INDOOR AIR POLLUTION AND VENTILATION

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A number of factors, including the reconsideration of ventilation standards, the use of new building materials and improved measurement techniques, taken with the fact that people spend 90% of their time within buildings, have lead to an increased recognition in recent years of the importance of airborne pollutants generated indoors. This paper reviews current knowledge concerning the major pollutant groups and discusses appropriate means of control where this is required.

INTRODUCTION

Since the early 1950s considerable attention has been paid to outdoor air pollution, particularly in relation to sulphur dioxide, smoke and, more recently, photochemical smog. However, people generally spend much more time inside buildings than outside. A recent survey (1) in the United Kingdom has shown that the average person spends 90% of his time indoors, and 75% in the home, confirming similar occupancy patterns found in a number of other countries by Szalai (2). Some groups, such as the elderly, very young children and non-working wives may spend even longer in the home. This has lead to the realization that in determining total exposure to a given pollutant the indoor component may be important, and will be the dominant component where indoor levels exceed those generally found in the outdoor air.

Indoor air pollution is a complex topic which involves the expertise of professional disciplines ranging from building services engineering through the pure sciences to medicine. A combination of factors, including the use of new building materials, improved measurement techniques, recognition of previously ignored pollutants and reconsideration of ventilation standards in the light of the need to use energy efficiently, has lead to a rapid increase in interest in this field over the past 5 to 10 years. This paper gives a broad review of the major indoor air pollutants and identifies the most appropriate approaches to control where this is required.

EFFECTS OF INDOOR AIR POLLUTANTS

The possible effects of air pollutants are many, including direct damage to the fabric of a building or its furnishings, reduction in amenity and quality of the environment and damage to the health of occupants. It is the latter which is generally of most concern and much of the discussion in this paper will relate to health effects.

Although airborne pollutants may be absorbed by or act on the skin and the surfaces of organs such as the eyes the main route of entry to the body is the respiratory system. This has a range of defensive mechanisms against invading agents. Fine hair in the nasal passages traps particles while mucous membrane in the upper respiratory system and tracheo-bronchial tract also absorbs particles and neutralises bacterial material. Long-term defence is supplied by the body's immune system. While providing a path for infection to the body as a whole, the respiratory system is itself, in many cases, the prime target for attack by airborne pollutants. Airborne pathogens may give rise to disease in particular organs. Non-pathogenic and inert pollutants may result in irritation or damage to the linings of the airways; overloading or reduction in the effectiveness defensive mechanisms or restriction of the transfer of oxygen via the bloodstream to other bodily tissues. Effects may be acute, i.e. short-lived, reaching a crisis and then receding or chronic, i.e. extended over a long time. Pathogens, for instance, generally result in a an acute response, varying in degree from the common cold to potentially lethal infections such as Legionnaires' Disease, wheras pollutants that damage the respiratory tissues may manifest their effects over a long period of increasingly reduced function or, as in lung cancer, there may be a long latent period before symptoms become apparent. It is clearly useful to establish some form of quantitative relationship between response and the dose received. If the response is immediate or short term then its severity will usually only be related to the magnitude of the exposure. If the response is long term cumulative exposure may be important. In the case of some pollutants, in particular carcinogens, it is the risk of disease occurrence, rather than severity of response, which will be related to exposure.

Further, the ability to resist the effect of an airborne pollutant or the severity of response will vary from person to person. Particular sub-groups within the population at large, such as children, the elderly and those whose health is impaired for other reasons may be especially susceptible. Otherwise healthy individuals may be hypersensitive due to allergic reaction of which there are many types, varying in mechanism and severity. Bodies such as the Health and Safety Executive set limit values for exposure but these are primarily designed for healthy adults in the industrial workplace and may not be appropriate for occupants of other buildings such as offices and dwellings due to differences in the nature of the populations concerned.

Despite the difficulties outlined above there is need for generally agreed standards for exposure applicable to buildings in general. The World Health Organisation has addressed this problem by the publication of air quality standards (3) but at present coverage is limited.

FACTORS DETERMINING EXPOSURE

For any individual, exposure to a given pollutant is determined by the levels of that pollutant in the spaces which the individual occupies and the manner in which the level varies with time and position within that space. The actual dose received may depend upon additional physiological factors, such as rate of breathing. Depending upon the nature of the effect and the dose-response relationship, interest may be directed to integrated exposure covering all of the locations (e.g. home, workplace, travelling, ambient air) in which the individual is exposed or, alternatively, to short-term exposure in a particular location. In either case it is important to know what levels are found in practice and to understand the factors which determine these.

The primary requirement is a source of the pollutant. Within buildings air pollutants may be generated by:

The soil beneath the building.

Building materials.

Furnishings and fittings.

Activities and processes being undertaken within the building.

Combustion (including tobacco smoking).

Human and animal occupants.

The factors which determine the concentration of a given pollutant and its variation with time and place within a building include:

Rate of production (and the way that this varies with time).

Rate of removal (e.g. by absorption, chemical reaction, radioactive decay).

Position of source.

Ventilation characteristics of the building.

Concentration in ambient air.

Mathematical models have been developed which allow concentrations to be computed when the factors above can be quantified. However, because these factors are rarely fully known in practice, such models have limited application at the present time.

In practice the best guide to exposure is obtained by measurement surveys made in selected buildings. Because of the expected variation in the factors noted above, concentrations, whether instantantaneous, short-term average or long-term average will vary considerably between buildings. A carefully designed survey will indicate the distribution of concentration and allow an estimate to be made of, say, the proportion of the population likely to be exposed above a certain level and, therefore, the likely incidence of resulting health effects. Such information is useful in deciding on policy in relation to any programme of remedial action, or in estimating the impact on public health of a general change in one or more of the factors which affect pollutant concentration, for instance, a national trend to reduced ventilation rates. Unfortunately, current information, in the case of most pollutants is sparse.

INDOOR AIR POLLUTANTS

Introduction

There are a number of ways of defining suitable categories for indoor air pollutants. These include (i) by effect (e.g. allergens, carcinogens, odour); (ii) by source (combustion products, tobacco smoke); (iii) by chemical name (e.g. carbon dioxide, carbon monoxide) or (iv) by group (e.g. organics, bacteria). For present purposes, in order to restrict topics for discussion, no single approach has been chosen and commonly used categories drawn from each have been used. Where any overlap is relevant this indicated in the discussion.

