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Indoor air pollutants: exposure and health effects

Report on a WHO meeting

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This publication is dedicated to the memory of Dr Craig D. Hollowell, Berkeley, CA, USA, a distinguished scientist in the field of indoor air quality and a participant-designate of the Working Group, who died suddenly on 18 January 1982 at the age of 41. The scientific community will miss a great scientist and a good friend.

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SUMMARY

The Working Group on Assessment and Monitoring of Exposure to Indoor Pollutants was convened by the WHO Regional Office for Europe in collaboration with the Government of the Federal Republic of Germany to discuss the assessment and monitoring of exposure to indoor air pollutants and of the resulting impact on health, recognizing that this presents special difficulties due to the number and variety of sources and spaces involved. There have been many case reports of serious impacts on human health due to indoor exposure to formaldehyde, to carbon monoxide and other products of unvented combustion, and to a variety of organic chemicals from consumer products. The as yet inadequately evaluated chronic exposures to imprecisely determined concentrations of a number of pollutants known to be released indoors is a matter of considerable public health concern.

The meeting reviewed current knowledge about the sources of a number of indoor pollutants of concern and considered the concentrations at which they have been reported. It assessed the effectiveness of the current technical means of measurement and the adequacy of the available monitoring data for estimating population exposure. It listed the adverse health effects to be expected from exposure to each of the pollutants, and assessed the adequacy of the present knowledge of the exposure–effect relationship for the purposes of estimating total public health impact in cases where acceptable exposure estimates are available. For each of the pollutants, the fraction of the population exposed to low concentrations was estimated, together with the fraction exposed to concentrations above the level of concern. To obtain an acceptably quantitative estimate of the adverse health impact of an air pollutant in a given population, the Group considered it first necessary to have a quantitative estimate of pollutant exposure, the exposed population and the exposure–effect relationship. They considered tobacco smoke (passive smoking), NO_2, CO, radon, formaldehyde, SO_2, CO_2, O_3, asbestos, mineral fibres, organics and

allergens. In general, it found that the instrumentation available for measuring exposure was usually of acceptable quality, but that the monitoring data and knowledge about the distribution of sources and concentrations were inadequate or marginal. It noted that the types of adverse health effect to be expected were largely known, but that in many cases knowledge of exposure–effect relationships was inadequate, especially with regard to delayed effects of chronic exposures.

It was concluded that current knowledge did not yet allow quantitative assessments of public health impact. With this understanding, and subject to modification in the light of improved knowledge, it prepared, for most of the pollutants considered, estimates of concentrations below which it was felt no unacceptable adverse health effects would occur in an indoor environment. Similarly, estimates were made of the concentrations above which serious concern about adverse health effects was to be expected.

The Group made a number of recommendations on priorities and methodologies for research designed to produce more precise estimates of the impact of indoor air pollution on public health, and to develop effective strategies for the improvement of indoor air quality.

INTRODUCTION

The increased concern about indoor air quality has led to the organization of a number of studies and meetings on the subject. They have included a first international symposium on indoor climate effects on human comfort, performance and health (*1*); a working group on health aspects related to indoor air quality (*2*); a study by the Committee on Indoor Pollutants of the US National Academy of Sciences and the National Research Council (*3*); a symposium on health aspects of indoor air pollution (*4*); a symposium on air quality in enclosed spaces (*5*); and an international symposium on indoor air pollution, health and energy conservation (*6*).

The Working Group on Assessment and Monitoring of Exposure to Indoor Pollutants was convened by the WHO Regional Office for Europe in collaboration with the Government of the Federal Republic of Germany. It was attended by 13 temporary advisers from 10 countries, as well as representatives of WHO headquarters and the Commission of the European Communities. Dr M. Fugaš was elected Chairman, Dr B. Seifert Vice-Chairman and Dr J.A.J. Stolwijk Rapporteur. Dr M.J. Suess acted as Scientific Secretary. The list of participants is attached as Annex 3.

The purpose of the meeting was to review the results of prior work in the field of indoor air quality, as well as the design of work currently in progress or planned, in order to evaluate the extent to which such work is likely to provide early estimates of actual population exposures and the extent of the health impacts that can be associated with them. The meeting was also asked to consider the relative contributions and limitations of laboratory characterizations of sources of pollutants; model predictions of such concentrations in actual spaces; field monitoring of pollutant concentrations; personal monitoring; and health effect determinations in the laboratory and in the field. Finally, it was expected that the meeting would discuss the need for and benefit of simultaneous studies in a number of countries and the coordination of such studies in time, approach and design, bearing in mind that the priorities of the component disciplines involved would not necessarily coincide with those needed to arrive at a rapid assessment of the overall health impact of indoor air pollution in its present form.

The participants divided into subgroups for discussion of nine main aspects of the problem that had been identified: state of knowledge about population exposure; state of knowledge about adverse health effects; indoor air quality concentration values of concern; examination of existing standards; international steering committee on indoor air quality; exposure assessment and priorities; "sick" building syndrome; SO_2 concentrations and indoor/outdoor relationships; and health effects assessment methodologies and priorities. The membership of the subgroups is given in Annex 1.

Although indoor air quality has always been a public and personal health concern, in recent years the problem has come into sharper focus. Additional and new sources of contaminants are being introduced, and increased energy costs have brought a tendency to reduce ventilation and infiltration, with resulting complaints by occupants. In some cases, studies have identified particular areas of concern. In view of the frequency of the occurrence of exposures and the consistency in their causes, more should be known about the quantitative relationships and factors governing indoor air quality so that the number of the problems can be reduced and their effects diminished.

Several countries have undertaken comprehensive studies of the factors governing indoor air quality, so that effective control measures can be evaluated and adopted. Such measures range from setting minimum ventilation standards to controlling, or even totally banning, certain products such as urea-formaldehyde foam insulation or unvented kerosene heaters. It is nevertheless recognized that some of the responsibility for maintaining acceptable and healthy indoor air quality will continue to rest on the householder and occupants, who must be supplied with responsible and accurate information on which to base informed decisions and choices.

In considering the appropriate measures to be adopted, it must be borne in mind that for almost any pollutant in the indoor air there are reports of serious adverse health effects requiring immediate correction. At the same time, studies in which a large number of spaces were monitored carefully have shown that many of the spaces did not contain indoor pollutant concentrations of health concern. There is thus a demonstrated potential for serious harm to health from indoor air pollutants but it is not possible to make a quantitative assessment of their overall importance for public health.

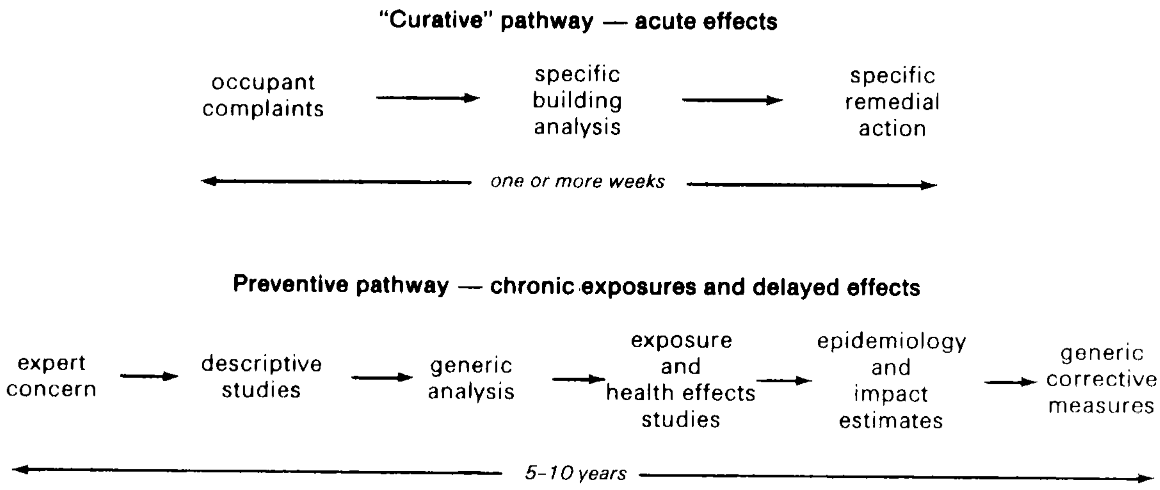
The air quality in an indoor space, and more specifically the concentration of a given pollutant indoors, depends on the outdoor air quality, on the presence and strength of emissions from indoor sources, on the ventilation rate and ventilation efficiency, and on the presence and effectiveness of absorbers, filters or barriers. Because equipment and furnishing and many other materials are chosen by the owners or occupants of a space and influenced by their behaviour, they are at least as important in determining the air quality in a space as the physical and chemical characteristics of the space and of the materials used in its construction. The manufacturers of consumer products also influence indoor air quality through the choice of chemicals incorporated in their products and through the clarity of product warnings and instructions for use.

