sampling and gas chromatographic analysis, Knöppel and De Bortoli (1990) did not find a distinct correlation.

Using the chromatograms of 12 indoor air samples the differences between the results of two separation procedures were determined (Ullrich and Seifert, unpublished results). The summation of 65 individually calibrated VOCs yielded a TVOC value that, on average, was about 50% (range: 30-90%) of the TVOC value obtained using the total area together with the response factor of toluene.

Hodgson (1995) investigated the use of FID, GC/MS and photoacoustic detectors (PAS) to measure TVOC of eight different mixtures of VOCs. The FID methods demonstrated an average accuracy of 93 ± 18 percent when the measured values were calculated as concentrations of carbon. The FID and GC/MS methods demonstrated average accuracies of 77 ± 37 and 75 ± 22 percent respectively, when the measured hydrocarbon-equivalent values were compared to expected mass concentrations of the mixtures. The higher uncertainty for the FID was largely due to the low mass response of 27 percent for chlorinated compounds. The response of the PAS detector varied between 6 and 560 percent for different classes of compounds. Air samples from 10 buildings were analyzed by both the FID and GC/MS methods. The results were highly correlated and similar, with the GC/MS values approximately 20 percent higher on average.

Krüger et al. (1995) investigated the use of PAS for measurements of TVOC indoors. They found that the instrument may be applicable for this purpose but that interference with various contaminants, in particular with methane which often is present in ppm concentrations, is a disadvantage of the PAS method.

2.5 Special organic compounds in indoor air

There are organic compounds in indoor air of high relevance for IAQ which are not detected using the sampling and separation methods specified below (see section 3.2) and usually applied for VOC analysis because they are not VOCs, occur at very low concentrations and/or are reactive. Special methods are needed for their measurement. Some relevant examples are: formaldehyde, acetaldehyde, acetic acid, amines, diisocyanates, β -glucan, most polycyclic aromatic hydrocarbons and many biocides.

There are also a number of odorous VOCs that are perceived by some individuals at concentrations below the analytical detection limit which frequently is of the order of $1 \mu\text{g}/\text{m}^3$ (Devos et al., 1990). As a consequence, if such special compounds appear indoors, complaints may be justified even if the TVOC value in indoor air is found to be low.

3 TVOC - PROPOSAL FOR A NEW DEFINITION

In the following a new definition of TVOC is proposed. First the rationales on which the definition is based are briefly outlined. Following is a practical procedure implementing the new definition.

3.1 Rationales for the proposed procedure to determine TVOC

The definition of TVOC given below is based on the three following considerations.

1. The range of compounds to be included in the TVOC value has to be clearly defined.
2. TVOC should represent the total concentration of VOCs in an air sample as closely as possible. As implied from the discussion above this means that a substantial proportion of the compounds in an air sample must be identified and quantified using their respective response factors.
3. The TVOC value should be constructed in a way that favours as much as possible its usefulness in the evaluation of indoor air quality.

The considerations above are taken into account by the following requirements.

- Identification of as many compounds as possible and at least the ten most abundant compounds in a sample.
- A prescription of which compounds to include in the TVOC calculation. This includes the definition
 - of an 'analytical window' and
 - of a list of compounds representing the most important chemical classes of VOCs encountered in indoor air. (This list may also allow to introduce weighing factors for VOCs accounting for their potency to cause particular effects if such factors should become available; see also chapter 1).

3.2 Recommended procedure

Following the rationales outlined above, the following procedure is recommended for the determination of TVOC values:

1. Use Tenax TA for sampling (see section 2.3.1). Other sorbents may also be used if the same (or better) retention and elution performance as for Tenax TA can be assured.
2. Use thermal elution to transfer the collected VOCs from the sorbent to the GC column.
3. Use a well deactivated non-polar GC column for analysis (stationary phase: pure methyl-silicone or methyl silicone with addition of not more than 8 % of phenyl-silicone). The system must permit a detection limit (three times the noise level) for toluene and 2-butoxyethanol of less than $0.5 \mu\text{g}/\text{m}^3$ and $2.5 \mu\text{g}/\text{m}^3$ respectively.
4. Consider the compounds found in the part of the chromatogram from n-hexane to n-hexadecane. Note that in this procedure the WHO definition has been slightly modified by replacing the range of boiling points by the definition of an "analytical window" in terms of specific compounds.
5. Based on individual response factors, quantify as many VOCs as possible, but at least those contained in a list of known VOCs of special interest and those representing the 10 highest peaks. The list of compounds of special interest is shown in Appendix 1. Calculate S_{id} (mg/m^3), i.e. the sum of the concentrations of the identified compounds.

6. Determine S_{un} (mg/m^3), the sum of concentrations of unidentified VOCs using the response factor of toluene.
7. An acceptable level of identification has been achieved if, after steps 5 and 6, S_{id} accounts for two third of the sum $S_{id} + S_{un}$. If this sum is lower than $1 \text{ mg}/\text{m}^3$, it may be sufficient if S_{id} equals S_{un} .
8. The sum $S_{id} + S_{un}$ is defined as the TVOC concentration or TVOC value.
9. If many and/or abundant compounds are observed outside the VOC range as defined at point 4 above, a note containing this information should be added to the TVOC value.

It is important to underline that the TVOC value determined according to the above procedure does not include **all** organic compounds in indoor air. As outlined in section 2.5 above, there are organic air pollutants highly relevant for IAQ that are not reflected in the TVOC value. This is particularly true for low molecular weight aldehydes that should always be analyzed in addition to TVOC during IAQ investigations, preferably using the dinitrophenylhydrazine (DNPH) method.

3.3 Quality assurance

Quality assurance is of utmost importance to obtain meaningful results. The principles and procedures of Good Analytical Practice (GAP) should be applied in every laboratory to guarantee that analytical results are accurate in terms of both trueness and precision as defined by ISO (1994).

In practice, a high level of trueness of analytical results can be achieved by the use of reliable calibration procedures taking into account the individual recovery rates of the measured compounds, including the sampling step if possible. The use of appropriate certified reference materials is recommended for internal quality assurance (detection of systematic errors).

The precision of the analytical procedure used has to be checked and evaluated in relation to the purpose of the measurement. Precision is usually expressed as the standard deviation of the test results.

For TVOC as discussed here, every step of the analytical procedure (VOC sampling, sample storage, sample transfer, separation, identification and quantification) should be carefully checked with regard to trueness and precision. In particular, special attention should be paid to ensure that no breakthrough occurs during sampling and that the sample is quantitatively recovered from the sorbent and to guarantee that blank values (e.g. sorbent, analytical system) are low and considered in an adequate way.

