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Ensuring good indoor air quality in buildings

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Introduction

According to the latest UN data, 54.5% of the world's population was living in urban settlements in 2016, with 23%, or 1.7 billion, living in cities with at least a million inhabitants. That percentage is estimated to rise to 60% by 2030. In the same period the number of cities with 10 million inhabitants is expected to rise from 31 to 41. With the growth in urbanisation comes the risk of increased air pollution, which the World Health Organization estimates is the cause of three million deaths globally each year.

While outdoor air pollution can impact the quality of indoor air in buildings, an array of other factors also negatively affect indoor environments and the health of occupants. This is a critical issue given that people living in developed countries typically spend 90% or more of their time indoors, with the most susceptible individuals – such as the elderly and those with pre-existing medical conditions – spending almost all of their time inside (Crump et al, 2009).

Creating good indoor environmental quality (IEQ) by improving factors such as indoor air quality, lighting and acoustics, is increasingly recognised as improving occupant health and comfort, and physical and mental wellbeing. It also provides opportunities to reduce healthcare costs. In 2015, for example, BRE updated its research into the cost of poor housing to the NHS and found that improving the 3.5 million 'poor' homes in England would save the NHS £1.4bn in first-year treatment costs alone.

Health and wellbeing have also risen up the agenda for companies who realise that unhealthy and poor-performing buildings directly impact their businesses. A growing body of evidence confirms that healthier buildings can lead to happier and therefore more productive employees. The World Green Building Council, for example, states in its 2016 report 'Building the Business Case: Health, Wellbeing and Productivity in Green Offices', that employees account for 90% of a company's operating costs. Just a 1% improvement will therefore have a significant impact on the bottom line. Developers and landlords also recognise that healthy buildings can improve sales, command higher rental incomes, and attract and retain tenants in longer term leases.

However, while health and wellbeing considerations have emerged in certification schemes (e.g. BREEAM and WELL), Building Regulations and guidance such as the UK Air Quality Strategy, there is still a lack of understanding of IEQ factors, particularly indoor air quality (IAQ). IAQ is complex with many factors affecting it, including a wide range of pollutants and sources, and building types, locations and décor. Exposure to different pollutants can cause varying health effects, from the worsening of asthmatic conditions and irritation of the skin, to premature deaths caused by heart and lung disease.

Buildings in urban areas are exposed to pollutants from outdoor sources, such as road traffic, boiler flues and other combustion plants, industrial processes and construction activities – so good ventilation is essential. In the past ventilation has depended on air permeability through cracks and gaps in the building fabric, combined with air bricks, windows and mechanical ventilation. This does not necessarily improve indoor air quality and can result in excessive energy consumption. The modern approach is to 'build tight, ventilate right'. This means making buildings airtight and installing ventilation systems that reduce the ingress of outdoor pollutants, while preventing the build up of indoor pollutants.

This publication summarises the issues that building owners, architects, designers and facilities managers face when seeking to provide good indoor air quality. It gives an overview of the sources and types of pollutants likely to affect different indoor environments in urban areas, and summarises current regulations, standards and guidance in the UK. It also includes short case studies to illustrate strategies for improving IAQ.

Air pollutants and their sources

The types and concentration of air pollutants present in any indoor environment will vary according to the building type and location in relation to outdoor sources, construction and building systems, and internal content, furnishings and occupant activities.

All types of domestic and non-domestic buildings, from detached and terraced houses, to offices and airports, are likely to be exposed to pollutants and their sources, examples of which are shown in Figures 1 and 2.