As a result of the large and intrinsic variability in the many factors that govern indoor air quality, there are special problems in attempting an assessment of population exposure to indoor air pollutants. We do not know enough about the characteristics of existing building stocks in terms of ventilation and infiltration rates to be sure about the distribution of dilution rates in them. We do not know how many cigarettes are being smoked in each of the spaces and our ability to estimate the distribution of cigarette smoking within building stocks is marginal. We lack adequate data about the use of unventilated space heaters, wood- and coal-burning stoves and gas-fired cooking stoves and ovens and their distribution in buildings. Nor is enough known about the distribution of building materials, maintenance and cleaning materials, foam insulation and other potential sources of indoor air pollutants, or about the ventilation habits of occupants.

We should not only know about the distribution of all these contributing factors but also about their associations and joint distributions and about the number of people exposed to these indoor environments. These data are important for the assessment of impact and for the design of effective strategies for reducing such impact.

The first recognition of a generic health problem usually results from case reports of excessive exposure. For example, in the last two decades a special pattern of exposure has been observed and has become of sufficient concern to be identified as the "sick" building syndrome. Fig. 1 shows the

Fig. 1. Sequence of steps and length of time involved in dealing with general population exposures and with acute complaints



steps involved in the more usual "preventive" pathway leading to generic corrective measures and in the "curative" pathway followed in the case of "sick" buildings.

In "sick" buildings the complaints by occupants tend to be stronger and more organized, with the result that specific "diagnostic" investigations are made and remedial action is sought for the particular building. The levels of exposure are often found to be very low. In the preventive pathway, the case reports initiating the chain tend to refer to very high-level exposures, thereby giving rise to concern about much larger populations.

ELEMENTS OF THE PREVENTIVE APPROACH

In the preventive approach outlined in Fig. 1 the original stimulus for action may be case reports of isolated excessive exposure. In such instances adverse health impacts on the relatively few people exposed are so serious that the events are reported to public health officials and in the literature. If the sources are common, the association with the adverse health effects strong, and the health effects serious, health officials and experts will be concerned about the as yet unreported impact on the general population, and descriptive studies will be initiated. Such studies may consist of monitoring the concentration of suspected pollutants in the field. This is usually done in a limited number of "typical" spaces or in spaces where potential sources are known to be present, using conventional recording equipment (*7,8*). In other cases it is possible to use specially designed equipment to determine personal exposure by means of active (*9*) or passive personal monitors. In descriptive studies a limited number of spaces may be examined for exposure characteristics (*7,8*) without simultaneous assessment of health effects, or for health effects without a precise description of the exposure (*10,11*). Alternatively, both methods can be considered in a not quite representative sample of a much larger population (*12*). Descriptive studies of this type improve our knowledge and allow sounder judgements by experts and health authorities about the nature and potential magnitude of the population impact of different air pollutants.

The deficiencies in knowledge at this point in the preventive approach are often still multiple: the exposure is still specific to the spaces studied and the exposure description may be insufficiently representative. The nature of the adverse health effects of an acute type is usually known, but in general we have only marginal knowledge of the nature and the exposure–effect relationship of delayed effects, especially in respect of specific groups within the population. With regard to many aspects of indoor air quality we find ourselves at the level of knowledge where initial concerns have been substantiated and there is evidence of considerable public health impact of indoor air pollution. Further research should be directed and coordinated to allow both quantitative impact assessment and the design of corrective measures. This implies that measurement and monitoring research should make it possible to estimate exposures in representative and general populations using models of such exposures based on selective but relatively limited information. Similarly, health effects research should concentrate on the determination of exposure–effect relationships for different subgroups of the population, so that the overall population impacts as well as remedial strategies can be evaluated with more confidence.

EXPOSURE ESTIMATES

Modelling

In the measurement, monitoring and modelling of indoor air pollution levels, it is important to bear in mind that it is not possible to measure and/or monitor levels of all air pollutants of concern in all spaces occupied by a sizeable population. It is thus necessary to estimate the indoor air pollution levels using some form of mass balance equation, with the best possible measurements or estimates of the relevant coefficients and constants.

In the simplest form such a mass balance equation for a single, well mixed compartment or space takes the form:

$$V\frac{dC_i}{dt} = P - E - Q(C_i - C_o) \qquad (1)$$

where V = volume of air contained in the indoor space,

C_i = concentration of the pollutant in the indoor space,

t = time,

P = rate of production or release of pollutant in the indoor space,

E = rate of elimination through reaction, filtration or settling,

Q = rate of air exchange with the outside atmosphere, through infiltration or ventilation, and

C_o = concentration of pollutant in the outdoor air.

In the steady state (1) reduces to:

$$C_i = C_o + \frac{P - E}{Q} \tag{2}$$

Equations (1) and (2) represent clear oversimplifications in the case of the episodic release of an air pollutant where the requirement of a well mixed compartment is not met, or in the case of the release of an air pollutant in one room where the concentration in another room must be evaluated. In many investigations versions of the model in equation (1) have been used. Applications have included estimates of CO and suspended particulates associated with smoking (*13*). Drivas et al. (*14*) used this form of modelling to evaluate ventilation systems. Jacobi (*15*) considered the interaction between ventilation and radon concentration. Berglund et al. (*16*) reported on different behaviours of several compounds when the ventilation rate of an office building was experimentally varied.

In applying modelling techniques for the investigation of indoor air pollution levels, the first requirement is to determine the constants and coefficients that characterize the space being modelled, since the model results can be no more accurate than those values. Hence it is essential to validate any application of indoor air pollution modelling estimates with measurements in at least some fraction of the spaces being modelled. This requirement and some results have been examined by Moschandreas et al. (*17*) and WHO (*18*).

In some cases it may be possible to reduce equation (2) even further by making the additional assumption that the rate of indoor elimination of some pollutants generated or released indoors is quite low or zero, and that their outdoor concentration is also quite low and often can be ignored; these terms can then be eliminated from the equation.

For a pollutant generated outdoors that does become absorbed or inactivated indoors there is a simplified equation, eliminating *P*. The infiltration or ventilation rate for a space is a very important characteristic because its magnitude is an important determinant of the indoor air pollutant level. In the case of unvented combustion, increasing the ventilation rate brings about a proportionate reduction in steady state or integrated exposure to products of combustion. In estimating indoor ozone concentration in locations with photochemical smog, the indoor concentration will normally be found to be lower than that outdoors, owing to the reactivity of ozone with furnishings and contents. Increasing the ventilation rate in this case will *increase* the indoor ozone concentration.

Source strength

For modelling of indoor air pollutant levels it is very important to obtain values of source strengths (*P*) for materials, equipment, human bodies and pets, and for activities that produce or release pollutants within the indoor environment under various circumstances.

Leaderer (*19*) determined the emission factors for kerosene space heaters. Mølhave et al. (*20*) studied the emissions from 42 commonly used building materials. Other sources can be characterized in terms of specific emission factors, such as cigarette smoking (*21*), radon from building materials, tap water (*22,23*) and formaldehyde (*24*). Source strengths are best measured under highly controlled laboratory conditions but it is also possible in many cases to estimate them from measurements made in the field, if these are sufficiently complete, by applying equation (2) to find the value of *P*.

In the case of products used in cleaning and maintenance, and many other consumer goods, source strength estimates can be made for all volatile constituents on the basis of the amount of material used and its composition and drying time.

Exposure assessments for indoor air pollutants would be facilitated in the future if experiments and measurements were designed to produce source strength data whenever possible.

Infiltration and ventilation rates

All spaces, unless hermetically sealed, exchange air with the outdoor atmosphere through infiltration and diffusion. In very many indoor spaces this constitutes the only form of air change. Some rooms may have a higher leakage rate than others, depending on wind direction and velocity, length of window and door cracks, etc.

Other buildings must rely on mechanically forced ventilation whereby a substantial fraction of the total air flow is usually recirculated, and a smaller fraction is exhausted and replenished with outside air. It is customary to express the infiltration and ventilation rates in terms of air changes per hour, i.e. the number of times per hour that outside air equal to the total volume of the space enters the space. Generally the rates are not lower than 0.2 air changes per hour (ac/h) and, when they are higher, substantial energy costs are incurred for heating and cooling the outdoor air. Two basic methods are used for the measurement of air change rates in a space. The most common is to introduce a tracer gas into the indoor space so that the concentration is rapidly increased to a value at least 10–100 times the minimum that can be measured by a monitoring instrument. If the space is well mixed, the reduction in this concentration, as observed by the monitoring instrument, will show the air change rate, in accordance with equation (1).

