Assuring indoor air quality

Increasing concern about problems in the office environment creates headaches for building services engineers. But these multi-faceted problems can give occupants worse symptoms. Paul Appleby here outlines recent work on indoor air quality (IAQ) and gives guidance on preventive medicine for healthy building

Occupants of some office buildings report a range of symptoms, including headache, fatigue, nausea, dryness of the mucous membranes, running and itchy eyes, stuffy or running noses, flu-like symptoms, and more rarely, tightness of the chest and itchy skin rashes. These symptoms recur with significant frequency and usually reduce in severity or disappear when the sufferers are away from the office environment.

A recent study (1) has shown a strong correlation between self-reported productivity and number of symptoms. It is clear also that absenteeism is also prevalent in buildings whose occupants experience a large number of symptoms.

These symptoms are most prevalent in air conditioned buildings, despite their higher ventilation rates and lower contamination levels compared with naturally ventilated buildings. Although it is likely that poor ventilation and indoor air quality (IAQ) contribute to sick building syndrome (SBS), there may be, perhaps more influential, causes which are a function of the types of building which require air conditioning. Many of the symptoms associated with SBS may result from poor IAQ, although it is usually easier to identify and quantify an IAQ problem than to establish the multiple contributory factors in a building sickness investigation.

Recent surveys have found that, although SBS-related symptoms are generally fewer in naturally ventilated buildings, specific complaints related to air quality and the thermal environment can be more prominent.

In all cases problems are more likely to occur in buildings which are neglected and poorly maintained, and where working conditions are poor. It is perhaps not surprising that, in the UK at least, occupants of public sector buildings experience more symptoms than those in the private sector. This may be due, in part, to the financial constraints imposed on the public sector, resulting in a cutback in preventive maintenance, densely occupied spaces and generally a low standard of office accommodation, plant and equipment.

What's in the air?

Exposure to the constituents of non-industrial atmospheres usually involves exposure to a cocktail of thousands of substances all having relatively low concentrations compared with their occupational exposure limits. Typical individual concentrations are frequently in the order of one thousandth of the occupational exposure limit, or less.

Substances found range from the relatively harmless products of metabolic processes, to low concentrations of highly toxic and, in some cases, carcinogenic substances. Table 1 gives a list of some common organic compounds found in past surveys of the office atmosphere and sources which have been identified for them.

In general terms, potential sources of contaminants include:

- the ground: natural source of gases such as radon and methane
- the ground: gases emanating from earlier dumping of waste
- outdoor air: industrial pollutants, vehicle exhaust, dust etc
- building materials: organic compounds, radon gas
- building furnishings and materials: mainly organic compounds
- cleaning, photocopying and other processes: organic compounds, particulates, ozone
- products of complete and incomplete combustion: unflued heaters, cooking, tobacco smoking: thousands of chemicals, respirable suspended particulates (RSP)
- mouldy surfaces
- poorly maintained water spray equipment, such as spray humidifiers: bacteria, amoebae, spores
- internals of ventilation and systems: particulates, micro-organisms, organic compounds
- human and animal occupants: mainly water vapour, CO_2 and particulates, plus low emissions of thousands of organic compounds.

Any one contaminant may emanate from a number of sources.

Table 1 Sources of some common volatile organic compounds found in office atmospheres