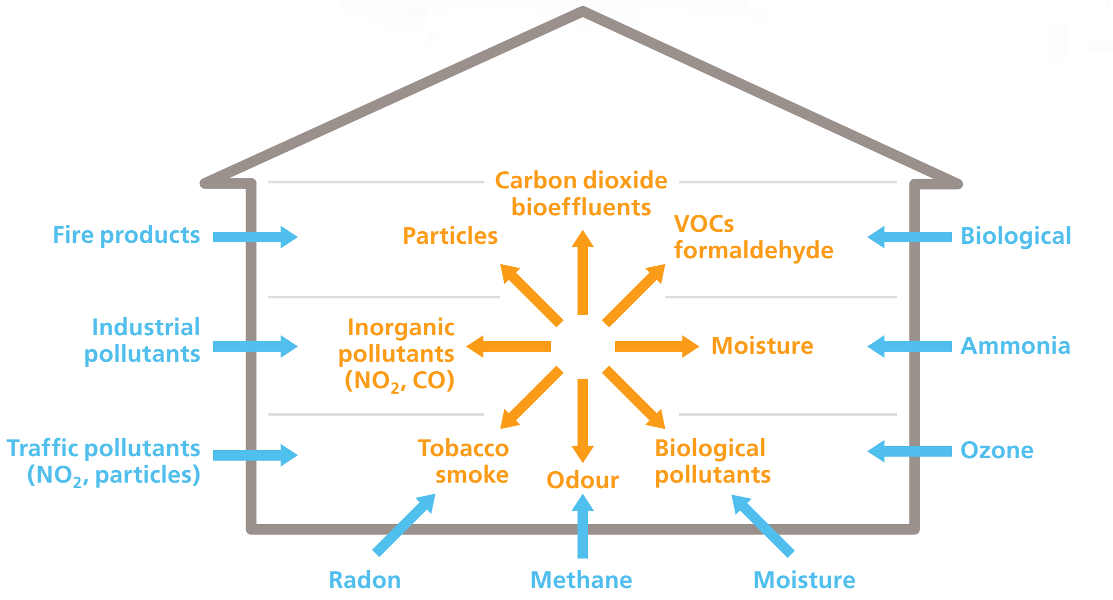


Figure 1. Examples of typical external (blue) and internal (orange) pollutants found indoors

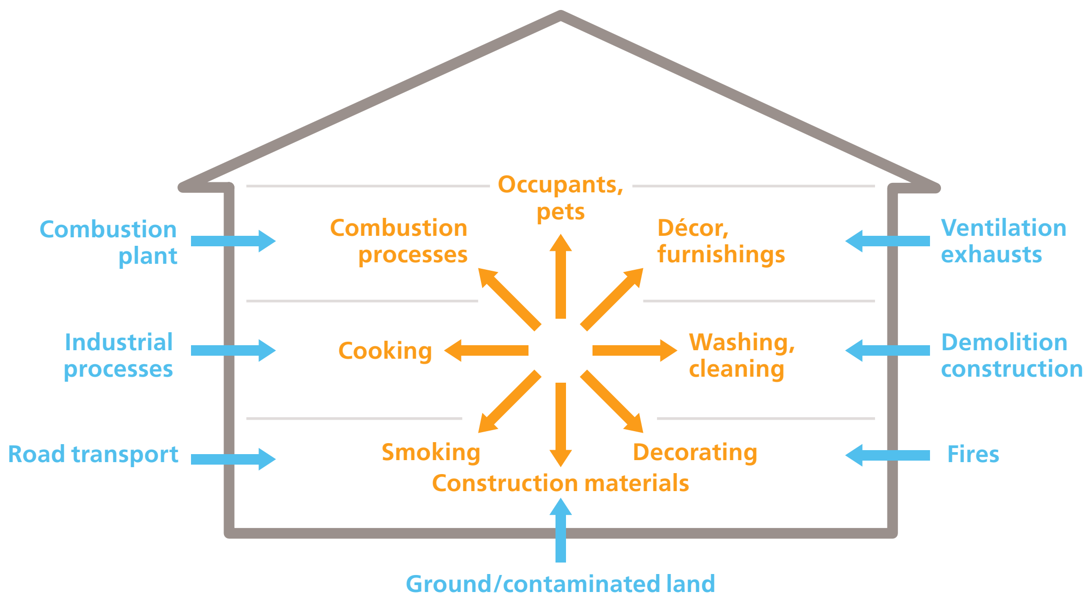


Figure 2. Examples of typical external (blue) and internal (orange) sources of pollutants affecting IAQ

Building occupants may be exposed to a variety of airborne pollutants, including organic, inorganic and biological (in both gaseous and particulate forms). Of particular concern are airborne pollutants that have the potential to cause serious health effects or exacerbate existing conditions. These include:

- **Volatile organic compounds (VOCs).** VOCs comprise a wide range of volatile chemicals, which may be emitted over periods of weeks or years from construction and furnishing products. Examples include concrete and masonry surface treatments, timber preservation and coatings, adhesives, sealants, paints and architectural coatings, damp proofing emulsions and membranes, wall coverings, floor coverings, cove base, roofing compounds, cleaning products, fungicide washes, fuels, spot removers, household cleaners, air fresheners and air cooling refrigerants for building services.