A number of gases can be used as a tracer, including radon, N_2O, CO_2 and SF_6. More recently Dietz et al. (*25*) described the use of perfluorodimethylcyclohexane as a constant-source tracer that can be used to calculate infiltration rates in steady-state concentrations.

A completely different method of characterizing a building in terms of its infiltration resistance is to pressurize the whole structure with a slight overpressure and measure the air flow required to maintain that level of pressure (*26*).

Such measurements have the advantage that they are not particularly sensitive to momentary wind speed and wind direction. Mattingly & Peters (*27*) studied the air infiltration rate as influenced by wind and other factors and found variations within the same unit space ranging from 0.2 to 2.3. ac/h depending on wind direction, windbreaks and the area of exposed outside wall of spaces within a given complex. There are a number of techniques that have been suggested for the estimation of infiltration rates based on building characteristics (*28–30*).

Grot & Clark measured natural air infiltration rates in several dozen houses in three climatic areas in the United States (*31*) and reported a distribution of air infiltration rates averaging 1.2 ac/h (standard error: 0.86 ac/h) in South Carolina with a moderate climate, and 0.77 ac/h (standard error: 0.57 ac/h) in North Dakota with a severe winter climate.

For assessment of indoor air pollution, the air infiltration or the ventilation rate must be measured or estimated. There are systematic variations determined by building types and construction practices that can help in estimations, but it is necessary to obtain measurements in a number of spaces to establish the average air change rate for each classification. Different spaces in a building often have different ventilation rates, and occupant behaviour can introduce an additional variation. Source strengths may show more variation from one indoor space to another than infiltration rates for some sources, but not for all. Infiltration rate or air change rate requirements are being incorporated into building codes and recommendations. In the Federal Republic of Germany, a value of 0.8 ac/h has been proposed (*32*). The 1980 Swedish building regulations specify that detached houses may not leak by more than 3 ac/h, and buildings above three storeys by more than 1 ac/h, at an internal overpressure of 50 Pa. At the same time, positive ventilation must be provided to ensure 0.35 l/s of outside air per m^2 floor area in residential buildings (*33*).

Methods of measurement

Indoor air measurements

The most direct method of determining air pollutant concentrations in indoor spaces is by measurement. Such measurements can be made for a variety of purposes, using a variety of approaches and types of instrumentation; most are relatively costly and time-consuming.

When there are consistent and continuing complaints of discomfort or acute or chronic adverse health effects by occupants of a building, indoor measurements are often carried out to identify pollutants and ascertain their concentration. In such cases the measurement methods, location of sampling stations and sampling schedule are chosen to solve an acute problem in a specific building. The measurements are likely to provide only a limited contribution to further understanding of the generic problem of indoor air pollution.

Many studies involving the measurement and monitoring of indoor air pollutant levels are concerned with the distribution of the pollutants in certain types of building, sometimes according to the presence of certain sources. If in such cases simultaneous measurements are made of the outdoor levels of the pollutants and of the air infiltration rate, the measurements allow an assessment of source strengths in the spaces. If the measurements are accompanied by detailed observations on building characteristics and contents, they can be used to develop predictive models of indoor air pollutant levels in similar buildings, or they can serve as validation of predictive models developed from other data sets.

Measurement of indoor air pollutant levels is accomplished by one of the following methods:

— spot samples, also known as grab samples;

— time-integrated samples;

— real-time continuous monitoring.

Spot sampling. The simplest procedure is to take a one-time air sample by filling a container with air, or by passing a known volume of air through an absorber. The containers may be plastic bottles, Mylon or Tedlar plastic bags, or glass tubes filled with absorbent (*34*); they must be impervious to the gas being sought.

If the concentration of the pollutant is expected to vary over time, it is necessary to take a number of sequential samples. Spot sampling is most effective if the analytical equipment is available only at a central location. It is an inexpensive form of measurement, but suffers from the fact that it reflects only a relatively short time period and the concentration may be far from "average".

Because only a relatively small amount of air is usually taken in spot sampling, the analytical equipment must be able to detect concentrations at the ambient and indoor levels directly. A large number of field measurements can be made with a single analytical instrument, but the reduction in the capital cost is often offset by higher costs of data acquisition and analysis.

Time-integrated sampling. For many pollutants, including total suspended particulates, and radon and its progeny, the effects are assumed to be proportional to a long-term average of the concentration, and the preferred measurement methods also show a time-integrated concentration. Typically, suspended particulate collected on filter paper through which a known air flow was directed are measured as a time-integrated average, usually over 24 hours or longer. Methodologically, time-integrated measurements are useful whenever the instantaneous concentration is below the detection limit of analytical instruments and the concentration to be analysed can be increased by accumulation on filter paper or by a sorbent (liquid or solid). Soluble gases such as formaldehyde and SO_2 can be collected in bubblers or gas washers. The total flow during the accumulation period must, of course, be known or determined. The lower cost of measurements based on integrated samples, and the higher sensitivity of cumulative sampling, are offset to some extent by the greater difficulty in maintaining quality control. Integrated sampling is less desirable when air pollutants have effects that are non-linear with concentration. Integrated sampling would therefore not be recommended for pollutants such as ozone, which has biological effects proportional to short-term concentrations that are not shown by longer-term integrated measurements.

Two principles underlie integrated sampling. Originally most schemes involved active sampling: an air sample stream was actively drawn through an absorber or a filter by means of a pump at a known and constant rate, and the accumulated or collected pollutant was weighed or measured by chemical and colorimetric methods. Portable instrumentation for active sampling requires battery-powered pumps, which add bulk, weight and expense.

Since the early 1960s a new form of integrated sampler has come into widespread use. An early version of the device was described by Palmes (*35*). Passive samplers rely on diffusion or permeation through a barrier for the acquisition of pollutant molecules from the ambient air. They basically consist of tubes or containers with a collector, which keeps the concentration of the pollutant within the device at a very low level or zero. Depending on the configuration, the pollutant diffuses down a gradient to the collector at a rate determined by the ambient concentration.

Passive monitors have been developed for a wide variety of air pollutants including sulfur dioxide (*35*), carbon monoxide (*36*), benzene (*37*) and nitrogen dioxide (*36*). In principle, any gas for which a selective and efficient absorber is available can be monitored in this fashion. It is also possible to use non-specific absorbers such as activated charcoal and to analyse the absorbed gases by gas chromatography (*9,38,39*).

Pollen concentrations in the air are commonly measured by counting pollen impacted on a sticky surface, using standard methods. Radon can be measured in the indoor environment with passive monitors (*40*). All integrated sample monitors have the characteristic that, at low ambient concentrations, the sampling time must be extended if accuracy is required. Integration times range from days to weeks or months; in general they will be of the order of hours only in the case of high ambient concentrations.

Real-time continuous monitoring. For many indoor air pollutants there are very large variations in concentration with time and location. Real-time continuous monitoring provides a record of instantaneous or short average time concentrations. Although there is a clear advantage in obtaining such a record when peak concentrations are important, or when source strength or infiltration rates vary over time, there are numerous disadvantages as well. Continuous monitoring equipment requires considerable electric power and is bulky, expensive and quite labour-intensive. In indoor air quality studies, continuous monitoring equipment is often placed in a mobile laboratory which draws air sampling streams from the space concerned. Maintenance, adjustment and calibration, as well as reading of output recordings, all require considerable effort. In view of the competence and care required for continuous monitoring, as well as the intrusiveness and expense of the process, it is usually used only for research. Standardized instrumentation is available for a large number of gases and for suspended particulates.

Monitoring of personal and population exposure

With the growing recognition that air pollutant concentrations often vary considerably according to location and time, and that people often spend 80–90% of the whole day within enclosed spaces, it is necessary to determine the total exposure of individuals and populations to different air pollutants in order to assess the adverse health effects associated with them. Epidemiological studies of the health effects of air pollution should ideally be based on personal total exposure, although in practice this is not always possible and personal passive monitoring is often the only feasible way of acquiring such exposure data.

At the same time any efforts aimed at reducing exposures will require monitoring of the spaces which people occupy and which contain most of the sources of indoor air pollutants. Alternatively the air pollutant concentration in such spaces may be estimated by modelling the spaces on the basis of certain characteristics of their structure and contents and the type of activities taking place in them.

In practice, most spaces will have to be characterized by modelling, validated by passive monitoring in a number of the spaces, and further validated by real-time continuous monitoring in an even smaller number of spaces.