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Chemical	Potential source
Acetone	Lacquer solvent, tobacco smoke
Benzene	Tobacco smoke, adhesives, spot cleaners, paint remover, particle board
2-Butanone (MEK)	Caulking, particle board, floor & wall covering, fibre board, tobacco smoke
Carbon tetrachloride	Grease cleaners
Chlorobenzene	Paint solvent, DDT, phenol
Chloroform	Clothes washing
Ethylbenzene	Floor/wall coverings, insulation foam, chipboard, caulking, jointing, fibreboard, calcium silicate sheet, adhesives, lacquer, grease cleaners
Methylene chloride	Paint removers, aerosol finishers
Styrene	Insulation foam, jointing, fibreboard, tobacco smoke
Perchloroethylene	Dry cleaning
Toluene	Adhesives, sealing tape, wall paper, jointing compound, calcium silicate sheet, floor covering, vinyl, caulking, paint, paraffin stoves, tobacco smoke, grease cleaners
1,1,1 Trichloroethane	Cleaning fluid, dry cleaning, correction fluids
Trichloroethylene	Paint solvents, grease cleaners
Xylene	Adhesives, jointing, wall paper, caulking, floor coverings, lacquers, grease cleaners, shoe dye, tobacco smoke
Hexane	Floor covering, wall paper, chipboard, gypsum board, insulation foam, tobacco smoke
Heptane	Floor covering, varnish, kerosene stoves
Ethanol	Fibreboard, solvents, tobacco smoke
Ethyl acetate	Linoleum, varnishes, perfumes, artificial leather
Cyclohexane	Tobacco smoke, lacquers, resins, paint removers
n-Nonane	Wall paper, caulking, floor covering, chipboard, adhesives, cement, jointing, floor varnish, kerosene stoves, floor wax
n-Decane	Floor adhesive, floor wax, wood stain, polyurethane, room freshener
n-Undecane	Wall paper, gypsum board, floor/wall coverings, jointing compounds, chipboard, floor varnish, paint, paint removers
n/i-Butanone	Edge sealing tape, jointing compound, linoleum, floor lacquer, cleaners, paint removers, tobacco smoke

Comfort, health, odour and irritation

Comfort has been defined as "that condition of mind which expresses satisfaction with the . . . environment". Most comfort standards are based on the concept of an acceptable level of dissatisfaction, normally taken as 20%. The North American standard "Ventilation for Acceptable Indoor Air Quality" (2) uses this level of dissatisfaction in its definition of acceptable indoor air quality. A more elaborate model for acceptable indoor air quality may be evolved by combining this concept with the World Health Organisation's basis for establishing comfort guideline values for individual chemicals (3). Thus, indoor air quality may be said to be "acceptable" if less than 50% of the occuants can detect any odour, less than 20% experience discomfort, less than 10% suffer from mucosal irritation and less than 5% experience annoyance for less than 2% of the time. Although not defined by WHO, in this context annoyance probably refers to the case during which odour and irritant effects are sufficiently prominent to be distracting.

A comfortable indoor air quality is primarily one which is not unacceptably malodorous. However some contaminants which cannot be detected by the olfactory sense may produce mucosal irritation or long term health effects, some of which might be life-threatening.

In this context, Occupational Exposure Limits (4) provide limits on occupational exposure to airborne substances hazardous to the health, and are primarily used for assessing compliance with the UK Health & Safety at Work etc Act 1974. In theory, they apply equally to the non-industrial and the industrial workplace. Where a single substance dominates (high "signal to noise" ratio) these may be used to determine dilution ventilation rates or as an indicator of the toxicity of the substances and hence aid the evolution of a strategy for the control of exposure. However, in most non-industrial environments the signal to noise ratio is low and ventilation strategy must be based on empirical data and past experience.

Occupational Exposure Limits are designed for healthy people working a normal working week, with no allowance for other stresses. Some people may suffer health effects due to exposure to some contaminants at concentrations below the Occupational Exposure Limit. For example, some sensitised individuals may experience allergic reactions.

The human nose is extremely sensitive to low concentrations of some chemical substances. For example it can detect 1 mg m^{-3} of Toluene (see Table 2), one of the most commons VOCs to be found in the non-industrial atmosphere, whereas the UK Occupational Exposure Limit, time weighted for a 40 hour working week (OEL TWA) is 375 mg m^{-3}.

A substance which enters the nasal cavity may be sensed by two separate detection systems. The olfactory sense, which is responsible for odour detection, and the common chemical sense, which is sensitive to irritants. These two senses interact, for example it is possible for an odour to be disguised by irritation and vice versa. A single substance may evoke sensations of both odour and irritation. Humans are known to adapt to odours with time, whereas irritation may be compounded with time. In the specific case of exposure to environmental tobacco smoke, a recent study (5) has found that irritation intensity increases by a factor of two during the first hour of exposure, after which steady state occurs. The same study found that perceived odour intensity fell off by a factor of 50% and levelled out after only a few minutes.

Many of the sources mentioned above produce odours, some of which may be perceived as pleasant, some unpleasant. Some evolve from the release of potentially harmful substances, although it is not usual for exposure to airborne contaminants in non-industrial buildings to be associated with irreversible health effects. Exceptions have been thought to include exposure to radon gas—mainly in homes—and lead from emissions in vehicle exhaust.