  VOCs also arise from using consumer products such as aerosols used in cleaning and personal care products. Other indoor sources include cooking, cigarette smoke and plug-in air fragrances. VOCs from sources such as road traffic may also be drawn in from outside by ventilation and infiltration.
- **Formaldehyde.** Formaldehyde is a very volatile organic compound (VVOC) that is released directly into indoor air from various sources such as resins, phenol-formaldehyde and urea formaldehyde (UF) from wood-based products such as particleboard in furniture, UF-based lacquers and UF foam cavity wall insulation. It is also a constituent of tobacco smoke and of combustion gases from fossil fuel burning appliances.
- **Carbon dioxide (CO_2).** CO_2 sources are human and animal respiration and combustion products. Plants also give off carbon dioxide, but if (and only if) the light is bright enough to initiate photosynthesis, they can reduce levels of carbon dioxide.
- **Ozone (O_3).** O_3 primarily arises from photochemical reactions in the ambient air, and is also produced indoors by some electronic equipment such as printers and photocopiers. Ozone may undergo reactions with surfaces and other airborne pollutants indoors to produce new compounds and particles.
- **Nitrogen dioxide (NO_2).** The main outdoor sources of NO_2 are from combustion and transport. Major indoor sources of NO_x are gas-fuelled cookers, and poorly-flued (or unflued) fires, water heaters and space heaters.
- **Carbon monoxide (CO).** This is a colourless, odourless gas produced by the incomplete combustion of most fuels. Incomplete combustion can occur, for example, when inadequate ventilation to an appliance results in depletion of the oxygen content of the air at the point of combustion. Other sources of carbon monoxide can include smoking, the burning of candles and the ingress of the exhaust from internal combustion engines.
- **Particulate matter (PM).** Particulate matter is made up of a complex mixture of solid and liquid particles suspended in the air. These can include carbon, complex organic chemicals, sulphate, nitrates, ammonium, sodium chloride, mineral dust, water and a series of metals. The main sources of PM are from combustion and transport. Construction and demolition activities are important local sources in urban areas. Particulate matter is also produced by certain cooking activities (e.g. frying). The particle mass fractions $PM_{2.5}$ (up to 2.5 μm in diameter) and PM_{10} (up to 10 μm in diameter) are commonly measured due to the significance of these particle sizes with regards to the human respiratory system.
- **Biological pollutants.** These include faecal pellets from house dust mites, mould, fungal particles, bacteria and pollen. Other allergenic particles may be present due to domestic animals and pests.
- **Moisture.** Moisture arises generally from respiration and activities such as cooking and washing. The amount of water vapour present in the air directly affects occupant health and comfort, and also the presence of biological pollutants such as mould spores.
- **Odour.** Common sources of odour discharges are ventilation extracts, including those from kitchens and restaurants, diesel emissions, cooking, consumer products such as aerosols, cosmetics, plug-in air fragrances, cleaning and personal care products, and cigarette smoke.
- **Industrial pollutants.** A variety of 'industrial' pollutants may be generated in urban areas, for example from waste incinerators, laboratory fume cupboards, vehicle spray booths, small generation plant such as combined heat and power (CHP) and diesel-powered standby generators.
- **Ground pollutants.** It is possible that gases from the soil beneath the building contain hazardous substances; these may be of natural origin such as radon released by the bedrock or be contaminants such as organic chemicals present because of previous historic uses of the site or neighbouring land (Crump et al, 2004).

Tables 1 and 2 show the relationship between pollutants, their sources and the indoor environments in which they are likely to occur.

Table 1. Examples of types of pollutant sources found in different indoor environments

Internal environments (buildings only)	Pollutant sources										
	Outdoor air	Construction materials	Furnishing materials	Consumer activities: Decorating paints, adhesives and varnishes	Consumer activities: Washing and cleaning products	Combustion products from e.g. gas appliances	Office equipment e.g. photocopiers, electrical goods	People	Animals (e.g. pets, assistance dogs, pests, mites)	Tobacco smoke	Ground/ contaminated land
Domestic	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Offices	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Schools	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Hospitals	✓	✓	✓	✓	✓	✓	✓	✓			✓
Hotels	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Restaurants	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Public places e.g. museums	✓	✓	✓	✓	✓		✓	✓	✓		✓
Industrial / factories	✓	✓	✓	✓	✓	✓	✓	✓			✓
Shops and shopping malls	✓	✓	✓	✓	✓			✓	✓		✓

Table 2. Examples of types of pollutants emitted from different sources likely to affect indoor environments