Regarding the sampling strategy (sampling duration, time and frequency, position of the sampler, etc.) see ECA-IAQ (1994).

4 VOCs AND HEALTH EFFECTS: EXPOSURE - RESPONSE RELATIONSHIPS

The health effects of exposure to VOCs in the non-industrial indoor environment range from sensory irritation at low/medium levels of exposure to frank toxic effects at high exposure levels. The latter may include neurotoxic, organotoxic and carcinogenic effects. Little is known about the effects of exposure to low levels of VOCs (Berglund et al., 1992). In general, the responding tissues are mucous membranes of the eyes, nose and throat, skin on the face, neck and hands, and the upper and lower airways (Mølhave, 1991). Most effects observed under controlled conditions seem to be of an acute nature and may show adaptation (e.g. olfactory adaptation) (Clausen et al., 1985). Some effects (e.g. headache) are of sub-acute nature and tend to increase in frequency and intensity over time (Otto et al., 1990). In the following, the existing data correlating health and comfort effects with exposure to VOCs is reviewed.

Although little is known about the dose-response relationships, a threshold both for odour and for irritant effects can be assumed. For compounds that are both odorous and irritant, the odour threshold has been shown generally to be the lowest. At higher concentrations of VOCs, the prevalence of perceptual and health effects covary with the VOC concentration.

4.1 Single compounds and interactions

There are several perceptual differences between the olfactory and the trigeminal systems: (a) Perceived irritation has a longer reaction time than perceived odour, (b) it may persist for a longer time, and (c) it is more resistant to sensory adaptation. Some airborne chemicals are believed to be pure odours, whereas others are non-odorous and are suspected to be pure sensory irritants. However, it has been proposed that chemicals which have been described as pure odours are likely to stimulate the trigeminal system also, especially at high concentrations. The trigeminal response may be an inherent part of the perception of odour. It follows that there may be a mutual interaction between the olfactory and trigeminal systems.

Sensory intensity interactions have been studied using a number of approaches (for a review see e.g., Berglund, Berglund & Lindvall 1976; Berglund & Olsson, 1993). Widely different aspects of the perceptions of mixtures have been the focus of outcome measures, for example, detection thresholds, iso-intensity functions and psychophysical functions.

The most common approach is the psychophysical approach, the basic assumption of which is that the perceived intensity of pollutant mixtures is related to the concentrations of a set of pollutants. Complete addition, synergy and partial addition have been reported. However, there are interpretation difficulties due to methodological differences between the few experiments conducted, and usually the investigated combinations are too few for drawing general conclusions.

Another approach is the perceptual approach. Various models have been proposed for perceived odour intensity interactions (Berglund & Olsson, 1993). Comparison of the odour interaction models shows that the odour intensity of binary mixtures has a systematic relation to the odour intensities of the components; hypoadditivity is the prevailing rule. The odour intensity of the mixture is seldom substantially below the odour intensity of the strongest component.

4.2 Specific complex mixtures

Some experiments have been performed in which humans have been exposed in the laboratory to specific mixtures of VOCs with compositions and concentrations similar to those found in non-industrial indoor environments.

In one series of experiments, humans were exposed to concentrations of a specific mixture of 22 VOCs typically occurring in indoor air (Mølhave et al., 1986; see Table 2). These compounds are all known to

be emitted from building materials. In the experiments, where the subjects exposed were humans who previously had felt SBS-symptoms, a number of subjective reactions and neurobehavioural impairment occurred at TVOC concentrations of 25 mg/m³ and odour appeared at 5 mg/m³, which was the lowest concentration used in these experiments. The effects occurred within minutes after the start of exposure. No statistically significant adaptation was seen except for odour intensity. Some indications of physiological effects related to odour threshold, to chemical changes in eye and nose mucous, and to performance and mood were found.

Table 2. The specific mixture of 22 VOCs used in various controlled exposure studies and the concentration ratios used (Molhave et al., 1986; Otto et al., 1990; Kjergaard et al., 1991)

Compound	Ratio
n-Hexane	1
n-Nonane	1
n-Decane	1
n-Undecane	0.1
1-Octane	0.01
1-Decene	1
Cyclohexane	0.1
m-Xylene	10
Ethylbenzene	1
1,2,4-Trimethylbenzene	0.1
n-Propylbenzene	0.1
α-Pinene	1
n-Pentanal	0.1
n-Hexanal	1
Iso-propanol	0.1
n-Butanol	1
2-Butanone	0.1
3-Methyl-3-butanone	0.1
4-Methyl-2-pentanone	0.1
n-Butylacetate	10
Ethoxyethylacetate	1
1,2-Dichloroethane	1

In another study, the major aim was to measure dose-response relationships between human sensory reactions and exposure to the same specific mixture of 22 VOCs as above. (Kjergaard et al, 1991). Odour was perceived at 3 mg/m³. The air quality was reported to be unpleasant only at concentrations above 8 mg/m³ with the need for additional ventilation or removal of sources becoming evident. Also, the irritation of the mucous membranes was statistically significant only at concentrations of 8 mg/m³ or higher for an exposure period of 50 min.

In a controlled chamber study (Kjergaard et al., 1995) the reactions of 21 healthy persons were compared with a group of 14 persons suffering from the sick building syndrome (SBS subjects) when

exposed to 25 mg/m³ of the same specific mixture of 22 VOCs as above. A tendency to a stronger response was seen among the SBS subjects. Physiological measures indicated exposure-related reduction of lung function among the SBS persons. Both groups had an increased number of polymorpho-nuclear leukocytes in tear fluid as a result of exposure. This was not seen in nasal secretions.

Otto et al. (1990a; 1990b) used a series of 14 neurobehavioural tests to characterise the possible effects of the same specific mixture of 22 VOCs as above in young healthy men. Most subjects showed adverse subjective reactions at 25 mg/m³. As in the case of Mølhave's earlier experiments, ratings of general discomfort (defined as irritation of the eyes, nose and throat) as well as symptom questionnaire responses on odour intensity, air quality, eye and throat irritation, headache and drowsiness and mood scale measures of fatigue and confusion all differed in predicted directions between clean air and VOC exposure conditions. However, no convincing evidence was found of any neurobehavioural disturbances associated with exposure to the VOC mixture.

4.3 Complex mixtures from materials and buildings

Various attempts have been made to base the risk assessment of complex mixtures of air pollutants either on similarity with respect to the evoked effects (see e.g. Nielsen et al., 1995; ECA-IAQ, 1997), or on similarity with respect to the chemical structure of the pollutants (HSE, 1995).