Time-budget reports by a number of individuals in a study population can be used to validate time-budget data obtained from other studies (*41*).

Biological monitoring

Some pollutants and the human exposure to them can be measured by determining their level in the blood, urine or hair. Exposure to heavy metals such as lead or mercury can be assessed effectively by such means. Exposure to CO can be assessed by determining the level of carboxy-haemoglobin in the blood, or the level of CO in expired air. In many cases of odours in the atmosphere, appropriate psychophysical measurements (*42,43*) applied to human observers may be the only means of assessment.

ASSESSMENT OF HEALTH EFFECTS

The methods for the assessment of adverse health effects depend on the features of the pollutant and the type of health effect produced. In some cases, we may know the exposure–response relationship, but lack information on the population exposed (e.g. to CO). In other cases, we may also lack knowledge about the effects. In general, pollutants whose characteristics and effects are inadequately known (e.g. most volatile organics) must first be characterized chemically and studied toxicologically prior to any assessment of their health effects. In the case of pollutants that have been characterized, but are coupled chemically, further toxicological study may be required in order to characterize the mechanisms and interactions of the effects and to estimate the exposure–effect relationships (e.g. organic components of tobacco smoke). Some pollutants may be well characterized, but occur in concentrations sufficient for study only in occupational settings, within the limits of our present knowledge (e.g. asbestos, some mineral fibres, some volatile organics); the adverse health effects of those pollutants are therefore best characterized in occupational studies.

To obtain more information about the exposure–response relationship in respect of acute effects, it may be necessary to make human controlled exposure studies (e.g. for odorous organics, NO_2). When further knowledge is required concerning chronic or delayed adverse health effects, partly in order to quantify the exposure–response relationship, the most feasible and efficient method is to make case-control epidemiological studies such as those undertaken to evaluate long-term effects of formaldehyde. Descriptive surveys are often the most effective means of obtaining initial information about the population exposed to different levels of a pollutant, as well as the effects occurring in complex unknown environments (e.g. "sick" buildings). For quantitative assessments of adverse health effects in community populations, it is necessary to use more difficult and costly epidemiological techniques whereby one can measure interactions and try to check for confounding variables. Such studies normally take much longer to complete.

Animal toxicological studies

Most volatile organics from solvents, cleansers and maintenance products, and sidestream tobacco smoke are complex and poorly understood, so toxicological studies are required first (*44*). Synthetic mineral fibres may yield adverse health effects not previously seen, and thus require further toxicological studies. These studies should be done in 1–3 species of animals, and require acute and chronic exposures over a wide range of concentrations, and biochemical and pathological techniques for evaluation.

Occupational studies

Some pollutants are well characterized, but occur primarily in occupational settings. Further definition of their effects and exposure–effect relationships requires additional occupational studies.

Asbestos-related studies have mostly been conducted in an occupational setting, but may also be undertaken in the population or in association with cancer registries with case-control methods if an appropriate exposure assessment is possible. The pollutants that may require such studies include synthetic mineral fibres, and some volatile organics that have been characterized and located in the work setting (e.g. toluene, formaldehyde). Radon daughter effects in uranium and non-uranium miners have provided most of the information on exposure–effect relationships, but only at relatively high dosages and in the presence of high concentrations of other pollutants such as dust and diesel fuels. Epidemiological studies of radon daughter effects in the general population would appear to deserve only a low priority, given the small likelihood of significant results.

Controlled exposure studies in man

Knowledge is still lacking concerning acute exposure–response relationships in man for some well-characterized pollutants. Thus, studies of controlled acute exposure at different doses, in individuals with potentially different sensitivity (e.g. asthmatics, allergic dermatitis patients) under different conditions, are still needed for NO_2. Odours are best studied using controlled exposure methods, often in conjunction with other methods such as descriptive surveys and psychophysical assessments (*42,43*).

Design of sequential studies

There is a sequence of studies for carcinogenic substances. They usually start with studies of mutagenesis in cell cultures and are then followed by long-term studies in animals to study carcinogenicity and mutagenicity. Occupational and/or case-control studies may follow. To obtain more complete information, these are often followed by epidemiological studies in community populations. Studies of teratogenesis may proceed in a similar fashion.

There is also a sequence of studies in "sick" buildings. Following exposure assessment and descriptive surveys of health, pattern analysis will yield hypotheses about possible exposure–response relationships. These are then tested using other methods, including laboratory studies. Studies of odours may follow a similar sequence:

(*a*) mapping of symptoms, analysis of complaints (part of an early warning system);

(*b*) determination of associations between symptoms and common environmental factors;

(*c*) construction of hypotheses about exposure–response relationships;

(*d*) testing of hypotheses in controlled studies:
- — animal
- — human;

(*e*) validation of findings in the laboratory and field; and

(*f*) investigation of etiology:
- — animal models
- — other studies.

Methods used to assess specific health effects are dependent on those effects. Both the methods and their quality control have been widely discussed (*45*). They include questionnaire surveys, tests of function, bioassays and biological monitoring. Applications of clinical and psychophysical methods in studies of indoor pollutants have also proved successful recently.

Epidemiological studies

The suitability of epidemiological methods for studying the relationship between a pollutant and adverse health effects is influenced by several factors. From knowledge provided by studies of pollutants alone in the environment and by toxicological experiments, it is possible to make an assessment of the information that might be obtained from population studies. However, this will vary according to the expectations of the studies and the way in which the results are to be used. Some studies may be descriptive, being designed to determine possible health effects in the population exposed to certain kinds of pollutant. Others may seek to quantify a dose–response relationship between a pollutant and adverse health effects. In the latter case, the study design must be such that precise measurements can be made of the exposure and health effects, independent of the effects of other factors related to health.

The following points should be considered.

1. The availability of methods to measure the pollutant. For example, some methods may be impractical or too expensive to use in large surveys.

2. The distribution of the pollutant in time and space. As measurements cannot be made for an unlimited period in large surveys, exposure may be impossible to assess precisely. This may lead to biases or random error which, in turn, may weaken an epidemiological study.

3. The availability of methods to measure the adverse health effect to be studied. For example, practical methods may not be available for use in large surveys or, alternatively, some methods or measurement techniques may be unsuitable for use in certain groups of the population, such as children.

4. The frequency of occurrence of the health effect. For example, when the frequency is low, a large sample must be used if the effect of the pollutant on health is small, or a small percentage of the population is likely to be affected.

5. The time interval expected between the exposure and the eventual health effect. For example, carcinogenic effects are identified several years after exposure to the pollutant.

6. The interaction between pollutants and other factors such as socio-economic characteristics of the home, smoking, and occupational exposure which might not easily be shown in population studies.

Consideration of these points with reference to epidemiological studies of the effect of indoor pollutants has important implications for the design of future studies. Sample size can be considerably reduced by designs that allow the selection of people who have undergone known heavy exposures and are of high sensitivity or vulnerability, together with controls of similar characteristics but not the exposure in question. As a result much better exposure determinations can be made, further increasing the power of the study. What might be referred to as a staged design might thus be particularly suitable for epidemiological studies of the effect of indoor air pollutants. In a staged design, initial estimates of indoor air pollution exposures are made by simplified modelling of a large number of dwellings in a sample representative of an even larger universe. If the population of each of these dwellings is characterized in terms of demographics, pollution sources and a simple health profile, then small cohorts of people with particular exposures, as well as appropriate controls, can be studied using prospective or cross-sectional methods. This smaller sample may in many cases allow more decisive studies than would be possible in the much larger original sample, which has much greater random variation in exposure and vulnerability.

LEVELS OF KNOWLEDGE ABOUT EXPOSURE AND HEALTH EFFECTS

In its initial discussions, the Group agreed on the range of complex and single indoor air pollutants it wished to focus on, but did not establish an order of importance for them. The final list included: tobacco smoke (passive smoking), NO_2, CO, radon, formaldehyde, SO_2, CO_2, O_3, asbestos, non-asbestos mineral fibres, organics and allergens (Table 1). In assessing current knowledge about exposure the Group considered, for each pollutant, the fraction of the population exposed to minimal or low levels of concentration and the fraction exposed to levels high enough to be of public health concern. An attempt was made to identify the types of location where such exposures occur. All the pollutants have been observed in homes, and most in offices, schools and other public buildings. CO and O_3 have been noted in cars and aeroplanes, respectively, and CO and NO_2 have been measured in skating rinks when gasoline-powered ice treatment vehicles are used indoors. Organics and allergens have been noted especially in hospitals. In addition, the Group rated the present knowledge about sources of indoor air pollutants, about the distribution of such sources, and about the characteristics of sinks including ventilation. It also considered the adequacy of the instrumentation and current knowledge about population exposure based on monitoring of indoor concentrations and/or personal exposure.