Pollutant sources	Pollutants												
	Carbon dioxide (CO_2)	Carbon monoxide (CO)	Moisture	Odour, fragrances	Particles (PM_{10}, $PM_{2.5}$, dust, fibres)	Volatile Organic Compounds (VOCs)	Formaldehyde	Biological/ Allergens e.g. mould and spores	Nitrogen oxides (NO_x)	Ozone (O_3)	Methane	Radon	Ammonia (NH_3)
Outdoor air	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Construction materials					✓	✓	✓						
Furnishing materials				✓	✓	✓	✓						
Decorating (Paints, adhesives and varnishes)			✓	✓	✓	✓	✓						
Washing and cleaning products			✓	✓		✓	✓						✓
Combustion products from e.g. gas appliances	✓	✓	✓		✓				✓				
Electrical goods e.g. photocopiers					✓					✓			
People (including personal care products)	✓		✓	✓	✓	✓		✓			✓		
Animals	✓		✓	✓	✓	✓		✓			✓		
Tobacco smoke	✓	✓	✓	✓	✓	✓	✓		✓				
Ground						✓					✓	✓	

Impact of poor IAQ on health, wellbeing and productivity

Poor indoor air quality can cause a range of health effects ranging from headaches, dizziness and nausea, to asthma, cardiovascular disease, cancer and death. Table 3 shows the typical impact on occupant health and wellbeing of some common pollutants found indoors. As well as being detrimental to health and comfort, poor indoor air quality can adversely affect performance at work, learning in educational establishments and healing in healthcare settings.

The extent of the effect of a particular pollutant on human health depends on its concentration and the duration of exposure. Any effect also depends on the age and gender of the people occupying a space (CIBSE, 2011). Most current data on the impact of air pollution on health apply to people in good health and, in the case of working environments, to those aged between late teens (16-19) and normal retirement age (65 in the UK and Ireland). In the industrial workplace many of the most serious risks are addressed with local exhaust ventilation, with residual risk controlled by personal protective equipment (PPE) and exposure monitoring. However, in domestic and many non-domestic environments, the control of indoor air pollution may not be achieved as easily.

Workplace Exposure Limits (WELs) may apply for healthy people of working age who are exposed to a pollutant directly as part of their work. For those people not in good health, and for those younger or older than working age people, lower ('environmental') exposure limits are usually employed. These lower limits should also be applied if a person is exposed to the pollutant for significantly longer than 8 hours, or if their work activity does not directly involve the pollutant.

