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ELEMENTS OF A STANDARD PROTOCOL FOR MEASUREMENTS IN THE INDOOR ATMOSPHERIC ENVIRONMENT

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Abstract—Measurements in the indoor atmospheric environment are often performed to test postulated relations between complaints about air quality, etc. and the atmospheric environment. The measurements often fail to confirm the expected causalities even when performed by experienced investigators. As the causality may be multifactorial including factors like technical, chemical, physical, medical, psychological, sociological and economical factors, the planning of measurements has to be multidisciplinary. A corporation of such different disciplines can only be done efficiently if a proper protocol is established. This protocol must cover sampling, analyses and evaluation and should identify the specific aims and specify how they are achieved in cooperation between the investigators. The present paper discusses elements of such a protocol.

Key word index: Air pollutants, indoor air, indoor air quality, sampling protocol, sick buildings.

INTRODUCTION

The number of measurements in the indoor atmospheric environment is increasing due to a growing number of complaints about indoor air quality. Many of these measurements are performed by researchers to test postulated hypotheses about causality between the complaints and their sources. Measurements are also initiated by the occupants themselves for example or other persons lacking medical or technical training. Many of these measurements, however, fail to confirm the expected causality even when performed by experienced investigators. The respective buildings are therefore often characterized as 'problem buildings'. In these the occupants are said to suffer from the sick or tight building syndrome (WHO, 1983).

The causes of the complaints may be multifactorial and include technical, chemical, physical, medical, psychological, sociological and economical factors. Thus, the planning of a strategy for investigations in a problem building must be multidisciplinary (Mølhave, 1986). A successful investigation of a multifactorial relation depends on a coordination between several investigators with different training. To coordinate such cooperation a protocol covering sampling, analyses and evaluation is an essential tool. This protocol should identify the specific aims and specify how they are achieved in the cooperation between the investigators. These are often the persons who want an evaluation of the indoor atmospheric environment (e.g. the HVAC engineers), those performing the sampling and subsequent analysis (e.g. the analyst) and those making the evaluations and decisions (e.g. the hygienist). The protocol should further ensure a proper collection and recording of all information needed for the specific aims.

In the present paper, which is based on a previous work by Seifert (1984), elements of such a standard protocol are discussed.

IDENTIFICATION OF RELEVANT MEASURING PARAMETERS

The first step in the preparation of a protocol is the definition of the sampling objectives or of the hypothesis to be tested. These objectives may be problem orientated and as such include mapping or documentation of exposures in a residential area, control of compliance/non-compliance with federal or local standards or recommended exposure limits, or identification of the source of a previously identified problem (NIOSH, 1984). Other objectives are the evaluation of methods for measurements of individual human exposures to contaminants (Wallace *et al.*, 1982), the identification of the effect of reduced ventilation on indoor air quality (Turiel *et al.*, 1983) or proof of any test hypothesis. Each of these objectives calls for different protocols and a detailed description of the aim is therefore an essential first step in any planning of the protocol.

Once the sampling objectives have been defined the next step is to establish a list of all relevant sampling variables and their variation ranges. Table 1 indicates some of the major variables to be considered either in direct relation to dose–response models or as cofactors or confounders. The range of variation for each variable may be found in the literature or via a pilot study. A pilot study will give the order of magnitude of

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Table 1. Major classes of variables related to problem building

The indoor atmospheric compartment
Biological exposure
Allergenes or microbiological
Chemical exposure
Dust, aerosols or vapours
Physical exposure
Actinic environment, acoustic environment, air humidity, air movement, dust, fibers, ions, thermal environment
Emission controlling covariables
Qualitative variation in time and space:
Building site and type
Materials
Processes
Type of ventilation system
Biological sources for pollutants
Outdoor pollution
Quantitative variation in time and space:
Emission rates
Elimination rates
Covariables for human reactions
Genetic factors
Personal or environmental cofactors
Building related cofactors
Social environment
Work environment
Exposure times
Human reactions
Symptoms from:
Eyes
Nose and upper airways
Throat, mouth
Lower airways
Stomach
Ear
Heart
Hyper-reactivity
Skin reactions
Heat balance
Neurological effects
Psychological effects
Other human reactions
Change in human activity pattern
Non-human reactions
Reaction of other biological systems
Animals
Plants
Effects on buildings and other properties

frequencies and variations as well as other basic quantitative information. Additionally, important confounders and covariables may be identified prior to the planning of a main survey.