Water vapour

Water vapour is a major consituent of the atmosphere, but is generally found at a higher concentration within buildings due to the presence of internal sources. These include metabolic production by human and animal occupants, unflued combustion, and activities such as clothes washing, cooking and bathing. As an indication of typical production rates, an average adult engaged in sedentary activity will generate approximately 35 to 40 g/h. Flueless combustion of common fuels yields a range from 100 to 160 g/h per kW appliance rating. Rates for general household activities are less easily defined but experience indicates that for the total household production will lie within the range 5 to 10 kg/day.

There are no direct health effects from exposure to water vapour and under normal conditions of temperature, experimental studies (4,5) have shown that most people will not be able to discern differences between a relative humidity of 20 and 70%. Below 40% some people may, however, experience dryness and irritation of throat and eyes and, according to some evidence (5), low humidities may be associated with increased respiratory infection. The presence of water vapour and high relative humidities are associated with condensation and colonisation by moulds and other micro-organisms, such as house dust mites. These may engender both mild and serious allergic responses in sensitive individuals, as well as cause damage to the building fabric and furnishings and reduction in amenity. A general condition to prevent the onset of condensation is to maintain relative humidity below 70%.

Carbon dioxide

Carbon dioxide is also a natural constituent of the atmosphere, with a typical concentration of 350 ppm (630 mg/m^3). The major sources within buildings are respiration and combustion. Production rates from these sources are relatively well defined and for common fuels are in the range 0.025 to 0.035 l/s (160 to 290 g/h) per kW appliance rating. For an average adult, engaged in sedentary activity, the production rate is approximately 0.005 l/s (32 g/h), but values an order of magnitude higher than this occur during strenuous exercise. Small quantities of carbon dioxide are produced during tobacco smoking but these are negligible in comparison with those produced by respiration.

Concentrations found within buildings are generally within the range 500 to 1000 ppm (900 to 1800 mg/m^3) although higher values, up to 3000 to 4000 ppm (5400 to 7200 mg/m^3) may be found in poorly ventilated spaces either with a high occupant density, such as school class rooms, or containing unflued combustion equipment.

The respiratory system compensates naturally in ordinary individuals for carbon dioxide concentrations of up to 2 to 3%. As noted above, concentrations as high as this are unlikely to occur in buildings except under wholely exceptional circumstances. The current Threshold Limit Value for occupational exposure is 0.5%. Thus, carbon dioxide presents no serious health hazard in itself but, because of its ubiquity and relative ease of measurement, it has often been used as an indicator of general indoor air quality within buildings (8). For this reason quite low values are often quoted in standards (see for instance ASHRAE 62/81 (9)).

Odour

The human olfactory system is sensitive to a wide range of airborne substances. The degree of sensitivity varies from one substance to another, but in many cases the nose is capable of detecting concentrations well below those which can be measured analytically. Although odours are unlikely to constitute a direct health problem they result from the presence of gaseous or volatile chemicals which may themselve be a hazard or be indicative of the presence of other harmful but non-odorous airborne pollutants. Odours may be perceived as unpleasant and reaction to odour by occupants is a major determinant of indoor air quality and forms the basis of many ventilation standards. The characteristics of odour such as intensity, quality and acceptability cannot be measured by instrumentation but have to be assessed by carefully designed trials using human observers.

In practice the occupants of buildings are rarely exposed to individual odorants but to complex mixtures of odorous components. These are often grouped together and characterised by the assumed source, the most common being body odour, tobacco odour, cooking odour and toilet odour. Body odour derives, inter alia, from volatile fatty acids excreted in sweat and components of flatus. For many years, its control has formed the basis of ventilation standards, in the absence of smoking, for many types of buildings, drawing on studies by Yaglou (10) carried out in the United States in the 1930s. Several recent studies (11,12) have been undertaken to check the current validity of the earlier work.

Carbon monoxide

Carbon monoxide is produced primarily by the incomplete combustion of fuel but also occurs as a product of tobacco smoking. Concentration in combustion products is generally small since most fuel authorities operate type approval schemes for appliances which limit the allowable production rate of carbon monoxide, typically to 2% of that of carbon dioxide. In practice actual rates will depend upon the fuel and the nature and condition of the burners. Typical production rates lie in the range 50 to 500 mg/h per kW appliance input rating. However, incomplete combustion, arising from vitiation of the combustion air can give rise to substantially higher rates (13,14,15). Although primarily of concern with appliances which are designed to operate unflued, conventionally flued appliances can allow combustion products to enter occupied spaces due to mal-operation of the flue due to blockage or inadequate air supply to the space containing the appliance.

Dutch studies (16) found typical 1-hour average concentrations of carbon monoxide in housing in the range 1 to 10 mg/m^3, with the higher levels in kitchens. The operation of flueless water and space heaters can result (17,18) in high short-term concentrations, of the order of 100 to 500 mg/m^3, and a recent study (19) in the United Kingdom found instantaneous carbon monoxide concentrations in the range 5 to 50 mg/m^3 in rooms being heated by gas radiant heaters.

The health effects, illustrated in Figure 1 from data compiled by the U.S. Environmental Protection Agency (20), are primarily related to its ability to combine with haemoglobin and to reduce the oxygen-carrying capacity of the bloodstream. These effects are time related due to the lag before the blood reaches equilibrium following a change in carbon monoxide content of the inspired air. The limits shown in the diagram are lower limits representing the most sensitive individuals. For short term exposures (approximately 1 hour) there are no effects below approximately 50 mg/m^3 and noticeable physiological effects (i.e. slight headache, lassitude etc.) occur in the range 200 to 500 mg/m^3. However, for long-term exposures (approximately 10 hours or more) the concentrations for the same effects become approximately 15 mg/m^3 and 80 to 200 mg/m^3.

Nitrogen oxides

Of the oxides of nitrogen, often collectively referred to as NO_x, that most commonly found in the indoor air is nitrogen dioxide. As with carbon monoxide production rate is dependant upon fuel, appliance type and combustion conditions. Typical values have been determined by laboratory studies in the USA (21,22) and generally lie in the range 10 to 100 mg/h per kW input rating.

A number of field studies (23,24,25), in both the United Kingdom and the United States, have shown significant differences in long term average concentrations of nitrogen dioxide between dwellings with gas and electric cookers. Averaged over a number of houses with gas cooking, concentrations were of the order of 100 μg/m^3 in kitchens and approximately 50 in other rooms in comparison with approximately 15 μg/m^3 in houses with electric cooking. The averaged quantities not only mask variations between dwellings but also the occurrence of very high peak levels, illustrated by recent studies in the Netherlands (16) in which typical maximum 1 hour average concentrations of 500 to 1000 $\mu g/m^3$ were measured.