The consensus of the Group on these questions is presented in Table 1. The estimates of the fraction of people exposed to either low or high levels of each pollutant were based on the following rating: "few" denotes an estimate of less than 10% of the population, "some" an estimate of between 10% and 50%, and "most" an estimate of more than 50% of the

Table 1. Current levels of knowledge about population exposure

Pollutant	People with low exposure	People with high exposure	Sources	Distri-bution	Instrumen-tation	Indoor/ personal monitoring
Tobacco smoke (passive smoking)	most	some	+	±	±[a]	±
NO_2	some	some	±	0	+	±
CO	most	few	±	0	+	±
Radon and daughters	most	few	±	0	+	0
Formaldehyde	most	few	±	±	+	±
SO_2	few	few	±	±	+	0
CO_2	most	few	+	±	+	+
O_3	few	few	±	+	+	±
Asbestos	few	few	0	0	±	0
Mineral fibres	few	few	0	0	±	0
Organics	most	some	±	0	±	0
Allergens	most	some	0	0	±	+

[a] For respirable particulates.

+ = adequate
± = marginal
0 = inadequate

population. Exposure to infectious agents was considered, but because of the numerous differences between these and all the other agents it was decided not to include them in the analysis. It was, of course, recognized that in the case of airborne infectious agents, the ventilation and recirculation rates are important parameters governing concentration as well as spread through a building. In general the available instrumentation was judged to be adequate to determine indoor concentrations of pollutants, with some weaknesses in respect of the organic and gaseous fractions of tobacco smoke, mineral fibres, organics and allergens. The costs of much of the instrumentation are high and this limits its usefulness in contributing to population exposure estimates. In general, indoor monitoring and personal monitoring data were judged marginal or inadequate. It was felt that in many cases the identification and quantitative characterization of pollutant sources and their strength was marginal to adequate. Their distribution is known to a much smaller degree, and as a result population exposure data cannot easily be derived from the somewhat better knowledge available about sources.

The Group then assessed current levels of knowledge about exposure–response relationships (Table 2). It considered the level of knowledge about the population exposed to indoor pollutants, and especially the distribution of exposure among the population, and assessed the ability to estimate exposures of special groups such as young children, the elderly, and those with chronic cardiorespiratory impairments. Table 2 shows that our knowledge about exposure distribution in the population was considered inadequate, and marginal for a few pollutants with mostly outdoor sources, such as O_3 and SO_2. Tobacco smoke is ubiquitous and its distribution was regarded as being at least marginally known. There was complete agreement about the nature of the adverse health effects expected or suspected to be associated with each pollutant. The exposure–response relationship is very important in making health impact assessments and in only a few cases was an adequate level of knowledge deemed to be available. It was felt that typically exposure–response relationships were better understood in acute responses, but that carcinogenic and systemic effects tended to be much less accurately described. Because of the nature of chronic exposures and delayed effects, it is impossible to determine exposure–response relationships in controlled human exposures, and epidemiological information is scarce. Organics could not be effectively considered because of the variety of chemicals involved and the variety of specific responses to them. Once a particular chemical is identified, data on the responses can often be found in the occupational health literature to allow an initial assessment. Usually it is not possible to assess any additive or synergistic effect of combinations of such chemicals. The Group also considered for each of the pollutants the means of control that are available and appropriate, in the categories of technical, regulatory, social, educational and preventive medical intervention.

It is clear from the assessments in Tables 1 and 2 that the Group deemed the current level of knowledge inadequate to arrive at estimates of impact on a population. There are clear differences in the types of source and the public health concerns in different countries. Because of the widespread use of unvented gas-fired instantaneous water heaters in the Netherlands (*46*), there is naturally special concern about CO and NO_2 levels in that population. In Scandinavian countries where unvented combustion sources are uncommon or prohibited, but where building envelopes are tighter and radon releases from the soil higher, there is greater concern about exposures of radon and daughters and exposures to formaldehyde and other organics from building materials, furnishings and consumer products. In other countries the major concern may be about indoor levels of pollutants emitted outdoors, or organic substances emitted indoors from the use of consumer products. The Group noted the regional differences in priorities based on climate, building characteristics, types of fuel in use, and outdoor levels of pollutants.

Although estimates of overall public health impact are still very difficult to make, the Group did arrive at a preliminary consensus regarding pollutant levels below which concern would be minimal, and pollutant levels above which enough concern exists to call for corrective action. The estimates are given in Table 3, together with the concentrations reported in indoor non-occupational environments. It should be pointed out that these are estimates based on current knowledge and are subject to revision if additional data become available. Moreover, it should be emphasized that all the gaseous pollutants were considered on their own, excluding other contaminants.

In conjunction with its discussions on concentrations, the Group considered the general problems in applying the considerable body of research findings, guidelines and standards concerning the outdoor environment and the occupational indoor environment to the non-occupational indoor environment. Uncritical application would clearly lead to serious difficulties. The concentration indoors may be higher or lower than the level outdoors, depending on the origin of the pollutant and the presence of sinks and indoor sources. The time pattern of concentration may be different: in the case of outdoor pollutants, the indoor concentration lags and its peak is lower than the peak concentration outdoors. Alternatively, with indoor sources, the peaks may be much more pronounced than those observed outdoors. Occupational exposures are of shorter duration than indoor non-occupational exposures, and specially sensitive populations tend not to experience them; conversely the indoor population that is the most vulnerable may also spend almost 100% of its time in the indoor environment. In the outdoor environment, "indicator" air pollutants such as SO_2 may be regulated in part because of their potential for conversion to sulfates and acid precipitation, an outcome which is not of importance in the indoor environment.

Table 2. Current levels of knowledge about exposure-response relationships

Pollutant	People with low exposure	People with high exposure	Population exposed	Adverse effects at levels of concern	Exposure-response relationship	Means of control
Tobacco smoke (passive smoking)	most	some	±	irritation	±	regulatory
				odour	±	technical
				airway respiratory	±	social
				carcinogen	0	educational
				systemic	0	
NO_2	some	some	0	airway respiratory	0	technical
				odour	±	regulatory
				systemic	0	educational
CO	most	few	0	systemic	+	technical, regulatory
Radon and daughters	most	few	0	carcinogen	±	technical, regulatory
Formaldehyde	most	few	0	irritation	±	technical
				odour	±	regulatory
				airway respiratory	±	
				carcinogen	0	
				systemic	0	
SO_2	few	few	±	airway respiratory	0	technical, regulatory
CO_2	most	few	0	systemic	±	technical
O_3	few	few	±	irritation	+	technical (indoors)
				airway respiratory	±	
				odour	+	
				systemic	0	
Asbestos	few	few	0	respiratory disease	±	technical
				carcinogen	±	regulatory

Table 2 (contd)

Pollutant	People with low exposure	People with high exposure	Population exposed	Adverse effects at levels of concern	Exposure–response relationship	Means of control
Mineral fibres	few	few	0	airway respiratory	±	
				irritation	±	
Organics	most	some	0	odour	0	technical
				irritation	0	regulatory
				systemic	0	educational
				airway respiratory	0	
				carcinogen	0	
Allergens	most	some	0	airway respiratory	±	social
				odour	±	regulatory
				irritation	±	medical[a]

[a] The medical measures are *preventive*.

\+ = adequate.
± = marginal.
0 = inadequate.

THE "SICK" BUILDING SYNDROME

The first "sick" buildings were recognized prior to 1960, and since then there have been increasing numbers of case reports in several countries, particularly during the last six years.

Symptoms

The symptoms reported, primarily in the Scandinavian countries and the United States, are of a broad spectrum but have many features in common such as:

— eye, nose and throat irritation

Table 3. Consensus of concern about indoor air pollutants at 1982 levels of knowledge

Pollutant[a]	Concentrations[b] reported	Concentration[b] of limited or no concern	Concentration[b] of concern	Remarks
Tobacco smoke (passive smoking)	0.1 - 1 respiratory particulate	≃0	—[c]	Japanese standard 0.15 mg/m³
NO_2	0.05- 1	< 0.19	> 0.32	according to WHO EHC 4 (*47*), 99.9%
CO	1 - 100	< 11 (2% COHb)	> 30 (3% COHb)	continuous exposure
Radon and daughters[d]	4 -8 000 Bq/m³	≃0	> 70 Bq/m³	Swedish standard for new houses
Formaldehyde	0.06- 1.3	< 0.06	> 0.12	long- and short-term
SO_2	0.02- 1	< 0.5	> 1:35	SO_2, alone, short-term
CO_2	600 -9 000	<4 500	>12 000	Japanese standard 1 800 mg/m³
O_3	0.04- 0.4	< 0.12	> 0.15	WHO EHC 7 (*48*)
Asbestos	<10⁶ fibre/m³	≃0	>10⁵ fibre/m³	for long-term exposures
Mineral fibres	—	—[c]	—[c]	
Organics	—	—[c]	—[c]	

[a] All gases were considered on their own without other contaminants

[b] Concentrations are given in mg/m³ unless otherwise indicated

[c] Because of the complex nature of these pollutants, meaningful concentrations cannot be given

[d] 1 Bq/m³ = 0.027 nCi/m³.