For each of the selected variables a sampling or measuring specification is then established. This specification includes the discussion of the topics mentioned in Table 2.

INSTRUMENTATION

For each of the relevant variables a separate measuring or sampling instruction should accompany the

Table 2. A general description of a measuring procedure

Instrumentation or type of sampling
Calibration and validation
Location
Time
Duration
Number of measurements
Status of confounders and covariables
Administration of the measurements

analytical protocol. The preparation of sampling instructions involves an evaluation of the available methods of sampling to ensure that the finally selected combined sampling and analytical method meets the objectives of the investigations. A consultation of the analytical laboratory is therefore essential prior to the selection of analytical methods. Table 3 shows a few common sampling and analytical methods for measurements of exposure factors. The table illustrates some of the methods available.

The list of instrumentation and sampling methods for biological effects is endless. The main tool in relation to indoor air quality seems to be the subjective questionnaire. A questionnaire by itself is, however, neither able to prove causality, nor to show if complaints are caused by hypersensitivity or high level of atmospheric pollutants.

CALIBRATION

The sampling instrumentation must be calibrated. It is customary to calibrate against a secondary standard, prior to and immediately following sampling. If possible the instrumentation should be regularly calibrated against a primary standard. Addition of blank and replicate samples will be discussed later.

SAMPLING LOCATION

The optimal sampling site depends on the sampling objective. If the investigation focuses on specific environments only, sampling locations inside these environments may be relevant. However, if the survey is supposed to be representative for a given type of residence or environment, the investigator must secure this representativity in his selected sampling sites.

When proper sampling sites are selected, the sampling locations inside the environment or building must be considered. This is important as the air within occupied spaces is not uniformly mixed (Janssen *et al.*, 1982; Maldonado and Woods, 1983). One strategy could be identification and investigation of areas with highest concentrations of contaminants. The location of the highest concentrations within a building depends on the air movements and on the locations of the

Table 3. Examples of sampling and measuring procedures used in the literature for measurements of exposure factors

Contaminant	Sampling procedure	Analytical procedure	Reference
Volatile organic compounds (VOC)	Dual section charcoal tubes Polymer absorber Tenax–GC	Solvent elution and GC–MS Thermal elution GC–MS	
CH_2O, Formaldehyde	Liquids in impinger	Chromotropic acid Acetyl acetone method	Godish, 1985 Bisgaard *et al.*, 1983
Particulates	Filters	Gravimetric	Loo *et al.*, 1976
Total suspended particular	Real time	Light scattering device	ACGIH, 1978
CO_2	Real time	IR	ACGIH, 1978
CO	Real time	Electrochemically	ACGIH, 1978
Microbiological contamination	Modified Andersen sampler	Light scattering device	Dimmick and Wolochow, 1979
Odour	Grab sampling	Test panel	Dravnick and Prokop, 1975 Marks, 1974

sources of contaminants. Woods *et al.* (1985) suggest a procedure for choosing the sampling locations inside a residence using four concepts: (a) location of the problem or contaminant source, (b) the Relative Exposure Index, REI or (c) the Ventilation Effectiveness, VE and (d) occurrence of complaints. The use of REI and VE for locating the zones of a building representing the greatest potential exposure to contaminants have previously been reported (Maldonado and Woods, 1983). REI is a measure of the relative importance of a specific source at different zones in the room, while VE indicates the general ventilation level in the same zone. To determine REI or VE, a tracer gas is released. The resulting concentrations of the tracer gas in different zones is a consequence of the internal air movement and infiltration. A brief release of tracer gas is used for measurements of REI at a specific location, e.g. at the location of a suspected source, while for VE measurements the tracer gas is uniformly mixed throughout the residence. Usually the highest concentrations of contaminants coincide with the largest REI (or smallest VE) (Maldonado and Woods, 1983). Such locations therefore indicate high risk areas. REIs and VEs for specific contaminants do not necessarily coincide with those identified by using tracer gases as physical and chemical properties like molecular weight and polarity of the contaminant and tracer gas may be different (Maki *et al.*, 1983).