Because odour perception is highly subjective it is extemely difficult to measure. Olfactometers have been developed for use by trained panellists but no automatic sensor has yet been developed which accurately simulates the response of the nose. Sensors are available which give an approximate indication of air quality. For example CO_2 sensors provide a signal which is indicative of the contribution of body odour to the overall odour levels. Unfortunately odours are also emitted by processes and materials which do not emit CO_2.

Studies have indicated that general perceptions of odour are at their lowest at humidities in the range of 45 to 65% sat at normal comfort temperatures, although this varies with the nature of the contaminant. However the odour emission rate from many materials, such as paint, rubber, upholstery, floor coverings, etc, tends to reduce with falling humidity.

The adsorption of odours onto internal surfaces, and their subsequent desorption as temperature, air velocity and vapour pressures change, can lead to a considerable increase in odour levels as conditions become favourable for desorption. During one recent study (14) a panel of non-adapted people were asked to judge the odour intensity in bars after all occupants had left and compare it with the odour intensity from the ETS generated by the equivalent smoking level in a non-adsorptive chamber. On average, odour intensities were judged to be higher in the unoccupied bars. This was thought to be primarily due to the desorption of gaseous components of tobacco smoke, which had been adsorbed onto internal surfaces, along with the particulate matter, during occupancy.

It has been suggested (6) that for every occupant and associated odours in an air conditioned building, there could be up to 6 or 7 odour equivalents (olfs) associated with environmental tobacco smoke, building materials, furniture, mould spores and the internal components of the air handling system. This survey (6) of office buildings in Copenhagen found that, on average, there were 17 people, each emitting 1 olf, smokers emitted 35 olf per office room, building materials, furniture etc emitted 28 olf and the ventilation or air conditioning system emitted 58 olf.

Laboratory tests have found that odours are released from the fungicides used to treat filter material and thermal wheels, as well as the lubricants and fan belts associated with motors and fans. Poorly maintained air handling systems release odours from accumulated dirt in filters and other internal surfaces. Bio-fouling of cooling coils, moisture eliminators and spray ponds is a problem.

A recent survey of existing air handling units (7) found that the filters, thermal wheels and spray humidifiers were major polluters in nearly all systems examined.

Room air movement & ventilation efficiency

Sufficient uncontaminated outdoor air must be available to dilute locally produced contamination throughout the occupied zone of a building. This air must be provided in such a way as to ensure an acceptable quality of inhaled air for each occupant.

The precise contaminant distribution within a room depends on the room air movement and may be quantified in terms of the ventilation index, which is determined from:

$$\text{Ventilation index} = \frac{\text{contaminant concentration in extract air}}{\text{contaminant concentration in inhaled air}}$$

This is known as the ventilation efficiency or effectiveness.

In theory, values for ventilation index could lie between zero and infinity. For example, if all the air supplied to a room were extracted before it diluted any of the contaminants in the occupied zone, then the ventilation index would be zero. At the other extreme, if all the contaminants released were carried away in the extract system, resulting in no measurable concentration in the inhaled air, the index is infinity.

Most air-conditioning and ventilation systems rely on grilles and diffusers to discharge supply air across a ceiling, which may also contain extract openings. Heat transfer and contaminant dilution rely on mixing of supply and room air, most of which occurs above the heads of the occupants. The usual aim is to create uniform temperature and air purity throughout the occupied zone.

with [illegible] ventilation index of unity. [illegible]ome short-circuiting occurs, [illegible] in values less than unity. The momentum from supply jets can generate draughts and carry contaminants, such as tobacco smoke, from source to recipient.

Systems which discharge air into the lower part of the room (8) are not usually designed to mix the supply and room air. Room air movement is primarily due to upward room con[illegible] currents, displacing room-[illegible]ed contaminants which strati[illegible] above head level. Hence values for ventilation index are usually much higher. Unfortunately contaminants which are generated below head level, such as smoke evolving from a cigarette lying in an ashtray, may find their way into the breathing zone of nearby occupants.

Ventilation requirements

[illegible]ational standards or guidance on ventilation rates give outdoor volume flow rates per person or, in some cases, per unit floor area. In Section B2 of the 1986 CIBSE Guide separate recommendations are given for rooms in which there is no smoking and for various densities of tobacco smoking (see Table 2). These rates are based on achieving 80% [illegible]ction for non-adapted occ[illegible]. They do not account for any additional emission of contaminants from the materials and equipment which may enter the occupied areas of a building.