The potential health effects of nitrogen dioxide are better understood than those of other nitrogen oxides. Concentrations above approximately 200 mg/m^3 are likely to lead to death and respiratory and nasal irritation has been noted at concentrations of the order of 10 mg/m^3. The results of clinical tests are summarised in Figure 2, taken from reference (26).

In view of the possibility that low concentrations of nitrogen dioxide could increase susceptibility to respiratory infection a number of epidemiological studies have been undertaken. In many of these the presence of a gas cooker was used as a proxy for measured concentrations. In a recent review Vedal (27) noted that of nine studies with children as subjects, only in five was an association between exposure and increased incidence of respiratory symptoms found. A similar lack of consensus was also found in relation to adult subjects. More recently Ogston et al (28) carried out a survey of 1581 children in their first year of life. In reviewing their findings in the context of earlier studies they concluded that a very large, and probably impracticable, sample would be required to demonstrate any association and that should it exist "... it is small and evidence indicates that it is outgrown or hidden by other damage to the lung by the age of 10 to 20".

Tobacco smoking

Tobacco smoking is now widely recognised as damaging to the health of smokers. While exposure by non-smokers to tobacco smoke is known to cause irritation to mucous membranes (29,30) and to result in annoyance due to odour (11) it is only fairly recently that direct health effects have been considered.

Tobacco smoke consists of 'main stream' smoke i.e that which is inhaled by the smoker and the remainder, termed 'side stream' smoke. Environmental tobacco smoke consists of the latter plus the proportion of the main stream smoke which is exhaled by the smoker. Tobacco smoke is a complex mixture of particles (primarily tar, nicotine and small quantities of organic particulates), gases and organic vapours. Actual constitution in any given case will depend upon a number of factors, including the type of tobacco and the mode of smoking. However Table 1, taken from the U.S. Surgeon-General's Report on 'Smoking and Health' (31), indicates typical composition of mainstream and sidestream smoke.

Production rates in any indoor situation depend upon the number of smokers and rate of smoking. Recent surveys indicate that about one third of the adult population are regular smokers. Rates of smoking vary considerably between individuals but, in the USA, Cain and Leaderer (30) suggest an average rate of 2 cigarettes per hour, while, in the United Kingdom, Meade and Wald (32) found 1.5 to 2.0 cigarettes per hour for heavy smokers and 0.5 to 0.8 for light smokers.

The health effects of many of the components of tobacco smoke, including carbon monoxide, nitrogen dioxide and respirable particulates, are covered in other sections. It is, however, convenient to discuss the effects of exposure to tobacco smoke as an entity here. Particular concern recently has centred on possible carcinogenic effects. A number of epidemiological sudies have been undertaken but none appears to have produced conclusive and undisputed findings. In reviewing eight of these, Samet (33) noted that three investigations showed significant effects of exposure on lung cancer risk while the other five, although generally indicating a positive association, were not found to be significant. Samet concludes that although an association between exposure to environmental tobacco smoke and lung cancer in non-smokers is indicated, it "...does not yet meet the criteria applied to active smoking in the 1964 U.S. Surgeon General's Report...", largely because of methodological difficulties in estimating exposure.

Organics

Organic pollutants arise from materials within the building and from the building fabric itself. Other sources include occupants and their activities as well as combustion and tobacco smoking. The form in which organic pollutants are found depends upon their volatility. Low molecular weight compounds, with high vapour pressures, are found primarily as gases and vapours while those with higher molecular weights are less volatile and tend in airborne form, to be found absorbed on to particulates.

In general the concentration of individual organic compounds in the indoor air is substantially lower than for the inorganic compounds discussed in previous sections, often is often in the ppt to ppb range. This has, until recently, been a major barrier to the identification and measurement of organic pollutants. However the past five to ten years has seen considerable advances in the development of analytic and collection techniques and instrumentation (36). It is becoming feasible to undertake field studies on a sufficient scale both to identify and to determine typical concentrations of organic pollutants in the indoor air. Wallace (37) notes that over 800 volatile organic compounds alone have been identified. Those of most immediate interest, and about which most is known, are formaldehyde and wood preservatives.

Formaldehyde. Formaldehyde is a colourless gas with a wide range of possible sources within buildings due, in part, to the widespread use of urea-formaldehyde resin as a bonding agent. Common sources include paper products, floor coverings, carpet backing, as well those already noted - combustion and tobacco smoking. Two major sources are pressed wood products, such as particle board, and urea-formaldehyde foamed insulation (UFFI). Concentrations of formaldehyde in the ambient air range widely. Everett (38) found concentrations from 2 to 30 $\mu g/m^3$ and suggested a typical value for U.K. urban environments of 7 $\mu g/m^3$. This accords with values noted by Meyer (39) for the United States. Indoor values for houses without the major sources noted above are typically in the range 10 to 100 $\mu g/m^3$. In a survey of 50 U.K. buildings Everett found an arithmetic mean concentration of 58 $\mu g/m^3$ and quotes Canadian results for a sample of 378 houses giving a mean of 42 $\mu g/m^3$. In each case the distribution was highly skewed with a small percentage of results in excess of 100 $\mu g/m^3$. Higher values, ranging up to 1000 $\mu g/m^3$, have been found overseas in buildings containing large quantities of particle board, particularly mobile homes in the United States (40,41). Similarly high levels have been found in homes in the United States and Canada which have been treated with urea-formaldehyde foamed insulation. In the United Kingdom the incidence of problems arising from the use of UFFI has been much lower than in North America due to the different forms of construction and standards for installation. Everett found concentrations of formaldehyde in buildings treated withh UFFI ranging from approximately 10 to above 1000 $\mu g/m^3$ with a mean of 114 $\mu g/m^3$. Again, the distribution was highly skewed with 70% of the results were less than 120 $\mu g/m^3$. The highest concentrations were found in situations where the insulation had been installed contrary to recommendations in the appropriate standards. It should be noted that the levels of exposure noted above are much lower than those found in many working situations, where levels above 1 mg/m^3 are common.

The 8 hour occupational exposure limit, in the U.K., is 3 mg/m^3, considerably in excess of the concentrations generally found in buildings, even with the presence of the major sources noted above. However, as noted earlier, occupational limits have limited relevance to the general exposure of the population at large. Table 2, taken from reference (42), lists reported acute health effects of short term exposure to formaldehyde, those most commonly found at concentrations occurring in buildings being mucous membrane irritation and odour. Individuals vary considerably in sensitivity, and it is difficult to set a lower limit for any particular response. Long-term exposure to formaldehyde at high concentrations (of the order of 18 mg/m^3) has been found to induce nasal cancers in rats (43). This result has lead to concern that formaldehyde might also be a human carcinogen and has resulted in considerable debate. At present there does not appear to be any direct evidence for human carcinogenicity and Meyer (39) quotes a number of epidemiological studies in occupational groups which show no significant increase on mortality from formaldehyde exposure.