[e] Account was taken only of short-term effects of SO_2 on its own, without particulates, or sulfates or NO_2 which may be present simultaneously and are then likely to be the limiting factor. For long-term exposures, outdoor air quality standards or guidelines will provide a better margin of safety

- sensation of dry mucous membranes and skin
- erythema
- mental fatigue
- headaches, high frequency of airway infections and cough
- hoarseness, wheezing, itching and unspecific hypersensitivity
- nausea, dizziness.

The frequency of the above symptoms is high in any population, and as a result it is difficult to establish an association with the indoor environment in a single case.

The number of case reports describing similar symptoms is now so large that it is reasonable to assume that we are dealing with a true environmental health problem, which is often referred to as the "sick" building syndrome.

Frequency

In a nationwide survey of about 1500 Danish citizens aged 15–67 years, 15–30% reported symptoms of the type described above (at home and at work).

In the city of Stockholm occupants of 110 nursery schools out of a total of 1800 have complained about similar symptoms. In a survey by the Swedish Teachers' Union more than 40% of schools, nursery schools and similar institutions built since 1976 are reported to have indoor climate problems similar to the "sick" building syndrome.

Common features of "sick" buildings

A first category of so-called temporarily "sick" buildings must be distinguished. It comprises either newly constructed or newly remodelled buildings, where the symptoms decrease in time and mostly disappear after approximately half a year. It is possible that the decline in symptoms is due to evaporation of the volatile compounds in building materials, paints, etc.

In the second category of permanently "sick" buildings, the symptoms persist for years and are sometimes resistant even to extensive remedial action. Normally no obvious cause is evident in this category, even after extensive investigations of the composition of the air and performance of the ventilation system, and of the building structure itself. However, it appears that such buildings have certain features in common.

1. They almost always have a forced ventilation system, usually serving the whole building, or large sections of it, and relying on partial

recirculation of the air. Some buildings have an inappropriately located air intake, while others use heat exchangers that transfer pollutants from the return air into the air supply.

2. They are often of relatively light construction.

3. The indoor surfaces are to a large extent covered with textiles, including wall-to-wall carpets, and other features of the interior design favour a large interior surface-to-volume ratio.

4. They are energy-efficient, are kept relatively warm, and have a homogeneous thermal environment.

5. They are characterized by airtight building envelopes (in the United States windows often cannot be opened).

Suggested causes of the "sick" building syndrome

It has to be stressed that our present knowledge about the causes of the "sick" building syndrome is fragmentary, and provides only a weak basis for recommended control measures.

Thermal factors often play a role, in which case it is recommended that an analysis of the thermal environment is carried out to ensure that temperatures and temperature gradients are not excessive, and that clothing, air humidity and air velocity are appropriate.

As regards airborne irritant pollutants, one should ensure that formaldehyde is not present in adverse concentrations. It should be noted that other irritants may cause symptoms almost identical to those produced by formaldehyde. Such irritants may originate from building and surface materials, furnishings, and human use of household or hobby products. At present we know very little about interactions among low-level irritants. It is possible that, in the case of some compounds at subthreshold concentrations, a summation or potentiation takes place, causing sensory reactions to the mixture of pollutants. It is also possible that chemical reactions take place, converting less irritating compounds to more irritating ones.

The homogeneous thermal indoor environment and the homogeneous air quality produced by recirculation may increase the probability of locally generated pollutants spreading throughout the building and exposing all the occupants to them for a long period of time.

The reasons for complaints may also be subjective. In a study of attitudes towards airconditioning, carried out in a large office building in Zagreb, two thirds of the respondents showed a negative attitude, mostly caused by psychological factors (*49*).

It is usually not possible to find suitable controls to establish the background prevalence of complaints in a comparable population, but in one case where this was done an identical prevalence of the same symptoms was reported in the other building (*50*).

METHODOLOGY AND PRIORITIES FOR FUTURE STUDIES

Future exposure studies should focus on the following three major objectives.

1. Determination of the distribution of population exposures so that the exposures of different population groups at risk can be evaluated.

2. Improvements in health effects' evaluation by determining individual exposures of the subjects studied.

3. Development of effective control strategies and evaluation of the effectiveness of such strategies.

As previously indicated, studies of the effect of indoor air pollution often follow a sequence of steps. The first of these is frequently exploratory: a few indoor spaces are selected for a study in which, using a predetermined approach, a number of field measurements are made of the pollutant concentration. Usually such a study does not involve simultaneous health effect evaluation but deals only with exposure assessment. The second step consists of a more systematic investigation whereby, on the one hand, more complete field studies are complemented by measurement of source strengths and sink strengths in special chambers in the laboratory and, on the other, field measurements are made of ventilation rates and the effects of human activity patterns. Such measurements allow the development of a predictive model, which can be used to estimate pollutant concentrations in a given space if a limited number of characteristics of the space is known. Such models must be validated by field measurements in a number of spaces, after which they can be applied to many more spaces with some confidence. Epidemiological studies can then be mounted to give better estimates of exposure, not only to one pollutant but to a number of pollutants simultaneously.

Although a large number of controlled human exposure studies have been performed for many pollutants, the number using subjects with special sensitivities or with cardiorespiratory impairment is still quite limited. To assess non-occupational indoor exposures it will be necessary to carry out such studies on vulnerable populations.

Especially in field studies, where a large number of measurements must be made in many locations, it is most important that a number of precautions be carefully observed. For intercomparison and evaluation of measurements, information must be recorded and reported on the following points:

(*a*) the type, model and sensitivity of the instruments used;

(*b*) the experimental schedule, consisting not only of the daily schedule but also a record of the periods during which observations were made;

(*c*) a detailed description of the methods used to ensure and control the quality of measurements (see reference 18 for recommendations concerning suitable programmes of measurement procedures);

(*d*) the location of the sampling units, given in enough detail to allow the measurements to be repeated, especially if point sources are involved;

(*e*) the averaging time and the time resolution of the measurement, as well as the data reduction procedures; and

(*f*) the building characteristics, ventilation rate, sources of other pollutants, the pattern of smoking by occupants, and other relevant factors.

Although instrumentation should be available for almost all needs, the Group agreed that in a number of cases it is either inappropriate or too costly for large-scale studies. The following needs were specifically identified.

1. For personal exposure assessment, there is a need for a portable monitor capable of recording NO_2 concentration continuously or with a short time constant. Similarly, there is a need for a system that can provide assessments of average exposure to formaldehyde over 6–24 hours, and exposure to allergens over short periods of time.

2. For survey measurements of spaces, there is a need for passive monitors capable of 24-hour time resolution and other simple and inexpensive detection methods. There is also a need for simpler and less expensive (and less intrusive) methods of measuring ventilation and infiltration.

3. For laboratory applications and detailed field measurements, there is a need for instruments that can sense acids and reactive organic compounds.

4. There is a need for further development of bioassay and biological monitoring methods. Standardized psychophysical methods are needed for odour evaluation. Although in principle procedures for the analysis of complex organic chemical mixtures are available, the existing instrumentation is costly, complex and often inaccessible.

The Group considered the priorities it would assign to the different pollutants in further exposure assessment work, taking into account the relative importance of the exposure and the current state of exposure assessment. High priority in exposure assessment was assigned to organic chemicals, respirable suspended particulates, NO_2 and allergens; medium priority to CO, formaldehyde, radon and infective agents; and lower priority to CO_2, asbestos, non-asbestos mineral fibres, O_3 and SO_2.

With regard to adverse health impact assessment it was noted that, although epidemiological studies have been undertaken to investigate the possible carcinogenicity of passive smoking and its relationship to respiratory diseases, further work is clearly required. NO_2 and its effects in the indoor environment have been evaluated in a number of epidemiological studies, some using personal samplers to assess exposures (*51*). Since this method does not provide information on peak values of NO_2 concentration, which may be the relevant factor, additional studies will be required. It will be necessary to study controlled human exposures to NO_2 on its own to observe the acute responses.