The new ASHRAE Standard (2) allows for the designer to calculate an appropriate ventilation rate from first principles. This "Indoor Air Quality Procedure" involves the calculation [illegible]ation or displacement ventila[illegible]ate, based on limiting concentrations for non-industrial exposure to contaminants and a prediction of the ventilation efficiency or index. There is, however, a dearth of published comfort limits for non-industrial exposure to specific contaminants, and little data on the emission rates of chemicals from the sources found in office buildings.

Table 3 summarises the standards currently published, which fall into 3 categories: (a) Comfort guidelines, based on 30 minute odour detection thresholds. (b) External pollution health-based standards for continuous exposure and allowing protection for vulnerable individuals. (c) Occupational exposure limits, health based, 8 hour per day exposure of healthy individuals.

[illegible]ger (9) provides a method by which a ventilation rate can be calculated using a form of dilution equation based on diluting the total malodorous contaminant load, the "olf load", to an acceptable perceived air quality level in decipol, assuming a perceived outdoor air quality level.

Since little data is yet available on odour emissions from specific sources, Fanger provides typical "olf loads" for different types of building, based on field studies using panels of "sniffers". For a typical office he suggests an olf load of 0.4 olf m^{-2}, whilst for a "low-olf" building an olf load of 0.1 is suggested. This implies that if a building is designed with low emission materials, smooth cleanable internal surfaces, minimal shelfing and smoking is prohibited, ventilation rates can be reduced to a quarter of that required for a typical office building. For example, for acceptable indoor air quality, with 20% dissatisfaction, he suggests a perceived air quality of 1.4 decipol, whereas a typical outdoor vote in a (Danish) town gives 0.2 decipol. A typical office would need around 32 litres s^{-1} per person to achieve acceptable indoor air quality, whereas a "low-olf" building would need 8 litres s^{-1} per person. The ventilation rate can be further reduced if a ventilation index greater than 1.0 is predicted.

Conclusions

There are many potential sources of contaminants in buildings. Sometimes they are at sufficiently high concentrations to create odours, but little is known about health effects of these substances in mixtures, and when combined with other stressors associated with the workplace. Although airborne contaminants may contribute to the symptoms associated with sick building syndrome, it is unlikely that they are a major contributing factor in most cases.

Good ventilation is an important means of reducing contaminant levels and odours in office buildings. Ventilation rates should not simply be based on the number of occupants, but allowance should be made for other odour sources.

Room air movement influences the proportion of outdoor air entering the space which reaches each occupant, and the distribution of contaminants throughout the building.

Hence air quality problems can be avoided in most buildings providing attention is paid to the selection of low emission materials, consideration is given to the banning of smoking and the provision of smoking lounges, sufficient ventilation air is provided, and ventilation efficiency is maximised by careful design of the room air diffusion system.

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Table 2 Recommended outdoor air supply rates for sedentary occupants (CIBSR Guide 1986)

Condition	Recommended outdoor air supply rate (litre/s per person)
with no smoking	8
with some smoking	16
with heavy smoking	24
with very heavy smoking	32

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Table 3 Comparison of UK Occupational Exposure Limits (OELs), WHO guidelines and ASHRAE standards

Substance	OEL ($\mu g/m^3$)	WHO Guideline ($\mu g/m^3$)	ASHRAE Standard 62-1989 Outdoor air ($\mu g/m^3$)	ASHRAE Standard 62-1989 Indoor air ($\mu g/m^3$)
Carbon monoxide	55×10^3	10×10^3	10×10^3 (8h)	
Carbon dioxide	9×10^6			1.8×10^6 (continuous)
Formaldehyde	1.5×10^3	100 (30min)		
Particulates	10×10^3	70 (thoracic particles)		
Nitric oxide	30×10^3			
Nitrogen dioxide	6×10^3	210 (1 hour) 80 (24 hour)	100 (1 year)	
Ammonia	18×10^3			
Acrolein	250			
Ozone	200	150–200 (1h) 100–120 (8h)	235 (1h)	100 (cont)
Sulphur dioxide	5×10^3	500 (10min)	365 (24h)	
Toluene	375×10^3	7.5×10^3 (24 hour) 1.0×10^3 (30 min)		
Styrene	215×10^3	800 (24h) 70 (30 min)		