Pesticides. Pesticides are commonly used in buildings as preventive or remedial treatment against wood-boring insects and fungal attack. Dobbs et al (44,45) have measured airborne concentrations of three commonly used compounds - pentachlorophenol (PCP), gamma-hexachlorocyclohexane (gamma-HCH) and dieldrin - both in the the immediate period after application and in a number of houses in which the intervening period following treatment ranged from about 1 to 10 years. Typical concentrations of PCP were of the order 30 $\mu g/m^3$ in the period immediately after treatment, for heavily treated houses, falling to 1 to 10 $\mu g/m^3$ in the long-term, and lower ranges for those with only light treatment. Similar concentrations have been found in Germany (46). Fischer (47) quotes unpublished results from German studies which indicate that typical levels in untreated houses are negligible by comparison. Concentrations, depending upon ventilation rate, of 6 to 30 $\mu g/m^3$ were found, by Levin et al (48), in a California office building containing extensive, exposed, PCP-treated timber.

Dobbs et al (45) found long-term concentrations, in dwellings, of gamma-HCH were found to be in the range 0.1 to 10.0 . g/m^3, showing a significant decrease with time over the number of years since treatment. A similar concentration range, of 0.1 to 4.0 . g/m^3, was found for dieldrin, but in this case, no significant reduction was found with time.

PCP is toxic to human beings (49) and a number of fatalities have occurred in the occupational environment, although primarily by skin contact. Conjunctivitis and irritation of the upper airways have been observed. Isolated cases of cancer have been blamed upon exposure to PCP, but, more importantly it is often associated with small quantities chlorinated dioxins which are highly toxic to man and are known animal carcinogens (49). The occupational long-term exposure limit is 500 $\mu g/m^3$ but there are no recommended acceptable air concentrations for PCP. Dobbs (45), however, derived a limit of 11 $\mu g/m^3$, based upon WHO values for acceptable daily intake (the daily exposure level which during a lifetime appears to be without appreciable risk) which applies to all sections of the population. Similar levels were derived for gamma-HCH and dieldrin of 38 and 0.4 $\mu g/m^3$ respectively.

Comparing these values with the measured concentrations indicates that the health risks in treated buildings are negligible for PCP and gamma-HCH but could give cause for concern in respect of dieldrin, particularly as there may be paths of intake other than the air, such as food and water.

Other organic compounds. A number of general studies have been carried out, designed both to identify organic pollutants present in the indoor air and to measure concentrations, predominantly in dwellings but also in other buildings such as schools. A number of these, carried out in homes and including work done in the U.S.A. (50,51,52), Denmark (53), West Germany (54), Netherlands (55) and Italy (56) have been recently reviewed by Wallace (57) who drew the following general conclusions;

(a) Indoor concentrations are almost invariably higher, on occasion much higher, than outdoor concentrations of the same compound.

(b) Range of concentration between sites is large, often two orders of magnitude.

(c) Sources are numerous.

It has become clear that some simplification of approach is required and current research is primarily aimed at identifying organic pollutants that are common to most buildings and situations and secondly at identifying groups of pollutants that are often found together and which may be correlated with a particular type of source.

In general, concentrations of individual pollutants are very low, usually two to three orders of magnitude lower than occupational levels. It is possible to aggregate the individual concentrations to obtain a total which gives a measure of the impact of volatile organic compounds on the indoor environment. Molhave (58) has reviewed a number of studies and, inter alia, noted that new buildings were found to have a total concentration 10 times higher than old buildings. There are several possible reasons for this:

(a) New buildings may contain more recently developed materials which may have higher emission rates for organic compounds.

(b) Emission rates may reduce with time (as noted previously for formaldehyde).

It is clear that, although guidelines are being established, much more research is needed to establish the nature of personal exposure to indoor airborne organic compounds and to investigate sources and emission rates.

At the present time information is inadequate to assess the health effects of organic pollutants at non-occupational indoor exposure levels. However, the fact that some of these substances are known or suspected carcinogens and that many give rise to acute health effects at higher exposure levels indicates caution and the need to maintain continuing research to characterise sources and to improve knowledge of health effects. A major unkown area is the combined, and possibly synergistic, effect of a large number of organic pollutants, albeit at low concentrations.

Non-viable particulates

Both the ambient air and indoor air contain a wide range of suspended matter, covered by the general term - particulates. Viable particulates, i.e. those comprising or containing living matter, are dealt with in the following Section. 'Non-viable' particulates may be sub-divided, by convention into the following categories:

Dusts and fibres (solids arising from dispersion).

Smoke and fume, (solids/liquid arising from condensation).

Mists (liquid, arising from dispersion and condensation).

Particles vary in shape, but for comparison of sizes it is usual, except for fibres, to refer to the diameter of an equivalent sphere which would have the same terminal velocity in air. Because of their elongated shape, fibres are generally characterised by both diameter and length. Larger particles, say with an equivalent diameter greater than 50 μm, with high terminal velocities, tend to be deposited on surrounding surfaces, and it is only particles smaller than these that remain suspended for significant lengths of time. Although modern instrumentation does allow sizes to be measured, most measurements are made of total mass of particulate matter per unit volume, and referred to as total suspended particulates (TSPs).

In the present context it is convenient to define a sub-range - respirable, suspended particulates (RSPs) - consisting of particles with equivalent diameters less than 5 μm. These cover the range of particles that may penetrate the respiratory system. Larger particles are intercepted in the nose or oesophagus, intermediate particles are deposited in the tracheobronchial region and smaller particles, of the order of 0.5 μm, may reach the alveolar region. The majority of particles smaller than this tend to remain suspended and are expired.

In considering, prevalence and health effects, fibres will be dealt with separately.

Respirable suspended particulates. In comparison with other pollutants measurements of indoor RSPs are sparse. In a substantial study of indoor and outdoor pollution in homes in six American cities Spengler et al (59) found mean monthly indoor concentrations of RSPs only marginally higher than outdoor levels. The mean monthly values of both, averaged over the six cities, varied in the range 20 to 30 $\mu g/m^3$ over a two year period. Broadly similar results were obtained by Lebret (16) in two surveys of Dutch homes. Both studies indicated a substantial increment in RSPs resulting from tobacco smoking which appears to be the prime source within buildings. It is probable, in the absence of smoking, that a high proportion of indoor particulates may originate from outdoors. The detailed physical and chemical nature of RSPs is poorly understood at the present time, although limited studies of trace elements have been made (60).