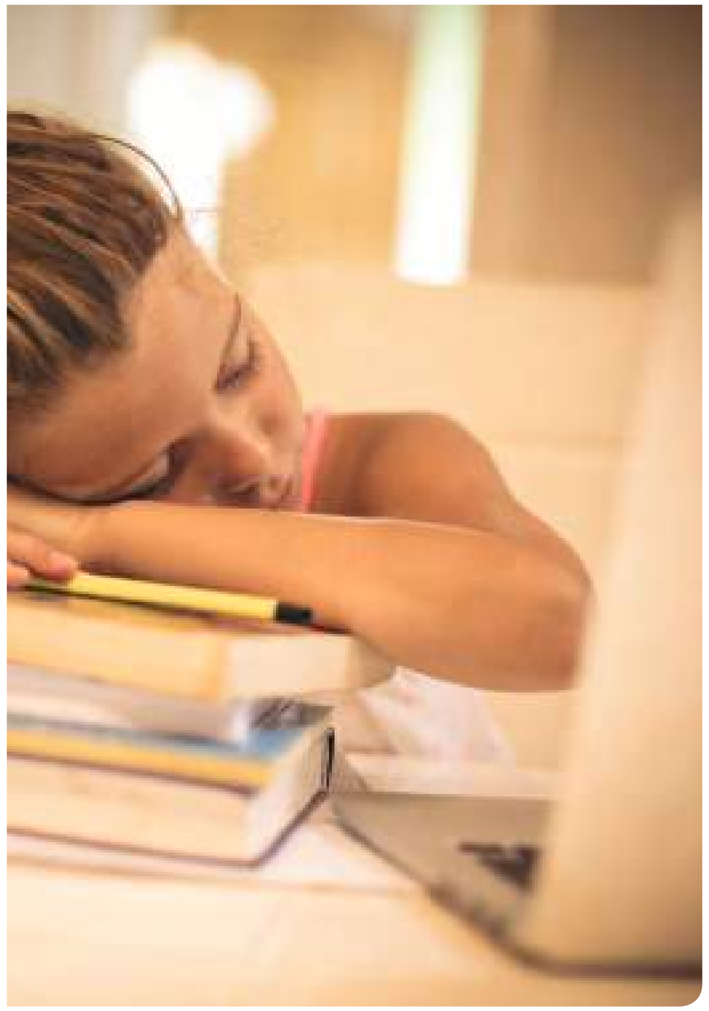


Table 3. Typical health impacts of some common pollutants found indoors

Pollutant	Impact on health
Carbon monoxide (CO)	Carbon monoxide can cause headaches, dizziness, nausea and at very high levels, death. Elderly people, pregnant women, young children and people with heart disease and lung disease are more sensitive to the adverse effects of carbon monoxide.
Formaldehyde	Formaldehyde can cause eye, nose and throat irritation and is considered a potential human carcinogen.
Nitrogen dioxide (NO_2)	Exposure to nitrogen dioxide can cause inflammation of the airways, respiratory illnesses and possibly increases the risk of lung infections. Young children and people with asthma are the most sensitive to NO_2. It plays a major role in the development of chronic obstructive pulmonary disease in adults which will affect more people than heart disease by 2020 (Environmentalist 2012). Long-term exposure may also affect lung function and can enhance responses to allergens in sensitised individuals.
Odour	Odorous discharges are subjective and cause nausea and irritation for some people.
Ozone (O_3)	Ozone exposure can cause asthma, irritation and damage to the eyes, nose and airways. Prolonged exposure to high levels may result in damage to the lungs and airway linings.
Particulate matter	Inhalable particles have been linked with a number of respiratory illnesses, including asthma and chronic bronchitis. Long-term exposure to fine particles can cause premature death from heart disease and lung disease including cancer. Short-term exposure to higher levels of fine particle concentrations have also been linked with cardio-vascular problems and increased death rates. Exposure to fine particles has also been linked to prevalent anxiety and hypertensive disorders.
Volatile organic compounds (VOCs)	Key symptoms associated with exposure to VOCs include eye irritation, nose and throat discomfort, headache and allergic skin reaction.

Indoor air quality standards and guidelines

Regulations, standards and policies

There is limited information in the UK, and in fact worldwide, on recommended concentration guidelines and standards specifically for indoor air pollutants. Those that exist are summarised in the following sections.

a) World Health Organization
In 2010, the World Health Organization (WHO, 2010) published guidelines for the protection of public health from risks due to a number of pollutants affecting indoor environments including, benzene, carbon monoxide, formaldehyde, nitrogen dioxide, polycyclic aromatic hydrocarbons (PAHs – especially benzo[α]pyrene), radon, trichloroethylene and tetrachloroethylene.

The guideline values provide the basis for evaluation of these pollutants to a level below which lifetime exposure, or exposure for a given average time period, would not constitute a significant risk to the health or well-being of people.

b) Committee on the Medical Effects of Air Pollution
In the UK, the Committee on the Medical Effects of Air Pollution (COMEAP) provides independent advice to UK government departments and agencies on how air pollution impacts on health, and has published 'Guidance on the Effects of Indoor Air Pollutants' (COMEAP, 2004). COMEAP recommends concentrations for formaldehyde, benzene, and PAHs (as benzo[α]pyrene equivalent). NO_2 and CO are included in the recommendations for monitoring the indoor air of homes.

c) UK Building Regulations
Appendix A of Approved Document Part F of the Building Regulations (F1 Means of Ventilation) covering performance-based ventilation (CLG, 2015), sets maximum acceptable indoor levels for nitrogen dioxide, carbon monoxide and total volatile organic compounds (TVOC). These, in part, are based on values given by COMEAP (2004).

d) UK Air Quality Strategy
The Air Quality Strategy (AQS) for England, Scotland, Wales and Northern Ireland (DETR, 2000; Defra, 2007) sets out policies for the management of ambient air quality. These include air quality objectives for 10 key air pollutants in order to protect people's health and the environment without unacceptable 'economic or social costs'. These are Particles (PM_{10} and $PM_{2.5}$), NO_2, O_3, sulphur dioxide (SO_2), PAHs, benzene, 1,3 butadiene, carbon monoxide (CO), and lead.

e) Health and Safety Executive (HSE)
The Health and Safety Executive supports the regulatory framework for workplace health and safety in England, Wales and Scotland (in Northern Ireland this is covered by HSENI) through the Health and Safety at Work Act (HSE, 1974). Specific pollutants are covered by the Control of Substances Hazardous to Health Regulations 2002 (HSE, 2002). Within this Act, approximately 500 substances have been set legally-binding Workplace Exposure Limits (WELs) which are listed in document EH40 (HSE (2011 and subsequent revisions)).