A sufficiently high total concentration of any complex mixture of VOCs is likely to evoke sensory irritation among the majority of those exposed to the mixture. Likewise, a sufficiently low total concentration of the same mixture is unlikely to give the same effect among the majority. These concentrations probably are different for different complex mixtures. Presently, no data exist which can be used to assign exact values for the two probability levels.

In cross-sectional epidemiological studies associations have been found between ventilation characteristics and pollution sources potentially emitting VOCs, such as photocopying machines, handling papers, humidifiers, etc. (Sundell, 1994). Since ventilation characteristics are reported to be associated with occupant symptom reports (Sundell et al., 1994), pollutant concentration seems to be important as a risk factor for the occurrence of such symptoms. Studies have also shown that the acceptability of indoor air increases with increasing air flow rates (Yaglou et al., 1936; Fanger et al., 1988), which is most likely mainly due to a decrease in concentrations of odorous VOCs.

Despite a large number of field studies using a variety of measurement and analytical techniques, no consistent associations have been shown between measures of TVOC and discomfort or health effects. While in some instances, epidemiological studies have reported positive associations between concentrations of TVOC and symptom reports (Norbäck, 1990; Norbäck et al., 1990; Lundin, 1991; Hodgson et al., 1991; Hodgson et al., 1992), other studies revealed no such association (Skov et al., 1990; Nagda et al., 1991) or even a negative association (De Bortoli et al., 1990; Sverdrup et al., 1990; Nelson et al., 1991; Stridh et al., 1993; Sundell et al., 1993). In a sole longitudinal study of a building where the composition of the VOC mixture can be expected to vary less than in comparisons between buildings, a high positive correlation between TVOC and symptom reports was found (Berglund et al., 1989).

The main interest in indoor VOCs has been directed towards source strength, dilution, dispersion, sorption and deposition, but not on chemical transformation of VOCs (Otson and Fellin, 1992). Recent studies suggest the presence of a complex indoor air chemistry, possibly resulting in pollutants that are neither sampled nor analysed with the methods commonly used (Weschler et al., 1992a, 1992b; Wolkoff et al., 1992; Sundell et al., 1993; Zhang and Liou, 1994). The indoor chemistry may involve, among other, reactions between ozone, free radicals and VOCs yielding, for example, aldehydes and organic acids. The inconsistent association in epidemiological studies between TVOC levels and SBS symptoms

may be explained by the formation in some of the indoor environments studied of compounds other than the VOCs typically measured, but experimental evidence for this theory is still lacking. There are also theories that occupants respond to differences in VOC patterns rather than to the changing concentration of a mixture with a constant composition (Berglund et al., 1982; Noma et al., 1988).

4.4 Previous approaches for evaluation

Two possible approaches for deriving indoor air quality guidelines for VOCs (excluding formaldehyde and carcinogenic VOCs) have been proposed (Mølhave 1990; Seifert, 1990). Both use the term TVOC but adopting different definitions.

The approach used by Mølhave (1990) is generalised from the information on effects published in indoor air pollution literature. Mølhave suggested four exposure ranges of increasing concern (measured by GC techniques and a flame ionisation detector calibrated against toluene): a comfort range ($< 0.2 \text{ mg/m}^3$), a multifactorial exposure range ($0.2\text{--}3 \text{ mg/m}^3$), a discomfort range ($3\text{--}25 \text{ mg/m}^3$), and a toxic range ($> 25 \text{ mg/m}^3$).

In the approach suggested by Seifert (1990), empirical data from a field study in German homes have been used to estimate an upper concentration of TVOC which is not normally exceeded. Based on his empirical data Seifert advocates that $300 \text{ } \mu\text{g/m}^3$ of TVOC (the average value of the study) seems to be readily achievable in German homes and should not be exceeded. If this TVOC concentration was apportioned to different chemical classes, then the following concentrations resulted: $100 \text{ } \mu\text{g/m}^3$ for alkanes, $50 \text{ } \mu\text{g/m}^3$ for aromatics, $30 \text{ } \mu\text{g/m}^3$ for terpenes, $30 \text{ } \mu\text{g/m}^3$ for halocarbons, $20 \text{ } \mu\text{g/m}^3$ for esters, $20 \text{ } \mu\text{g/m}^3$ for carbonyls (excluding formaldehyde) and $50 \text{ } \mu\text{g/m}^3$ for "other". Furthermore, Seifert proposes that no individual compound should exceed 50% of the average value of its class or exceed 10% of the measured TVOC value. The values are not based on toxicological considerations, but on a judgement about what levels are reasonably achievable.

5 USES OF TVOC AS AN INDICATOR

The TVOC entity may be used for a number of applications. Examples of such applications are:

Testing of materials. When testing materials for emission of chemicals, TVOC may be used for categorising or screening the materials, except for substances that should not be found in the air at any concentration (see also ECA-IAQ, 1997). No health or comfort evaluation can be made based on emission rates. Rather, health and comfort evaluations must be based on exposure to concentrations in a given space. In order to calculate the steady-state concentrations in a given space, the amount of the source (material) and the quantity and quality of the supply air to the space (ventilation) must be known in addition to the emission rate or factor. In the absence of IAQ guideline values for most VOCs found in indoor air, the principle of ALARA (as low as reasonably achievable) provides a sensible procedure.

Indicator of insufficient or poorly designed ventilation. The concentration of any pollutant in a space is a balance between the net emission in the space and what is removed and supplied by the ventilation. If high TVOC concentrations occur in a building, this may either indicate that there are strong indoor or outdoor sources or, if this is not the case, that general or local ventilation is inadequate. In the first case, source control measures should be taken. In the second case or if source control cannot be applied, ventilation has to be improved. In these cases TVOC has the same function as CO₂ for human occupancy. In addition, TVOC (or more likely "total hydrocarbon" measured by a direct reading instrument) may be used to detect poor ventilation efficiency. This is done by measuring the concentrations at different positions in a space and comparing the relative variations in concentrations with that expected from the type of ventilation in use (e.g. displacement ventilation or fully mixed ventilation).

Identification of high polluting activities. If measured with an instrument with sufficiently high time resolution, TVOC (or "total hydrocarbon" measured with a direct reading instrument) may be used to identify high emitting processes such as working with some old type correction fluids by comparing concentration variations with the activity pattern.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

6.1.1 General aspects

Identification and quantification of all individual VOCs occurring in indoor air is difficult if not impossible. In addition, the reporting of all the individual data is cumbersome if a large number of samples has to be analyzed for many VOCs. For these reasons a simplified way of expressing the results of VOC measurements has been adopted by many researchers, namely the TVOC entity. TVOC has been used both for reporting exposures, that is, as indicator of air quality, and as a predictor of the probability of health and comfort effects.