In situations where complaints have been reported, and seem to be related to air pollution, the source of the pollution must be searched for and measurements must be obtained in the zone with the contaminant source, in the high risk zones, and in the zones with complaints. For control measurements where no complaints have been reported and where the locations of the suspected problem sources coincide with the zones of highest risks (REI and VE measurements), sampling at the locations of the sources may be sufficient. On the other hand, if the location of the source and the critical REI and VE do not coincide, it is recommended to sample at both locations even if no complaints have been reported.

Using tracer gas to decide where to sample is tedious. In most cases it is sufficient to register air movement and infiltration using a 'smoke-gun'. Releasing smoke in different zones allows rough estimates of the ventilation activity in each zone. The sampling locations may then be identified as mentioned.

It is essential to understand that each sampling location later will be taken as representative for a homogeneous microenvironment. In terms of statistics, this means that the variance of the variables under consideration in each microenvironment must be smaller than the variance among the averages for different microenvironments (Moschandreas, 1981). Each sampling location is thus assumed to represent a homogeneous microenvironment. The different microenvironments constitute together the entire non-homogeneous sampling environment. The size of each microenvironment may differ depending on the variation in space and time of the selected variables. All these microenvironments should be discussed prior to the sampling and a separate sampling protocol may have to be established for each of them.

In addition to sampling in the building environment samples from the macroenvironment—the outdoor samples—are of particular importance. These samples represent the local baseline level of the sampling environment and are together with samples from other subenvironments helpful for the location of dominating sources of contaminants.

TIME OF SAMPLING

The time of sampling must be considered as the concentrations of airborne contaminants normally vary from hour to hour, from day to day and from season to season. Formaldehyde concentrations may be seasonally varying as shown by Godish (1983) and

Godish *et al.* (1984), who in the northern climate found that low indoor relative humidity during the wintertime resulted in minimum formaldehyde levels 1/4 to 1/3 of peak values for a given residence. Such variations are often further correlated to the variations in cofactors or confounders like human activity, air temperature and humidity. The time for sampling may accordingly be chosen so as to minimize the influence of such variations, e.g. by sampling, when the potential cofactors are expected to be at a constant and average level. Such choice of sampling time is, however, not always achievable or acceptable in relation to the overall aims of the investigation. The sampling program should, therefore, always allow estimates of the range of variation of relevant covariables or confounders. If resources are limited the sampling strategy should aim at detecting the highest risk situations, i.e. the highest concentrations or exposures.

DURATION OF SAMPLING

Often sampling objectives call for measurements of the variation in both space and in time. These variations can be assessed through several subsequent samples from the relevant zones. A proper arrangement of sampling duration of this sequence of samples allows further estimation of both peak exposure and average exposure. Both short- and long-term sampling may be needed to reflect the desired time resolution of the sampling program. The time resolution depends on the duration of sampling and on the interval between each sampling. The greatest time resolution obtainable is the shortest sampling duration and interval. A balance between the acceptable sampling duration for the analysis and the time resolution needed for the conclusion must be found.

In addition to such considerations, the sampling flow-rate and sampling efficiency together with the sensitivity of the analytical methods will in many cases determine the sampling time. The analytical laboratory should be consulted about the coordination of the available analytical method and the defined sampling needs.

The parameters in the following list permit an estimate of the sampling time when the highest possible analytical sensitivity is needed for air sampling with bubblers.

Detection limit (in solvent)	: L
Flowrate	: F
Concentration in the air	: C
Solvent volume	: V
Sampling efficiency	: E
Sampling time	: T
Signal/noise ratio	: R.

The accumulated concentration in the solvent is calculated as:

$$\frac{C \cdot F \cdot T \cdot E}{V} \geqslant L \cdot R.$$

From this inequality it follows:

$$T \geqslant \frac{L \cdot R \cdot V}{C \cdot F \cdot E}.$$

The time resolution to choose is further related to the time scale of the anticipated biological effects. Short-term samples (less than 15 min) are usually used for investigations of acute effects of, for example, irritants, asphyxiants, sensitizers and allergenic agents. Chronic effects are usually investigated through sampling for several hours or even days as short-term fluctuations in these cases are less important for the body response. Other considerations are relevant to the evaluation of monitoring device performance, trends in contaminant concentrations in an area, etc.