More information is required on the distribution of population exposure to radon and its daughters, formaldehyde, SO_2, O_3 and CO_2. The need for and efficacy of epidemiological studies may then be assessed. The practicability of performing such studies on these pollutants may be limited because of difficulty in determining a suitable range of exposures and suitable measurement methods or, as in the case of radon, the limitation may be the long delay between exposure and response. A considerable amount of work has already been carried out on allergens.

As the complexity of epidemiological studies on the effects of indoor pollution increases, it will become advantageous to characterize a large number of buildings as to structural and pollutant source characteristics, together with the characteristics of the occupants. Such a register will allow the selection of a relatively small number of spaces with their occupants for a particular health effect assessment. The selection process can be used to control for other parameters, thus increasing the power of the study and reducing the cost. Successive studies on different pollutants can be carried out using the same original registry.

The Group recognized the need and desirability of having a steering committee in this complex area, that would be available to provide guidance and coordination on request. Suggestions concerning the objectives, membership and methods of operation of such a committee are given in Annex 2.

CONCLUSIONS

The Group reached a number of widely shared conclusions about the problem of estimating and measuring exposure to indoor air pollutants and the nature and magnitude of the resulting adverse health impacts.

1. An abundance of case histories shows that a variety of air pollutants at high concentrations cause serious adverse health effects, particularly of an acute nature. Much less certainty exists about the delayed adverse health effects of chronic exposure to indoor pollutants at concentrations moderately above background levels.

2. Although a considerable amount of indoor air quality monitoring has been carried out, the level of knowledge about population exposure is still inadequate. Estimates of population exposure will therefore have to be made from an appropriate description of the characteristics of the building stock and a description of the internal sources, including man. The combined distribution of these factors will be required for such an assessment.

3. Reports of "sick" buildings are increasing. In many cases it is difficult or impossible to associate the indoor pollutants with the reported health effects. The reported health effects are usually the sort which are also found in other similar populations.

4. The pollutants found in indoor air are also encountered in outdoor air, or in workplaces. For many of them, various authorities responsible for public health or occupational health have formulated and promulgated health criteria documents, concentration guidelines and even ambient air quality standards. The Group considered the applicability of such criteria, guidelines and standards to the indoor environment and concluded that it was limited. In adopting values for guidelines and standards, a great number of factors are taken into account such as the fluctuation of concentration over time, the mixture of pollutants involved, transformations in the atmosphere, etc. These factors vary widely according to the setting and guidelines; criteria and standards for the occupational environment, the outdoor environment and the indoor environment (e.g. for SO_2) may be quite different.

5. There was general agreement that, in principle, the required equipment for measuring indoor air quality is available, although the cost is often high. The ability to analyse and characterize complex mixtures of organic chemicals is still limited and cheap screening methods are not yet available.

6. Epidemiological studies of the adverse health effects of pollutants in the outdoor air are probably of very limited use in assessing the health impact of indoor pollution exposure, since most were carried out without taking into account how the indoor environment would modify the exposure. It is quite likely that new studies which do take the indoor environment into account will find significant health effects at concentrations that gave inconclusive results in earlier studies.

7. The level of knowledge about exposure of the population and about the exposure–effect relationship is inadequate, even to estimate the total impact on public health of indoor exposure to any one of the pollutants considered: tobacco smoke, NO_2, radon and daughters, formaldehyde, SO_2, CO_2, O_3, asbestos, mineral fibres, organics and allergens. The most serious inadequacies are in the knowledge of the distribution of sources of pollution, of the exposure–response relationship and of the population exposed. Data from monitoring of exposure were also inadequate. Emission characteristics of the sources, the measuring equipment and the type of adverse health effect to be expected were more adequately known.

RECOMMENDATIONS

The Group made the following recommendations.

1. A critical review paper on adverse health effects of formaldehyde should be prepared. It could conclude with recommendations about future research needs.

2. Building materials and furnishings with high rates of emission of toxic substances should be identified, as a first step in the process of classification of these materials according to their adverse health effects.

3. An assessment should be made of SO_2 and O_3 concentrations in multiple compartments in indoor environments, to provide data on total exposure and to make new risk assessments of these pollutants.

4. Adverse health effects of NO_2, CO and other pollutants due to passive tobacco smoking and improper indoor combustion should be studied together.

5. Organic substances are ubiquitous in indoor air, but very little is known about the form of exposure involved. Priority should be given to identifying and quantifying these chemicals in the indoor environment.

6. The exposure to radon and daughters is largely determined by the level of radon emission by soil, groundwater and building materials. Priority should be given to the study of the relative contribution of these three sources in various geographical areas.

7. Consumers should be encouraged to use appropriate technical means for the effective control of combustion products indoors. Unvented combustion indoors should be discouraged or prohibited. Education of the public is an effective way of bringing about improved indoor air quality.

8. It is recommended that a working group be convened to review the indoor air quality aspects of building and housing codes and, if appropriate, draft recommendations for indoor air quality sections in such codes.

9. In some countries, registries exist which contain specific information about buildings, such as construction materials, heating methods, room sizes, etc. Although these registries have been created for other purposes, they could also serve studies of the effect of building characteristics on the health of the occupants.

10. For surveys, the development of passive monitors using 24-hour time integration (the accumulation over 24 hours) is recommended for nearly all contaminants. Surveys also require the development of proper questionnaires to obtain ancillary information. For surveys measuring indoor air quality, a simple and inexpensive device for measuring ventilation rates is needed and its development is urgently recommended.

11. Field studies of exposure to indoor air pollutants and the adverse health effects associated with them should be carried out, whenever possible, on representative sample populations.

REFERENCES

1. **Fanger, P.O. & Valbjørn, O., ed.** *Indoor climate effects on human comfort, performance and health.* Copenhagen, Danish Building Research Institute, 1979.
2. *Health aspects related to indoor air quality: report on a WHO Working Group.* Copenhagen, WHO Regional Office for Europe, 1979 (EURO Reports and Studies, No. 21).

3. **US National Academy of Sciences/National Research Council.** *Report of the Committee on Indoor Pollutants.* Washington, DC, National Academy Press, 1981.
4. Proceedings of the Symposium on Health Aspects of Indoor Air Pollution. *Bulletin of the New York Academy of Medicine,* **57**: 825–1084 (1981).
5. **Aurand, K. et al., ed.** *Luftqualität in Innenräumen.* Stuttgart, Gustav Fischer, 1982.
6. Indoor Air Pollution. Proceedings of the International Symposium on Indoor Air Pollution, Health and Energy Conservation. *Environment international,* **8**(1–6): 1–531 (1982).
7. **Yocom, J.E. et al.** *A study of indoor–outdoor air pollutant relationships.* Washington, DC, National Air Pollution Control Administration, 1974, Vol. 1.
8. **Moschandreas, D.J. et al.** *Indoor air pollution in the residential environment.* Gaithersburg, MD, US Environmental Protection Agency, 1978 (document EPA-600/7-78-229).
9. **Wallace, L. & Ott, W.** Personal monitors: a state of the art survey. *Journal of the Air Pollution Control Association,* **32**: 601–610 (1982).
10. **Keller, M.D. et al.** Respiratory illness in households using gas and electricity for cooking. I. Survey of incidence. *Environmental research,* **19**: 495–503 (1979).
11. **Melia, R.J.W. et al.** Association between gas cooking and respiratory disease in children. *British medical journal,* **2**: 149–152 (1977).
12. **Letz, R.J. et al.** Pulmonary functions of children and indoor NO_2 concentrations in Portage, WI. *Indoor Air Pollution. International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, MA, 13–16 October 1981* (unpublished paper).
13. **Bridge, D.P. & Corn, M.** Contribution to the assessment of exposure of non-smokers to air pollution from cigarette and cigar smoke in occupied spaces. *Environmental research,* **5**: 192–209 (1976).
14. **Drivas, P.J. et al.** Experimental characterization of ventilation systems in buildings. *Environmental science and technology,* **6**: 609–614 (1972).
15. **Jacobi, W.** Activity and potential d-energy of radon-222 and radon-222 daughters in different atmospheres. *Health physics,* **22**: 441–450 (1972).
16. **Berglund, B. et al.** The influence of ventilation on indoor/outdoor air contaminants in an office building. *Environment international,* **8**(1–6): 395–400 (1982).
17. **Moschandreas, D.J. & Steck, J.W.C.** *The GEOMET indoor/outdoor air pollution model.* Gaithersburg, MD, US Environmental Protection Agency, 1978 (document EPA-600/7-78-106).
18. *Estimating human exposure to air pollutants.* Geneva, World Health Organization, 1982 (WHO Offset Publication, No. 69).