The WHO definition of VOCs refers to the behaviour of the compounds in traditional analytical procedures and not to their possibility through environmental exposures to cause discomfort and health effects. Also, some organic compounds outside the VOC range as defined by WHO may contribute to the relevant sensory effects.

Different authors have used different procedures for chemical analysis and integration of individual VOCs. Therefore, at present the reported TVOC values in the literature are mostly not comparable. To increase comparability, TVOC must be defined clearly. Such a definition is given in section 3.2. This pragmatic procedure is based on identifying pre-selected and/or abundant VOCs within a specified analytical window. The concentrations of the identified VOCs and the sum of the concentrations of non-identified compounds in toluene equivalents are added to give the TVOC value.

A relationship is expected to exist between exposure to any given VOC mixture in air and health effects and discomfort. However, these relationships, of which the exact forms are mostly unknown, are expected to be complex and much affected by other factors than the total amount of VOCs present.

Therefore, mass addition will not be the model which best reflects the biological principles involved neither for the sensory effects considered nor for discomfort and other health effects. However, better models, e.g. weighing concentrations of individual VOCs with factors expressing their biological activity (see chapter 1), may be established in the future.

6.1.2 For what can TVOC be used?

The group considers that, although TVOC is a crude way of describing the occurrence of VOCs in indoor air, it may still be useful if measured in the proposed way. The TVOC assessment procedure may start with a simple integrating detector reporting the concentration in toluene equivalents and be followed by more detailed analyses in which individual compounds are identified and quantified. The use of simple integrating instruments (e.g. FID or PID) for assessing TVOC should be restricted to situations where many samples of slightly varying composition (e.g. from the same source) are compared and where an adequate correlation between the TVOC indicator values based on the simple measures and those obtained with the recommended procedure has once been established for this specific purpose. If the value obtained with a simple integrating detector is above 0.3 mg/m^3 , detailed analysis should be made using the recommended procedure.

If one suspects that there are other compounds present which will not be quantified with sufficient sensitivity using the suggested GC/MS procedure alternative analytical procedures must be added. For IAQ investigations, in particular the additional measurement of low molecular weight aldehydes is recommended.

Most reported TVOC-concentrations in non-industrial environments are below 1 mg/m³ and few exceed 25 mg/m³. At these concentration levels only sensory effects are likely to occur, but other health effects can not be excluded after long term exposure. The sensory effects include sensory irritation, dryness, weak inflammatory irritation in eyes, nose, air ways and skin. At TVOC concentrations above 25 mg/m³, the likelihood of other types of health effects becomes of greater concern.

Based on theoretical considerations and experience from industrial occupational health, it can be argued that a sufficiently high total concentration of any complex mixture of VOCs is likely to evoke odour as well as sensory irritation among the majority of those exposed. However, in view of the fact that the controlled human exposure studies are few and the results are not confirmed, and that the results of epidemiological studies are inconsistent, it is today not possible to conclude that sensory irritation is associated with the sum of mass concentrations of VOCs at the low exposure levels typically encountered in non-industrial indoor air. Thus, at present, no precise guidance can be given on which levels of TVOC are of concern from a health and comfort point of view, and the magnitude of protection margins needed cannot be estimated.

The general need for improved source control to diminish the pollution load on the indoor environments from health, comfort, energy efficiency and sustainability points of view leads to the recommendation that VOC levels in indoor air should be kept as low as reasonably achievable (ALARA). Such an ALARA-principle will require that indoor environments, unless there are very good and explicit reasons, should not exceed the typical TVOC levels encountered in the building stock of today, when determined with the proposed procedure on representative samples of buildings and spaces.

TVOC, or other measures of volatile organic compounds, may be used for a number of other applications. Examples are: Testing of materials, indication of insufficient or poorly designed ventilation in a building, and identification of high polluting activities.

6.1.3 How the TVOC indicator should not be used

The main purpose of the TVOC indicator is to get a simple measure of the joint exposures to several VOCs in indoor air. The indicator should refer to a standardised analytical procedure. The group does not recommend the use of the term TVOC for summations based on identification and quantification only of a selected group of target compounds.

No documented background exists for the use of the TVOC indicator in relation to health and discomfort other than sensory irritation (e.g. not for cancer, allergy, and neurological effects). Even when assessed as described in the present report, TVOC can not be used as a surrogate for the intensity or acceptability of any effects.

It cannot be excluded that specific VOCs may turn out in the future to be much more potent in causing effects on humans than the average VOCs. In that case they should be evaluated individually, and a list of such compounds should be established.

The TVOC value must be used with caution in all cases, especially in non-industrial indoor environments where environmental factors such as temperature, humidity, noise, etc. are outside normal ranges.

6.2 Future research

6.2.1 Analytical procedures

The correlation of TVOC measures obtained with different measuring techniques should be studied in more depth using a variety of mixtures. Especially the correlation between TVOC as defined here and

direct integrating instruments should be investigated in more detail. The optimal set of separation columns and analytical procedures for measuring TVOC should be established. Since more information about exposure distributions is needed, less complicated and expensive methods should be developed. A first step would be to provide an automated analytical procedure for the determination of the TVOC value as proposed in this report.

6.2.2 *Health and comfort data*

More information about exposure-effect relationships are needed for a range of VOC mixtures. Specifically, the relation between TVOC, odours and sensory irritation should be investigated for different mixtures of VOCs. The development of effect related indicators of VOC exposure should be strengthened.

Carefully designed epidemiological studies are required to clarify the role of VOCs for health and comfort of building occupants.

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Chapter 5

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APPENDICES

Appendix 1: Minimum number of compounds to include in TVOC analysis

Chemical Compound	Cas No.	Boiling Point [°C]
AROMATIC HYDROCARBONS		
Benzene	71-43-2	80.1
Toluene	108-88-3	111
Ethylbenzene	100-41-4	136.2
m/p-Xylene	108-38-3 / 106-42-3	139.1 / 138.3
o-Xylene	95-47-6	144
n-propylbenzene	103-65-1	159
1,2,4-Trimethylbenzene	95-63-6	169.4
1,3,5-Trimethylbenzene	108-67-8	165
2-Ethyltoluene	611-14-3	165.2
Styrene	100-42-5	145.2
Naphtalene	91-20-3	218
4-Phenylcyclohexene	31017-40-0	251-3 ¹⁾
¹⁾ value of 1-phenyl-cyclohexene		
ALIPHATIC HYDROCARBONS		
n-C6 to n-C16		
n-Hexane	110-54-3	69
n-Heptane	142-82-5	98.4
n-Octane	111-65-9	125.7
n-Nonane	111-84-2	150.8
n-Decane	124-18-5	174.1
n-Undecane	1120-21-4	196
n-Dodecane	112-40-3	216.3
n-Tridecane	629-50-5	235.4
n-Tetradecan	64036-86-3	253.7
n-Pentadecane	629-62-9	270.6
n-Hexadecane	544-76-3	287
2-Methylpentane	107-83-5	60.3
3-Methylpentane	96-14-0	63.3
1-Octene	111-66-0	121.3
1-Decene	872-05-9	170.5