Possible health effects are likely to depend on the nature of the particle more than gross RSP concentrations. The main danger to health is likely to occur where the natural lung clearance mechanisms are either overloaded or impaired by other disease. Small particles can absorb gaseous pollutants and, by deposition within the lungs, can apply a concentrated dose to local areas of tissue. This may be important in the case of known and suspected carcinogens such as benzo (a) pyrene, found in tobacco smoke. Some non-viable particles have been shown, in the occupational environment, to cause allergic reactions (61). Particles can act synergistically to enhance the effects of other pollutants such as sulphur dioxide. Apart from tobacco smoke, as previously noted, it has not been possible to identify sources which allow assessment of health effects to be quantified. However in the absence of smoking existing indoor levels are likely to be within the standards set for ambient air.

Fibres. The fibrous material of most interest is asbestos, due to its known carcinogenic effects. The term asbestos covers a number of different forms of naturally occurring mineral silicates, the most common of which are crocidilite, amosite and chrysotile. Although primarily of concern in the occupational environment asbestos based materials have been commonly used in buildings for a number of purposes:

Sprayed asbestos insulation.

Pipe and boiler lagging.

Insulation board.

Floor tiles and other fabric components.

Recent measurements (62) of asbestos fibres indicate that exposures rarely exceed 500 fibres/m^3 above background in U.K. buildings containing asbestos.

It is now established from studies of the occupational environment that exposure to asbestos can lead to a number of diseases, including asbestosis, lung cancver and mesothelioma. Recent analysis by Doll and Peto (62) has enabled risk estimates for exposure to asbestos to be estimated. They calculate, using data from the textile industry, that exposure to chrysotile asbestos at a concentration of 500 f/m "...for 40 hours per week for 20 years would produce a lifetime risk of 1 in 100,000 of death from mesothelioma and lung cancer, while risks for longer periods of exposure would be proportionately greater." Taking into account exposure over the full period of a lifetime and including all types of asbestos this risk becomes approximately 1 in 10,000.

Man-made mineral fibres are becoming more widely used in building materials but few measurements of indoor concentrations made in the non-occupational environment have been reported. Health effects have not been established, although there is some suspicion that they may be responsible for irritation of the eyes and respiratory pathways.

Viable particulates

In this context viable particulates are living organisms sufficiently small to have low terminal velocities and to readily remain suspended in the indoor air. They include small insects, such as mites, protozoa, fungi, bacteria and viruses. Although these categories are useful for purposes of classification the boundaries between them are not always clear-cut.

The air both inside and outside contains many micro-organisms. They are not necessarily independent of non-viable particulates and are often found in combination with inert solid or liquid aerosols. House dust, for instance, contains mites, fungal spores and bacteria. Knowledge of the types and concentrations of micro-organisms in the indoor air is at present very limited in comparison with other pollutants. This is in part due to the very large range of species, but also due to the limited availability of appropriate measuring techniques and restricted applicability of such techniques as are available (6).

Outdoor air is a major source of many micro-organisms found in buildings. This is important in assessing exposure and in determining the relative importance and practicability of controlling levels indoors. However, if a suitable substrate and other conditions for growth, such as moisture and nutrients, are available colonies may be formed indoors which can give rise to higher concentrations than in the outdoor air because of the restricted air exchange rate in buildings, particularly in winter.

The presence of water is generally important particularly for most fungal growth, but also in relation to small insects, such as the house dust mite. The latter is known to prefer damp conditions (63,64). Certain types of humidifier and coolers within air-conditioning systems can provide suitable substrates for the growth of micro-organisms (65). In addition the function and design of such systems often provides a ready and rapid means of distribution to other parts of a building.

The occupants of a building are a major source of bacteria and viruses. These micro-organisms may be exhaled, although primarily during speaking, coughing or sneezing, rather than during normal breathing. Large droplets produced under the latter conditions tend to settle fairly rapidly, but small droplets remain airborne for long periods and may evaporate leaving a micro-organism as a remaining nucleus. Bacteria may also be carried by small particles shed from the skin, although these also have a relatively high terminal velocity. As an illustration of the effect of occupancy, in a recent investigation of the effect of relative humidity and ventilation on airborne bacteria in Canadian schools Green et al (66) noted that the number of colony-forming units increased by one to two orders of magnitude within a short time of occupancy.

Unlike other airborne pollutants, it is difficult even to attempt to estimate generation rates for micro-organisms. These may depend upon the disturbance of the source or of particles which have fallen out of the air on to surrounding surfaces or the floor. In fact the act of cleaning may actually increase the airborne content for a period of time (67)

Two broad types of health effect may arise:

(a) Allergy: Many airborne micro-organisms may provoke an allergic response in sensitive individuals. These include fungal spores and house dust mites. The more serious, and ultimately disabling, extrinsic allergic alveolitis, is rare outside of the occupational field.

(b) Infection: A number of common diseases are transmitted by airborne micro-organisms. Common examples include tuberculosis, measles, influenza and the common cold.

Radon

Radon is a gas which is formed as a radioactive decay product of radium. Radium and its parent uranium are widely distributed in the earth's crust and are present in nearly all soils and in building products derived from them. Radon has a half-life of approximately 3.5 days and decays through a series of 'daughter' products to a relatively stable isotope of lead. Possible sources are air passing through the underlying soil and entering through the substructure of the building, building materials and the water supply (if drawn from ground water). Miners and other workers exposed to radon and its daughters are known to exhibit a higher incidence of lung cancer.

Radon is perhaps the best characterised of all indoor pollutants since recent developments in simple instrumentation have allowed both national and regional surveys (68) to be carried out to estimate the distribution of radon concentrations throughout the the U.K. housing stock.

Induction from epidemiological studies on miners, exposed to relatively high levels of radon, and the use of lung dosimetry models has enabled the risk of developing lung cancer to be related to long-term exposure. Lifetime risk for exposure to an dose equivalent of 1 milli-sievert per annum is 1 in 1250. The arithmetic mean dose equivalent for the United Kingdom as a whole is approximately 1.2 mSv per annum (68), yielding an approximate annual risk of 1 in 70,000. The National Radiological Protection Board has recently advised (69) that action should be taken to reduce exposure in buildings where the effective annual dose exceeds 20 mSv. On the basis of national surveys (68) about 20,000 dwellings are likely to affected. For future dwellings an upper bound of 5 mSv/annum is recommended as a basis for implementing changes in building procedures in areas of the country where high levels of radon are likely.