19. **Leaderer, B.P.** Air pollutant emissions from kerosene space heaters. *Science,* **218**(4577): 1113–1115 (1982).
20. **Mølhave, L. et al.** [*Emissions from building materials*]. Copenhagen, Danish Building Research Institute, 1982 (report 137) (Danish, with summary in English).
21. **Leaderer, B.P. et al.** Ventilation requirements in buildings. 3. Particulate matter and carbon monoxide from cigarette smoking. *Atmospheric environment* (in press).
22. **Stranden, E. & Berteig, L.** Radon in dwellings and influencing factors. *Health physics,* **39**: 275–284 (1980).
23. **Castrén, O.** The contribution from bored wells to respiratory radon daughter exposure in Finland. *Natural radiation environment,* **3**: 1364–1370 (1978).
24. **Pickrell, J.A. & Griffis, L.C.** Formaldehyde release from formaldehyde-resin containing products: effect of conditioning at 100% relative humidity. *Indoor Air Pollution. International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, MA, 13–16 October 1981* (unpublished paper).
25. **Dietz, R.N. & Cote, E.A.** Air infiltration measurements in a home using a convenient perfluorocarbon tracer method. *Environment international,* **8**(1–6): 419–434 (1982).
26. **Sherman, M.H. et al.** *Air infiltration measurement techniques.* Berkeley, CA, Lawrence Berkeley Laboratory, 1980 (document UCLBL-10705).
27. **Mattingly, G.D. & Peters, E.F.** Wind and trees: air infiltration effects on energy in housing. *Journal of industrial aerodynamics,* **2**: 1–19 (1977).
28. **Bahnfleth, D.R. et al.** Measurement of infiltration in two residences. Part I. Technique and measured infiltration. *ASHRAE transactions,* **63**: 439–452 (1957).
29. **Coblentz, C.W. & Achenbach, P.R.** Field measurement of air infiltration in ten electrically heated houses. *ASHRAE transactions,* **69**: 358–365 (1963).
30. **Tamura, G.T.** Measurement of air leakage characteristics of house enclosures. *ASHRAE transactions,* **81**: 201–211 (1975).
31. **Grot, R.A. & Clark, R.E.** Air leakage characteristics and weatherization techniques for low income housing. *In: Proceedings of the Department of Energy/ASHRAE Conference on Thermal Performance of Internal Envelopes of Buildings, Orlando, FL, December 1979.* ASHRAE, Atlanta, GA, 1980.
32. **Wegner, J.** The significance of air exchange for indoor air quality. *In:* Aurand, K. et al., ed. *Luftqualität in Innenräumen.* Stuttgart, Gustav Fischer, 1982.

33. **Lindall, T. & Mansson, L.G.** *Minimum ventilation rates – biological demands.* Stockholm, National Institute of Environmental Medicine, 1981 (report 4/81).

34. **Johansson, I.** Determination of organic compounds in indoor air with potential reference to air quality. *Atmospheric environment,* **12**: 1371–1377 (1978).

35. **Palmes, E.D. & Gunnison, A.F.** Personal monitoring device for gaseous contaminants. *Journal of the American Association of Industrial Hygiene,* **34**: 78–81 (1973).

36. **Palmes, E.D.** *Personal samplers for CO, NO and NO_2 in air.* Washington, DC, US Bureau of Mines, 1977 (report 92-77).

37. **Bamberger, R.L. et al.** A new personal monitor for organic vapors. *Journal of the American Association of Industrial Hygiene,* **39**: 701–708 (1978).

38. **Gillespie, J.C. & Daniel, L.B.** A new sampling tool for monitoring exposure to toxic gases and vapors. *In: Proceedings of the Symposium on the Development and Use of Personal Monitors for Exposure and Health Effects Studies.* Washington, DC, US Environmental Protection Agency, 1979 (report EPA 600/9-79-032).

39. **Seifert, B. & Abraham, H.J.** Use of passive samplers for the determination of gaseous organic substances in indoor air at low concentration levels. *International journal of environmental and analytical chemistry,* **13**: 237–253 (1983).

40. **Fleischer, R.L. et al.** Dosimetry of environmental radon: methods and theory for low-dose integrated measurements. *Health physics,* **39**: 957–962 (1980).

41. **Moschandreas, D.J.** Exposure to pollutants and daily time budgets of people. *Bulletin of the New York Academy of Medicine,* **57**: 845–859 (1981).

42. **Berglund, B. et al.** Olfactory and chemical characterization of indoor air. Towards a psychophysical model for air quality. *Environment international,* **8**(1–6): 327–332 (1982).

43. **Cain, W.S.** *Ventilation and odor control: prospects for energy efficiency.* Berkeley, CA, Lawrence Berkeley Laboratory, 1981 (document UCLBL-4622602).

44. *Principles and methods for evaluating the toxicity of chemicals. Part I.* Geneva, World Health Organization, 1978 (Environmental Health Criteria, No. 6).

45. *Guidelines on studies in environmental epidemiology.* Geneva, World Health Organization (Environmental Health Criteria) (in press).

46. **Brunekreef, B. et al.** Indoor carbon monoxide pollution in the Netherlands. *Environment international,* **8**(1–6): 193–196 (1982).

47. *Oxides of nitrogen.* Geneva, World Health Organization, 1977 (Environmental Health Criteria, No. 4).
48. *Photochemical oxidants.* Geneva, World Health Organization, 1979 (Environmental Health Criteria, No. 7).
49. **Sverko, B. & Vulmirozic, Z.** [An investigation of attitudes towards air-conditioned offices]. *Arhiv za higijenu rada i toksikologiju,* **30**: 323–332 (1979) (Serbo-Croat, with summary in English).
50. **Levine, M.S. et al.** An investigation of health concerns and environmental measurements in a large office building. *Indoor Air Pollution. International Symposium on Indoor Air Pollution, Health and Energy Conservation, Amherst, MA, 13–16 October 1981* (unpublished paper).
51. **Florey, C. du V. et al.** The epidemiology of indoor nitrogen dioxide. *In*: Aurand, K. et al., ed. *Luftqualität in Innenräumen.* Stuttgart, Gustav Fischer, 1982.

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Subgroup 8 on SO_2 concentrations and indoor/outdoor relationships

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Subgroup 9 on health effects assessment methodologies and priorities

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STEERING COMMITTEE ON INDOOR AIR QUALITY

Research on indoor air quality (IAQ) has attracted increasing attention from the scientific community and regulatory agencies in recent years. A number of research institutes are involved in major investigations in this field. Experts from them attended the Working Group on Assessment and Monitoring of IAQ, convened by the WHO Regional Office for Europe in Nördlingen, Federal Republic of Germany, from 8 to 11 June 1982.

During that meeting the participants stressed the need to coordinate research activities and felt it would be useful and timely to set up a steering committee on IAQ research. For the purposes of such a committee, "indoors" should be understood to refer to such environments as homes, schools, public buildings, vehicles and other enclosed spaces to which people have access; however, industrial working environments would be excluded. In view of the recognized interest of the Regional Office in examining the problem of IAQ on an international level, the participants requested it to establish such a committee, and to act as a permanent secretariat.

The objectives, membership and mode of action of such a committee were defined as follows.

Objectives

1. To identify and assess research and other relevant activities in various areas within the field of indoor air quality, including monitoring, exposure assessment, effects on human health and comfort, control strategies and public policy.

2. To participate in the development and review of IAQ/environmental health criteria.

3. To encourage international coordination of research and thereby avoid unnecessary duplication, by providing a focal point for collecting and distributing newly generated information in conjunction with an appropriate WHO collaborating centre.

4. To provide consultant services, through WHO, to national authorities and intergovernmental organizations regarding specific research requirements in the field of IAQ, and to advise, if so requested, on the development of regulatory programmes.

5. To advise research establishments on research gaps to be filled.

6. To be available as a scientific programme advisory committee for IAQ conferences.

Membership

The Committee will maintain a suitable membership to enable it to discuss the health effects and the physical, chemical and biological characteristics of IAQ.

The Committee will consist of no more than 20 and no fewer than 14 members at any time, to enable effective operation. However, if and when necessary, the Committee may decide to call on the temporary assistance of other experts.

Mode of action

To pursue the stated objectives, the Committee will normally meet at least once a year. If and when appropriate, the Committee may be convened for other specific tasks. In a year in which an international conference on IAQ takes place, the meeting should preferably be held immediately following that conference.

Annex 3

LIST OF PARTICIPANTS

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