Chemical Compound	Cas No.	Boiling Point [°C]
CYCLOALKANES		
Methylcyclopentane	96-37-7	71.8
Cyclohexane	100-82-7	81
Methylcyclohexane	108-87-2	101
TERPENES		
3-Carene	13466-78-9	167
alpha-Pinene	80-56-8	156
beta-Pinene	181172-67-3	164
Limonene	138-86-3	170
ALCOHOLS		
2-Propanol	67-63-0	82.4
1-Butanol	71-36-3	118
2-Ethyl-1-hexanol	104-76-7	182
GLYCOLS/GLYCOETHERS		
2-Methoxyethanol	109-86-4	124-25
2-Ethoxyethanol	110-80-5	135
2-Butoxyethanol	111-76-2	171
1-Methoxy-2-propanol	107-98-2	118
2-Butoxyethoxyethanol	112-34-5	231
ALDEHYDES		
Butanal	123-72-8	76
Pentanal	110-62-3	103
Hexanal	66-25-1	129
Nonanal	124-19-6	190-2
Benzaldehyde	100-52-7	179
KETONES		
Methylethylketone	78-93-3	80
Methylisobutylketone	108-10-1	116.8
Cyclohexanone	108-94-1	155.6
Acetophenone	98-86-2	202

Chemical Compound	Cas No.	Boiling Point [°C]
HALOCARBONS		
Trichloroethene	79-01-6	87
Tetrachloroethene	127-18-4	121
1,1,1-Trichloroethane	71-55-6	74.1
1,4-Dichlorobenzene	106-46-7	173
ACIDS		
Hexanoic acid	142-62-1	202-3
ESTERS		
Ethylacetate	141-78-6	77
Butylacetate	123-86-4	126.5
Isopropylacetate	108-21-4	85
2-Ethoxyethylacetate	111-15-9	156.4
TXIB (Texanolisobutyrate)	6846-50-0	
OTHER		
2-Pentylfuran	3777-69-3	>120 (2-tert-butylfuran)
THF (Tetrahydrofuran)	109-99-9	67

Appendix 2: Indicators and their use

Introduction

Sometimes the mere presence or absence of an odour and/or a sensation of irritation determines human response to air quality, any other physical parameter being largely irrelevant. In such cases, chemical measurements can be useful in determining the cost-effective means of exposure control. Nevertheless, from a theoretical point of view, there can be little point in attempting to develop any complex chemical correlate (e.g. TVOC) to other effects than sensory effects or more complex cognitive evaluations. As emphasised in chapter 3 of the present report, the relationship between TVOC exposure in the field and observed effects is quite weak (if any), and there are commonly many other factors, some unknown, that contribute to the observed effects. In addition, there will often be a high degree of intercorrelation between candidate alternative environmental measures. Complex measures have typically been developed on the basis of laboratory research which cannot be properly validated in the field because of the lack of precise experimental control. Different complex environmental measures often cannot be differentiated in terms of their ability to predict a human response.

The perceived intensity of any given odorant or irritant increases as the concentration of the chemical increases but different chemicals with the same concentration will not have the same perceived intensity. In addition, other non-chemical factors often contribute to the final effect of chemical exposure.

Most chemical exposures vary over time. Averages of concentration often conceal the pattern of variation over time which may be important in predicting sensory response. It is important to distinguish between very-short term fluctuations in chemical concentrations over periods of seconds, medium-term fluctuations over periods of up to an hour, and daily and weekly fluctuations.

The underlying philosophy of various procedures for assessing perceived odour and irritation may include a distinction between perceived strength, perceived quality and (perceived) discomfort as separate distinguishable perceptual attributes. Whereas perceived strength and perceived quality to a large extent are sensory in nature, discomfort depends also on psychological factors not associated with physical-chemical factors. Thus, perceived odour and perceived quality of odorous irritants may possibly be predicted mainly from physical-chemical characteristics of exposures. This is particularly true for perceived strength and concentration for single substances and invariant mixtures.

Use of indicators

A phenomenon (e.g., IAQ) may be studied by measurement of several physical-chemical properties (e.g. air temperature, air humidity, VOCs, particles). For this, a measuring instrument is needed. Ideally, the instrument should be based on a physical mechanism (e.g., thermal expansion of mercury) allowing the quantity to be expressed in terms of a magnitude (e.g. volume increase of mercury). Thus measurement requires a reference magnitude and an accepted measurement rule (e.g. the Celsius thermometer). The measured magnitude should be expressed in a defined and calibrated unit of measurement.

Indicators are substitutes for measures. Usually indicators are used when suitable measures cannot be obtained. The basic requirements of an indicator are that it bears a relation to the underlying effects and mechanisms and is convenient to use, especially when no measure of the effect itself can be made (see Stevens, 1951). The construction of indicators is usually based on requirements for simplicity, economy and lack of technical possibilities for measurement (laboratory measurements not possible in the field). An indicator can be a simple measure of one marker pollutant (e.g. CO₂ for indoor air quality; hydrogen sulphide for pulp mill exhaust; coli count for microbiological contamination). It can also be a combination measure such as the arithmetic sum of several marker pollutants (outdoor air pollution indices), a complex equation of a defined set of pollutants, or a model for combining these (e.g. total hydrocarbons in outdoor air). The distinction between measures and indicators disappears when the

quantitative relation between the indicator and the effect of interest is known. The indicator can then be calibrated and used as a substitute measure with adequate validity (and convenience). Candidate variables do not per se have to have a casual connection to a (biological, physical, chemical etc.) process of interest. However, if the indicator is backed by a reasonable explanation, it becomes a much stronger predictive tool for assessing effects.

A wide range of parameters may be used to indicate exposure levels and their potential health and comfort consequences. TVOC has been suggested as such an indicator of chemical indoor air exposures. It has also been suggested as an indicator of effects on humans such as BRI or SBS, especially with a focus on sensory effects. In both cases the quality of the indicators depends on the degree of association between the indicator and either the exposure or the target response variable.

This association between the indicator and the variable it is indicating may only be of an acceptable quality within a limited range of variations and under certain conditions, depending on the confounding variables affecting the underlying physical or biological mechanisms. The acceptable quality relates primarily to the extent to which the relationship can be approximated with a monotonic function between the indicator and the variable or construct for which it is an indicator. Other important factors are thus the level of measurement obtained and the resolution that is possible to infer on the scale emanating from the indicator.