CONTROL OF INDOOR AIR POLLUTION

Introduction

Two important questions need to be answered:

(a) How important is each of these pollutants?

(b) What is the most appropriate means of control, should this be deemed necessary?

Relative importance of indoor air pollutants

The question addressed in (a) above may be expanded to consider importance in relation to;

- the population as a whole, and

- specific groups within the population.

Thus, although information on typical exposures and health effects may indicate that a pollutant may not be a cause for concern in relation to the general population, there may well be sub-groups, who for reasons of abnormal exposure or pre-disposition for whom it may be an important consideration.

Table 3 sets out the main categories of pollutant and proposes their relative importance in relation to buildings of different types. A separate indication is given where a pollutant may be of importance in a sub-group within any building category. Where information is at present limited but a pollutant may possibly be important this is also indicated. It should be noted that the assessments of degree of importance are the personal opinion of the author and need to be refined by exposure to general debate in order to obtain a consensus.

Thus, for example, for dwellings it is suggested that the most important pollutants are water vapour and combustion products, and that while body odour and tobacco smoke should be considered they are of less importance. Formaldehyde and radon may be important under conditions of high exposure, eg in the case of the former immediately after the installation of UFFI, and for the latter if the dwelling is in an area where high radon levels occur in soil gas. Information on organic compounds is insufficient to indicate their importance at the present time.

Means of control

A number of possibilities exist for the control of indoor air pollutants. These include

(a) Restriction on use, or removal, of pollutant sources.

(b) Restriction on emission rates, for instance by sealing.

(c) Direct extract ventilation of air close to the source.

(d) Filtration, or other similar form of removal from the air.

(e) Dilution by relatively unpolluted air.

In choosing any particular method the following factors may need to be considered and balanced against each other:

The nature of the pollutant.

The characteristics of the sources of the pollutant.

The effects of the pollutant.

The practicability of any proposed means of control.

The first cost of any proposed means of control.

The revenue costs of any proposed means of control.

The latter may include costs related to energy consumption. At the present time the implied cost-benefit analysis is difficult to carry out with any precision because in many cases required data are not available. However, it is important to bear in mind that the above considerations will be implicit, if not explicit, in any decision on methods of controlling a particular pollutant.

As a basis for discussion, Table 4 sets out suggested possible and preferred methods for the control of indoor air pollutants, using the same pollutant and building categories as Table 3.

VENTILATION

Ventilation standards

Situations where dilution ventilation is the most appropriate means of control provide, in principle, a basis for setting standards for fresh air supply. These generally occur where the pollutant source is source control or extract ventilation is inappropriate because the source of the pollutant is not well defined, is distributed throughout the space or moves around.

In principle, provided that the source strength is known, a limiting maximum acceptable concentration and, if necessary, the concentration in the outside air are given then the required ventilation flow rate can be calculated assuming steady state conditions (see for instance (70)). In practice it is rare that this approach is used, for a number of reasons, including the following:

(i) As noted earlier, uncontested values for limiting concentrations are rare. There is a need for generally agreed acceptable levels of common pollutants for indoor exposure by the population at large (as opposed to values appropriate to the work-place).

(ii) Source strengths, except in certain instances, are poorly defined and may vary by several orders of magnitude. The exceptions include carbon dioxide generated by respiration or combustion and, although less precisely defined, water vapour in dwellings.

Other problems include the possibility of coupling between the means of ventilation and the source strength, incomplete mixing of the pollutant with the ventilating air or inadequate distribution of the ventilation air. However, possible approaches to setting standards for two types of building - dwellings and offices are discussed briefly here.

Dwellings. The pollutants which most readily form criteria for setting ventilation standards for dwellings are (a) water vapour and, (b) unflued combustion products. They are likely to occur in most dwellings and have reasonably well defined production rates. Suitable criteria for limiting concentrations may also be defined. In the case of water vapour this is to keep indoor relative humidity below 70%. Taking into consideration other relevant factors, such as the levels of heating and insulation, this leads to a desirable range for whole house ventilation rate of 0.5 to 1.0 air changes per hour (71). The criterion for combustion product control may be taken as the need to keep carbon dioxide concentration below 0.5% This value is based upon the need to ensure complete combustion and, hence, to limit the production of the potentially lethal secondary combustion product, carbon monoxide, as discussed in 4.5. Depending upon the fuel this leads to a requirement in the range 5 to 7 l/s per kW rating of the unflued appliance.

Offices. It is more difficult to define a suitable criterion for ventilation requirements in an office space. Of those discussed in this paper only odour and tobacco smoke are likely to be found universally at reasonably well defined production rates. On the basis of recent studies of body odour (11,12) a fresh air supply rate of 8 l/s per person will ensure that 80% of observers entering from outside air will find the odour level acceptable.

It is much more difficult to define to define ventilation requirements in respect of tobacco smoke because of the wide range of possible criteria, including odour, irritation, respirable suspended particulates, carbon monoxide and other chemical components. Depending upon the choice of criterion and assumptions on rates of smoking, a range of ventilation requirements covering almost three orders of magnitude 0.2 to 200 l/s per person results.

Other considerations in relation to ventilation

Although dilution with 'fresh' air may not be the most effective or appropriate means of control where pollutant levels are high, reduction in ventilation, either on an individual or population basis, will generally result in increased exposure to an airborne pollutant in the long-term. Where the dose-response relationship in relation to some health effect is a continuum (eg where there is assumed to be no threshold) there will be an increased risk to the individual and a rise in the number of cases of ill-health in the population as a whole.

CONCLUSIONS

(i) On average persons spend 90% of their time within buildings. Internally generated pollutants may, therefore, contribute substantially to individual exposure and merit at least the same degree of concern that has been attached to outdoor air pollutants.

(ii) There are a wide range of potential indoor air pollutants, some of which have been discussed here. Current knowledge of these is, in many cases, limited and further research is needed to clarify important aspects such as source characteristics and health effects, particularly in relation to volatile organic compounds.

(iii) There are few agreed exposure limits for individual indoor air pollutants in buildings of different types, apart from industrial workplaces, and consideration should be given to developing these.

(iv) Although ventilation with outside air is one method of reducing the concentration of indoor air pollutants, source control will often be the most appropriate method of limiting exposure. Where ventilation is appropriate the approach to defining required flow rates has been discussed and illustrated with reference to dwellings and offices.