NUMBER OF SAMPLES

It is necessary to employ statistics to translate the raw analytical data resulting from the sampling and analysis into proper statements or conclusions. The number of samples required to obtain results within a given confidence limit can be estimated in the planning phase if information is available about expected frequencies, distributions and variances for each variable. In the absence of such information useful data may be obtained from pilot studies. Often the distributions of environmental contaminant concentrations can be approximated by a logarithmic normal distribution, which is characterized by the geometric mean and the standard geometric deviation. Assuming this distribution, a value of the geometric standard deviation of about 2.3 may be used to estimate the required number of samples within any desired confidence interval (Corn, 1985). In any event a minimum of three samples should be collected before any statement is made. If the range of these exceed 25% of their average, additional samples should be obtained (Corn, 1985).

In addition to this generalized procedure it is recommended to collect two–four replicate samples as quality control for each set of field samples from each location (NIOSH, 1984). The recommended number of field blanks to collect is two for each of 10 samples with a maximum of 10 for each sample set. Approximately five media blanks should also be included (NIOSH, 1984). Analysis of these samples should be included as quality statements in the final report.

COFACTORS AND CONFOUNDERS

It is essential prior to and during sampling to identify and measure all possible sources for covariations among the selected relevant variables. However, the multivariate nature of most indoor climate problems would call for an unacceptable large number of observations of a multitude of variables. In

order to overcome this a smaller number of samples may be accepted if some of the variables or cofactors are controlled to preset levels during the sampling.

Maintaining any of the sampling parameters to preset levels is often restricted to main variables, like indoor air temperature, relative humidity and ventilation status (Monteith *et al.*, 1984; Mølhave and Andersen, 1980; Turiel *et al.*, 1983). It should be considered if other cofactors or confounders should be controlled. Human activity can be avoided, e.g. by restricting the admission to or closing of the residence in order to achieve steady state concentrations during sampling (Godish, 1985; Mølhave and Andersen, 1980). However, by closing a residence a significant change in the human activity pattern is introduced, thus making the sampling situation unrepresentative for normal building use. The results may therefore be biased if human activity can be considered a cofactor. Even the steady state condition may represent an extreme in the residence rather than the average condition as steady state is seldom obtained in real life situations. The use of steady state conditions and other similar restrictions therefore should be followed by a discussion of the possible bias of the results in order to allow other users of the results to extrapolate to other types of environments.

SAMPLING ADMINISTRATION

The sampling protocol shall describe an unambiguous numbering routine for all samples and information collected during the entire sampling and analytical program to secure the history of the samples. The protocol therefore must include proper numbering of all samples and data sheets for each variable or covariable. Likewise strict shipping and storage routines should be established and tested to secure the validity of the samples, when they arrive to the laboratory. International databases containing information about the non-industrial environment are presently being developed and to support this, project reports should include all data relevant for the development of such databases.

A successful sampling will normally depend on the cooperation of the inhabitants, which calls for an active information plan. This plan must be directed to the individual occupant, the owner of the building, the producer of the building material, the authorities, the unions, etc. This information activity, however, should not introduce an unacceptable bias on these groups. The level of information given to the sampling population, the occupants, therefore should be discussed prior to the first contact.

CONCLUSION

This paper should be considered a brief discussion of a check-list for establishing a sampling protocol. After formulation of the hypothesis or aim of the investigation all relevant variables and co-variables should be identified based on the information given in Table 1, which is supposed to include the major classes of variables related to the indoor atmospheric environment. Table 1 may act as a check-list for selection of variables relevant for the hypothesis. Table 4 is a list of items to consider for each new protocol, and may act as a list of contents for a standard sampling protocol.

Table 4. Standard items to consider during establishing a sampling protocol

Sample identification
Sample numbering
Laboratory/operator identification
Sampling procedure
Sampling method
Analytical method
Calibration, validation
Number of parallel samples
Sampling date
Sampling duration and interval
Sampling site identification/characterization
Site
Type of building
Age of building
Room type and description
Floor level
Location in the room
Recent renovation activity
Confounders and covariables
Ventilation system time and status
during sampling
before sampling
Temperature and humidity
Meteorological conditions
The presence of: biological sources like people and pets
Consumer products
Smoking
Appliances
Effects
Comfort reduction
Health effects
Economic effects
Occupant activity

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