Associations, correlations and causality

An association indicates only that some type of covariation exists between two variables. Correlation usually refers to a statistically measurable association between the two variables. It reflects the amount of shared variance between two variables but does not mean that there is a causality between the two. Causality is defined as an explainable reason why a state is being changed. According to Henle-Kock (Mølhav, 1992) the criteria for causation are the following.

1. The number of affected persons in a population (prevalence) showing that the effect is significantly higher among the subjects exposed to the supposed cause than among controls not so exposed.
2. Exposure to the supposed cause should be present more commonly among those showing the effect than among controls without symptoms or signs when all other risk factors are held constant.
3. The number of new cases in a specified population (incidence) must be significantly higher among those exposed than among the non-exposed in prospective studies.
4. Temporally, the effect should follow the exposure with a normally distributed delay.
5. The spectrum of symptoms and signs related to the effect should follow exposure in a logical progression from mild symptoms to severe signs of health effects.
6. A measurable response following exposure to the supposed cause should regularly appear among those lacking such an exposure or should increase in intensity if present before the exposure. This pattern should not occur in persons not so exposed.
7. Experimental reproduction of the effect should occur in higher incidence in persons exposed than in those not exposed.
8. Elimination, prevention, or modifications of the exposure should decrease the incidence.
9. The whole thing should make biological sense.

An indicator does not per definition fulfil the requirements for establishing a causal relationship. However, according to the Henle-Kock Criteria, some indicators will support such conclusions on causality.

Probability models for exposure and effect

Predictions are forecasts of the future. For predicting the outcome of complex physical systems with many variables, such as using TVOC for prediction of IAQ, models are needed. Models formalise relationships between attributes and/or variables. The nature of the models can build on statistical relation, on classification according to some rule, or on quantitative mathematical equations. In practice, models may be developed from knowledge of biological or other mechanisms, probabilities of concurrent events, and from theoretical constructs.

Indoor air quality could be viewed as a theoretical exposure-construct including variables such as chemical contaminants, carbon dioxide, air humidity and particulate matter. Alternatively, perceived indoor air quality may be viewed as a theoretical effect-construct including the same variables but restricting them to fit the range within which they are perceived. In both cases, a mathematical equation can be constructed to describe the indoor air quality, or alternatively, the perceived indoor air quality.

Before accepting such an equation as a good model, the outcome has to be validated against an independent criterion variable. In order to use a TVOC model as a predictor of sensory irritation of indoor air, it has to be shown that an increase in TVOC concentration will be associated with an increase in sensory irritation. The association can be based on rank order, interval or ratio scales. Certain requirements have to be fulfilled for a predictive model to be effective. The predictor variable should cover a wide range of values combined with a sufficient resolution, and thus provide sufficient precision for its intended use. The simplest model is classification. In many practical instances such a model is sufficient, for example by classifying a chemical contaminant as mainly indoor-generated or outdoor-generated by comparing indoor and outdoor relative concentrations. A third class in such a classification is to distinguish between activity-related and other compounds estimated from time course patterns inside a building.

Measurement

In physical-chemical surveys of the indoor climate in buildings, it is imperative that the purpose of the survey includes a specification of the "measurement form" in which the results have to appear. There is a difference between (a) measuring a physical or psychological variable and (b) estimating the risk of an outcome. Social scientists usually focus on the former type of data whereas the health epidemiologists focus on risk estimation (probability of an event).

The measurement concept refers to a system of measuring methods and of measures as such; the act of measuring is often performed by comparison with a standard. Measurement scales may be characterised with regard to level of measurement, which will put restrictions on potential data analysis (e.g. Torgerson, 1958). The most common data are in the form of a nominal scale (presence/no presence of an occurrence or a set of qualitatively different classes). Sometimes the responses are assessed on ordinal (rank order), interval (distance is constant, relative to a zero-point), or ratio scales (ratios are constant, absolute zero-point). Physical-chemical measurements are usually interval or ratio scales in contrast to questionnaire data based on self reports that are commonly made on nominal or ordinal scales. The causal relationships sought between SBS and the physical-chemical variables may pertain to rank order causations.

Calibration

The procedure for calibration is linked to the level of measurement. Calibrations of scales are performed to rectify the grading of quantitative measurements obtained. Calibration procedures are imperative in chemical and physical measurements but are relatively new to psychological scales in environmental questionnaires (Berglund et al., 1976). Instead, to obtain comparability between scales in behavioural science, the practice has been to standardise scales by transforming the empirical response distributions to a standard distribution of z scores (e.g. Lord and Norvick, 1968) rather than to calibrate the scale as such.

Quality assurance

The reliability of a measurement refers to how well it measures the variable in question. The reliability is usually expressed as a reliability coefficient which is the proportion of obtained variance that is due to true variance in the variables. A number of practical methods for determining reliability are used:

- test-retest method, i.e., the same measuring instrument is applied on two independent trial occasions to the same sample of individuals;
- parallel-forms method, i.e., equivalent test versions administered to the same object at the same time;
- split-half method, i.e., the test may in some fashion be divided into two halves and two scores obtained from the same sample;
- internal-consistency methods, i.e., the method requires a knowledge of certain test-item statistics, for example, regarding dichotomous scoring.

The validity of the measurement refers to how well it measures what it is intended to measure. There are several kinds of validity. Empirical validity is defined as the degree of association between the measurement and some other observable measurement, for example eye irritation reports from a questionnaire and clinically diagnosed eye irritation (Franck and Skov, 1991). Validity is often expressed as a linear relationship between observable quantities expressed as a correlation.

The principles of quality assurance have been discussed by the World Health Organization (WHO, 1983) with regard to public health and the scientific community. This concept refers to all the steps that should be taken by the researcher to ensure that the findings are of good quality; quality assurance is accomplished by adequate self-evaluative and self-corrective strategies. Thus, quality assurance covers the use of scientifically and technically sound practices for the collection, transport and storage of samples, the laboratory analysis, as well as the recording, reporting, and interpretation of results.

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Appendix 3: Effect measures in relation to TVOC

Sensory effects and exposure to VOC's

Sensory effects are defined within the context of this report as the perceptual response to environmental exposures. Sensory perceptions are mediated through the sensory systems. These systems all contain various receptors, from which signals are transmitted to higher levels of the CNS where the message results in a conscious experience of smell, touch, itching etc.