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Compound	Mainstream	Sidestream	Ratio Sidestream/ Mainstream
Tobacco burnt	347 (20 sec)	411 (550 sec)	1.2 (27)
No. particles produced	10^{12}	3.5×10^{12}	3.5
Tar	20.8	44.1	2.1
Nicotine	0.92	1.69	1.8
	0.46*	1.27*	2.8*
Benzo(a)pyrene	3.5×10^{-5}	13.5×10^{-5}	3.7
Pyrene	13×10^{-5}	39×10^{-5}	3.0
Phenols	0.228	0.603	2.6
Ammonia	0.16	7.4	46
Nitrogen oxides	0.014	0.051	3.6
Carbon monoxide	19	88	4.7

* Filter cigarette

Table 1 Comparison of the components of mainstream and sidestream tobacco smoke. (Taken from reference (31))

Effects	Approximate Formaldehyde Concentration, ppm
None reported	0 - 0.05
Neurophysiologic effects	0.05 - 1.5
Odour threshold	0.05 - 1.0
Eye irritation	0.01 - 2.0*
Upper airway irritation	0.10 - 25.0
Lower airway and pulmonary effects	5.0 - 30.0
Pulmonary oedema, inflamation, pneumonia	50.0 - 100.0
Death	100.0 +

* The low concentration (0.01 ppm) was observed in the presence of other pollutants that may have been acting synergistically.

Table 2 Reported health effects of formaldehyde at various concentrations. (Taken from reference (41))

Key to symbols: (++) - very important; (+) - important; (o) - important in specific situations; (p) - possibly important, but current knowledge limited.

Building Type	Water vapour	Carbon dioxide	Body odour	Comb. products	Tobacco smoking	Form-aldehyde	Pest-icides	Organics	Partic-ulates	Micro-organisms	Radon
Dwellings	++		+	++	+	o	o	p			o
Living rooms	o		+	++	+	o	o	p			o
Bedrooms	++		+	+		o	o	p		o	o
Kitchens	++	o		++		o		p	p	o	
Bathrooms	++							p	p	o	
Toilets			++								
Office buildings											
Small offices			+		++	o/p		o/p	o/p	o	
Open plan offices			++		++	o/p		o/p	o/p	o	
Schools											
Class rooms	+		++	o		o		o/p	o/p	+	
Gymnasia			++								
Laboratories				+		o		+	o	o	
Auditoria											
Theatres, cinemas			++		++			o/p		+	
Lecture halls			++		++			o/p		+	

Table 3 Pollutants of main concern for different types of buildings

Building Type	Water vapour	Carbon dioxide	Body odour	Comb. products	Tobacco smoking	Form-aldehyde	Pest-icides	Organics	Partic-ulates	Micro-organisms	Radon
Hotels											
Bedrooms			+		+			p			
Bathrooms	++		+							+	
Public rooms			++		++			p	+	+	
Shops			++		++	o		o/p	o/p	+	
Hospitals			++		++	o	p	o	p	++	
Restaurants			+		++					+	
Sports Halls	+		++					p			

Table 3 (continued)

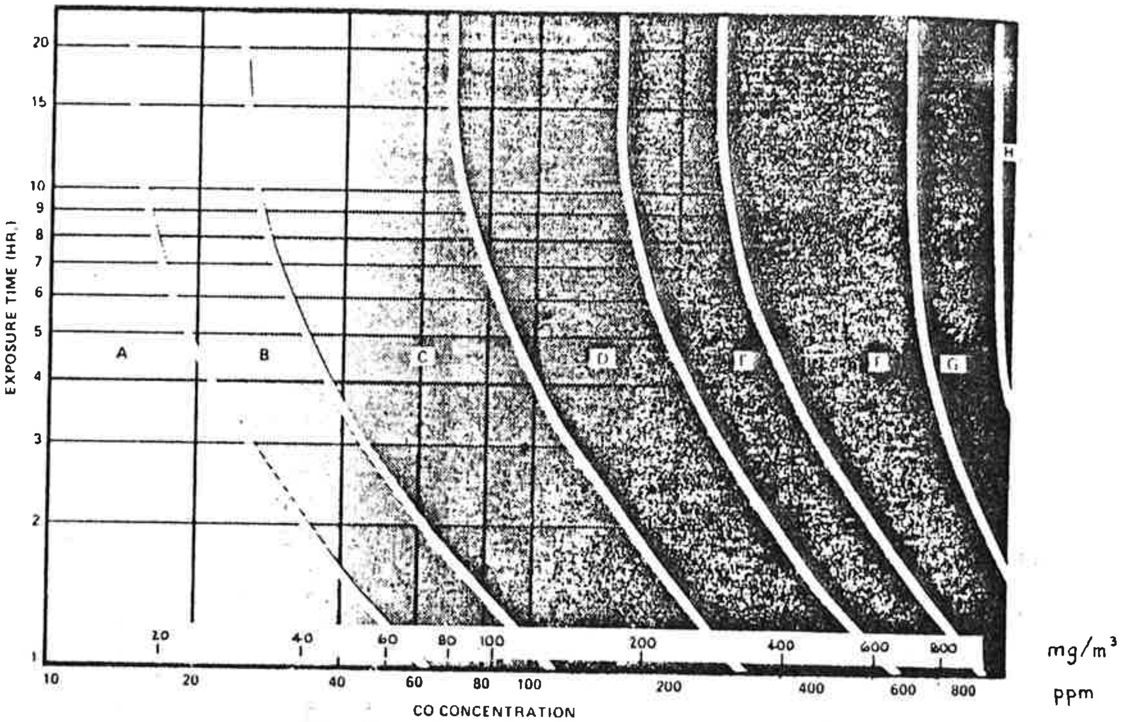
Key to symbols: (V/v) - Dilution ventilation; (E/e) - Local extract ventilation; (F/f) - Removal from air (by filtration or other means)
(S/s) - Source control (by sealing or similar means); (B/b) - Source control (by restriction on presence or use of source)
[Note: Preferred method - Upper case (ie V,E etc.); Possible method - Lower case (ie v,e etc.)].