Sensory effects are important parameters in indoor air quality control for several reasons. They may appear as:

- adverse health effects on sensory systems (e.g., environmentally-induced sensory dysfunctions);
- adverse environmental perceptions which may be adverse per se or constitute precursors of disease to come on a long term basis (e.g., annoyance reactions, triggering of hypersensitivity reactions);
- sensory warnings of exposure to harmful environmental factors (e.g., odour of toxic sulphides, mucous irritation due to formaldehyde);
- important tools in sensory bioassays for environmental characterisation (e.g., using the odour criterion for general ventilation requirements or for screening building materials to find those with low emissions of VOCs).

In the indoor environment, two main classes of sensory perception can be identified. Both classes include perceptions which are adverse or non-adverse. The first class includes perceptions attributed to the surrounding physical environment (environmental perception), for example perceptions of draft and odour. The second class includes perceptions of events inside the body or on the body surface (body perceptions). The body perceptions, for example, perceived eye irritation or dry skin, may or may not be attributed causally to the surrounding physical environment. The senses responding to environmental exposure are not only hearing, vision, olfaction and taste, but also senses located in the skin and mucous membranes (touch, warm, cold, pain and the systems that mediate sensory irritation). As pointed out by the WHO (1989), many different sensory systems that respond to irritants have receptors situated on or near the body surface. Some of these systems tend to facilitate the response rather than adapt and their reactions may also be delayed. Conversely, in the case of odour perception, the reaction is immediate but also influenced by olfactory adaptation upon prolonged exposures. In general, the sensory systems are tuned towards registering environmental changes rather than the absolute levels (Berglund, 1991).

Human beings are often unable to identify a single sensory system as the primary route of sensory irritation by airborne chemical compounds. The sensation of irritation is influenced by a number of factors such as previous exposures, skin and mucus temperature, competing sensory stimulation, etc. Since summation (spatial and temporal), interaction and adaptation processes are characteristic of sensory systems involved in the perception of odour and mucosal irritation, the duration of exposure will significantly influence the perception.

Human beings synthesise different environmental signals in their evaluation of complex concepts such as perceived air quality and their assessment of comfort or discomfort. By definition, comfort and discomfort are influenced by more complex psychological factors and for this reason the related symptoms, even when severe, cannot be documented without perceptual assessments. The same is of course true for environmental perceptions.

Sensory effects reported to be associated with indoor air contaminants are in most cases multi-sensory and the same perceptions may originate from different sources. It is not known how different sensory perceptions are combined into perceived comfort and perceived air quality. Perceived air quality is, for example, mainly associated with stimulation of both the nerves, trigeminus and olfactorius. Many odorous compounds are also significant mucosal irritants, especially at high concentrations. The olfactory system signals the presence of odorous compounds in the air and has an important role as a warning system for harmful exposure. In the absence of instrumentation for chemical detection of small amounts of some odorous vapours, the sense of smell remains the only sensitive detector system. There are large differences in sensory sensitivity between individuals as demonstrated for example, for vision, hearing and olfaction. Recent experiments have shown that the interindividual variation is even larger for sensory irritation (Berglund and Shams Esfandabad, 1993). The sensitivity is known to decrease with ageing in most individuals.

Methods for assessment of sensory effects

Sensory effects such as odour and mucosal irritation constitutes perceptions and, therefore, by definition are subjective in nature. The assessment of such perceptual aspects of sensory stimulation must involve human reports. Since the olfactory system adapts during prolonged exposure, olfactory measurement should always include a control for this adaptation. A consequence of olfactory adaptation is that two different responses to indoor air may be identified: that of the visitor and that of the occupant. A WHO expert group has recommended that odours should be measured through the immediate response of the un-adapted olfactory system (visitor situations) (WHO, 1989). It should be noted that odour intensity measured by visitors does not necessarily correlate with the perceptions reported by the occupants who will have adapted to the odorous content of the air. Sensory irritation may be measured with the same psychophysical methods as odour perception.

A number of indicators or substitute measures have been tried for predicting the mucosal irritation potency of chemicals. For example, the concentration TVOC has been suggested as a possible indicator of the overall perceived indoor air quality (Mølhave and Nielsen, 1992). Also QSAR-procedures have been suggested (Abraham et al, 1996).

A variety of psychophysical methods have been developed by which various aspects of perceptions may be measured (e.g., Torgerson, 1958; Baird and Noma, 1978). Depending on what phenomenon or attribute is to be measured, these methods may in principle be divided into three main classes: (a) methods for measuring detectability, e.g. thresholds, (b) methods for measuring supraliminal intensities, and (c) methods for classification or scaling of perceived qualities.

The methods for measuring absolute detection thresholds as well as discrimination thresholds (difference limens) were already developed by Gustav T. Fechner in the past century. These methods are based on statistical principles and are still used today. Examples are the method of limits, the method of constant stimulus, and the method of adjustment. In the former two, stimulus series are presented to subjects in systematic and random order, respectively, and the subject is to respond if, for example, an odour is detected or not. The method of adjustment requires an equipment by which the subject may vary the magnitude of another stimulus such that they are perceived to be equal. In all these methods, the absolute (or discrimination) thresholds are expressed in physical quantities, such as the concentration of an odorant or a sensory irritant. More recent theories on detectability claims that there is no such thing as a threshold. The Theory of Signal Detectability (TSD, Green and Swets, 1962) and the Choice Theory (Luce, 1963) both claim that the subjects' response criteria will vary with individuals and the task and, consequently, they advice procedures by which the response criterion, which is viewed as a bias, may be adjusted such that a pure sensitivity index is obtained (e.g., d' of TSD).

Perceived intensities as well as magnitudes of hedonic variables, such as unpleasantness, comfort or discomfort may be measured with three types of methods: (a) equal-intensity matching methods,

including cross-modal matching methods, (b) magnitude production methods, and (c) magnitude estimation or category scaling methods. The two former methods (a and b) both require equipment by which the matching attribute of interest may be changed quantitatively by the subject. Since it is difficult to provide such instrumentation for varying evaluative attributes such as comfort and discomfort, the procedures of category scaling and magnitude estimation are more useful and also convenient in field settings. By these methods, the magnitudes are expressed in numbers, either in fixed categories (category scaling) or in freely chosen number (magnitude estimation). Recently, these procedures have been developed in such a way that the resulting perceptual scales may be calibrated, for example, in the procedure named Master Scaling (Berglund and Lindvall, 1979; Berglund, 1990).

Perceived qualities may be measured by classification or multidimensional scaling. Although such methods have been popular in many areas of product manufacturing (e.g., food industry), their applications have been sparse in the field of indoor air quality. However, some of the computer programs developed for these methods are identical with the methods used in mathematical pattern recognition. Examples of such applications are reported in Berglund et al. (1982) who found that odour intensity patterns and chemical concentration patterns of air samples collected indoors and outdoors classify air samples according to different principles. Whereas the sensory system does not differentiate outdoor air samples from indoor air samples, the chemical system does. Thus, the outdoor VOCs will influence the odour of indoor air to a substantial degree.

The questionnaire survey is often adopted in indoor air studies. Several of the perceptual scaling methods are utilised in questionnaires for obtaining the reports of the respondents. The most popular scales are constructed from yes/no questions (e.g., prevalence of symptoms) and from category scales (e.g., response categories marked with words or numbers of increasing quantity).

Individuals, panels and populations do differ in sensory sensitivity, response behaviour and value judgements. Some of these differences are environmentally induced. Therefore, it is most important to specify the target groups for indoor air quality control based on whom the sensory effects should be measured and how they relate to large population groups. For sensory irritation it is also important to consider if persons with allergy or hypersensitivity should be included or not.

Neurotoxic and behavioural effects

It is well known that environmental pollution can affect the nervous system. The effects of occupational exposure to organic solvents can be mentioned as an example. A wide spectrum of effects may be of importance, ranging from those at molecular level to behavioral dysfunctions.

Since the nerve cells of the CNS typically do not regenerate, toxic damage to them is usually irreversible. The nerve cells are highly vulnerable to any depletion in oxygen supply. The risk of accumulation of hazardous compounds within the CNS is higher than for most other body tissues since the nerve cells are slow in metabolising intruding chemicals (Duffus, 1996). Many solvents affect the nerve cells or the transmission of nerve signals, e.g., by inducing narcotic effects.

Methods for assessment of neurotoxic and behavioural effects

Methods for assessing neurotoxicity in animal and human studies include a number of neurophysiological and behavioural diagnostic techniques designed to study selected central or peripheral nervous functions. Examples of neurobehavioural tests are reaction time, memory, manual dexterity, etc., and examples of electrophysiological techniques are measurements of visual or auditory evoked potentials, nerve conduction velocity, etc. These tests are increasingly being used because of their non-invasive nature. Neurobehavioural tests can be used in experimental laboratory settings as well as in epidemiological studies. However, the attribution of abnormal results to acute reversible dysfunctions or to irreversible brain lesions may be dubious.

Effects of VOC's on the skin and mucous membranes in the eyes, nose and throat

Exposure of the skin or mucous membranes to indoor air pollutants may cause effects on the sensory system and may result in tissue changes. Each of these may subsequently lead to the other. Two types of sensory irritation, therefore, appear in the literature on indoor air quality and climate: a primary sensory irritation caused by direct stimulation of sensory cells by environmental exposures and a secondary irritation following tissue changes of the skin and mucous membranes.

Inflammation is characterised by a sensation of heat, redness, swelling, pain and a certain loss of function as well as sensitisation in the tissues affected. Irritative effects in the tissues can cause a considerable annoyance both in terms of severity of effects on an individual and in terms of the number of persons affected. Symptoms and signs of effects on skin and mucous membranes may appear at the site of contact on the exposed skin, mucosa etc., or manifest themselves in other tissues due to reflexes. Irritative effects causing tissue changes in the skin and mucous membranes have been reported in many forms, although they have seldom been seen to follow exposure to indoor air in non-industrial buildings. The symptoms and signs are often non-specific and each may be caused by many different exposure factors (Mølhave, 1991; Berglund et al., 1992). The most frequent effects related to indoor air quality seem to be acute physiological or sensory reactions, psychological reactions and sub-acute changes in sensitivity to environmental exposures. Many VOCs are mucous membrane irritants and have been implicated as a cause of SBS. Studies of the acute effects of VOCs indicate that concentrations of VOCs found in new buildings may cause irritative tissue changes in the eyes (Kjærgaard, 1992).

The intensity of symptoms associated with irritative effects may vary due to interactions with other factors of the exposure. Air temperature and humidity have been demonstrated to influence the level of eye and nose irritation experienced by nonsmokers exposed to ETS. Altered mucosal clearance is known from exposure to NO₂ or particulate matter. Irritation due to agents such as biological contaminants, or due to other factors, have not been described in the literature to reach a level where a conclusion may be drawn.

Methods for physiological assessment of irritative effects

The possible effects of indoor air pollutants on the skin and mucous membranes can be measured at high exposure concentrations. The available methods have strongly varying sensitivity and specificity. Most physiological methods have not yet been documented to work at exposure levels relevant to the non-industrial indoor environment and there is a general need for development and validation of such methods. Physiological measurements of irritation of the eyes are at present the most promising.

Animal models are available for the evaluation of the potential of chemicals to cause irritative effects and they are currently used in experimental testing (Alarie, 1973; Nielsen and Alarie, 1982). However, these tests have not been used so far at exposure levels normally occurring in the indoor environment and the validity of extrapolations of the results of such animal tests to low levels of exposure in humans needs to be demonstrated.

Since few validated physiological methods exist for measuring effects that may be caused by low exposure levels in humans, 'markers' or substitute measures of irritative effects are being tried. Irritation of the eyes may be measured as changes in the chemical composition of the eye fluids (Thygesen et al, 1987). There are some indications of a changed tear film break-up time following exposure to irritants (Franck, 1986; Franck and Skov, 1989; Mengher et al., 1985). Irritation of the nose may be monitored as a changed mucociliary flow rate or a changed chemical composition of the nasal fluids (Pazdrak et al., 1993; Ichikawa et al., 1991; Franck and Boge, 1993). Only a few markers of irritative effects of pollution levels known from indoor air are available, and most of these are still at the stage of being developed, e.g. cells in tearfluids and eye redness (Kjærgaard, 1992; Kjærgaard et al., 1990; 1991; 1992).

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**EUR 17675 – European Collaborative Action ‘Indoor Air Quality and Its Impact on Man’:
Total volatile organic compounds (TVOC) in indoor air quality investigations.**

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The amount of volatile organic compounds (VOCs) in indoor air, usually called TVOC (total volatile organic compounds), has been measured using different definitions and techniques which yield different results. This report recommends a definition of TVOC referring to a specified range of VOCs and it proposes a method for the measurement of this TVOC entity. Within the specified range, the measured concentrations of identified VOCs (including 64 target compounds) are summed up, concentrations of non-identified compounds in toluene equivalents are added and, together with the identified VOCs they give the TVOC value.

The report reviews the TVOC concept with respect to its usefulness for exposure assessment and control and for the prediction of health or comfort effects. Although the report concludes that it is today not possible to use TVOC as an effect predictor it affirms the usefulness of TVOC for characterizing indoor pollution and for improving source control as required from the points of view of health, comfort, energy efficiency and sustainability.

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