Building Type	Water vapour	Carbon dioxide	Body odour	Comb. products	Tobacco smoking	Form-aldehyde	Pest-icides	Organics	Partic-ulates	Micro-organisms	Radon
Dwellings	E,V,s		V	E,v,s	V,b	B,s	B,s,v	B,s,v	S,b,v,f	b	S,v
Living rooms	V		V	E,v,s	V,b,f	B,s	B,s,v	S,b,v	S,b,v,f		S,v
Bedrooms	V	V	V			B,s	B,s,v	S,b,v		S	S,v
Kitchens	E,v			E,v			S,b,v	S,v	s		
Bathrooms	E,v		V	B,v							
Toilets			E,v								
Office buildings											
Small offices			V		B,v,f	B,s,f,v		B,s,v	B,s,f	b,s,f	
Open plan offices			V		B,v,f	B,s,f,v		B,s,v	B,s,f	b,s,f	
Schools											
Class rooms	v		V	E,v		B,s	B,s	B,s,v	S,v	b	
Gymnasia			V					B,s,v	S	b	
Laboratories	E,v			E,v							
Auditoria											
Theatres cinemas			V		B,v	B,s		B,s	s,f	b,s,f	
Lecture halls			V		B,v	B,s		B,s	s,f	b,s,f	

Table 4 Suggested possible and preferred methods of pollutant control

Building Type	Water vapour	Carbon dioxide	Body odour	Comb. products	Tobacco smoking	Form-aldehyde	Pest-icides	Organics	Partic-ulates	Micro-organisms	Radon
Hotels											
Bedrooms	V		V		V			S,b	S,b		
Bathrooms	E,v		V	B,v							
Public rooms			V	v	V,b						
Shops			V		V,b	B,s,v		B,s,v	B,s,f,v	B,s,f	
Hospitals	E,v		V	E,v	B,v	S,v		S,b,v	S,b,f	S,b,e,f	
Restaurants	E,v		V	E,v	V,b					B	
Sports Halls	V		V		B,v						

Table 4 (continued)

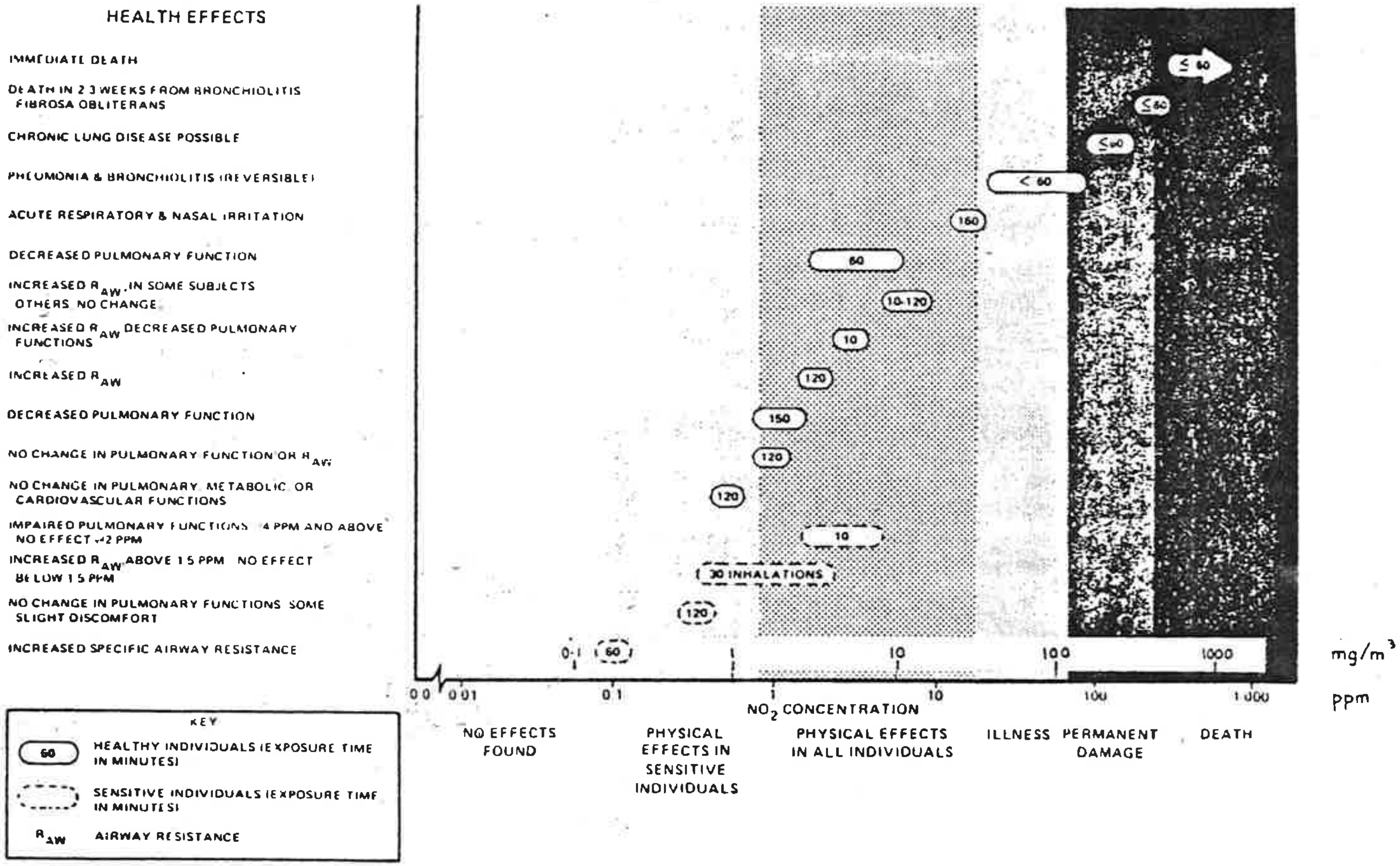


HEALTH EFFECTS KEY

CATEGORY	EFFECTS
A	Physiologic norm for non smokers.
B	Cardiac function decrements in impaired individuals; blood flow alterations; and, after extended exposure, changes in red blood cell concentration.
C	Visual impairments, vigilance decrements, reduced maximal work capacity. Norm for smokers.
D	Slight headache, lassitude, breathlessness from exertion, dilation of blood cells in the skin, abnormal vision, potential damage to fetuses.
E	Severe headaches, nausea, abnormal manual dexterity.
F	Weak muscles, nausea, vomiting, dimness of vision, severe headaches, irritability, and impaired judgement.
G	Fainting, convulsions, coma.
H	Coma, depressed cardiac activity and respiration, sometimes fatal.

Note: The thresholds shown are lower limits, applying to the most sensitive individuals.

Figure 1 Health effects of exposure to carbon monoxide. (Taken from reference(22))



<u>Figure 2</u> Health effects of short term exposure (less than 3 hours) to nitrogen dioxide in healthy and sensitive humans. (Taken from reference (26))