Maximum concentrations are given for short-term (15 minute) and long-term (8 hour) exposure limits in any 24 hour period. While largely relating to indoor emissions, these exposure limits set values for indoor environments that should not be exceeded whatever the source. HSE does not set limits for continuous (24 hour) exposures and therefore the WELs cannot be regarded as safe concentrations for longer than the period given.

f) European
In 2005, a European-funded study identified formaldehyde, CO, NO_2, benzene and naphthalene as 'Group 1' high-priority chemicals that could occur in high concentrations, pose a significant risk to the health of occupants and therefore require risk management action (INDEX, 2005). The 'Group 2', second priority chemicals include acetaldehyde, toluene, xylenes and styrene. These compounds could also occur in high concentrations indoors but the need for risk management action is considered less urgent.

Guidelines for ventilation requirements in buildings published by the European Commission, includes recommendations by some European authors for TVOC concentrations in indoor non-occupational environments (See Appendix, Table 4.1).

Selecting the most building-appropriate air quality standards and guidance

The selection of appropriate air quality standards against which to compare the indoor environment in buildings needs to be carefully considered. In homes and buildings open to public access, such as schools and hospitals, the World Health Organization guidelines and the objectives set by the UK Air Quality Strategy are the most appropriate. In more industrial environments, the Health and Safety Executive's (HSE), Workplace Exposure Limits (WELs) are the most suitable (HSE, 2011).

The HSE WELs are formally set as exposure limits for physically fit individuals in the industrial workplace, exposed for a nominal eight-hour day, and a five-day week. The limits therefore exclude vulnerable groups including the elderly, young and infirm, those unusually sensitive to some pollutants, and those inhabiting a building on a more permanent basis. Therefore, although typical office buildings are 'workplaces', it is doubtful whether the WELs are necessarily the most appropriate for these buildings. The occupants present in office environments generally represent a wider distribution of society members, including those that are less physically fit and able when compared with workers in industrial settings. Also, if workers are not in contact with a pollutant as a direct part of their work, they may not be aware that they are being exposed to it, and so appropriate precautions may not be in place. Her Majesty's Inspectorate of Pollution (HMIP), recommended (1993) that for the exposure of the general populace, a fraction of the guidelines given in the HSE WELs should be used.

In view of this, it is more appropriate in office environments to use the far lower outdoor air quality guidelines set for exposure of the general populace, as a part of the UK Air Quality Strategy (Defra, 2007) and the World Health Organization guidelines. For pollutants not covered by these, the HMIP (1993) recommended limits may be used.

For a summary of recommended guidelines for a number of air pollutants found indoors, please refer to Tables 4.1 to 4.9 in the Appendix.

Certification schemes

There are a number of environmental assessment schemes that award credits to new developments and building refurbishments if the air quality meets certain specified criteria. These are usually based on either the UK Air Quality Strategy or the WHO Guidelines. The major schemes of this type are BREEAM (2014a and 2014b), LEED (USGBC, 2016) and WELL (IWBI, 2016).

BREEAM (Building Research Establishment's Environmental Assessment Method)

'BREEAM UK New Construction: Non-domestic buildings' (BREEAM, 2014a) contains a section on indoor air quality, including measures for preventing the ingress of outdoor pollutants. It covers pollutant removal, requirements on air intake and exhaust positioning, HVAC system filtration, the use of carbon dioxide and other indoor air quality control sensors, restrictions on total volatile organic compounds (TVOC) and formaldehyde emissions and the performance of actuator, vent and window controls. Recognition is given for the provision of fresh air.

BREEAM Section 5: Health and Wellbeing: HEA02 Indoor Air Quality (BREEAM, 2014a) focusses on VOCs and formaldehyde in particular and awards credits for complying with set requirements. It encourages a healthy internal environment through specifying and installing appropriate ventilation, equipment and finishes. Indoor pollutant measurements made to establish compliance must meet relevant British Standards. Such measurements must be taken in representative habitable rooms, with the building having been in operation for a period of time sufficient to ensure that equilibrium has been reached in terms of internal environmental conditions.

Where present, HVAC systems must incorporate suitable filtration to minimise external air pollution, as defined in BS EN 13779:2007 Annex A3 (BS, 2007). This therefore links BREEAM to a standard that requires the quality of outdoor air to be taken into account. Further credit is also given for having an air quality plan for the building/development.

WELL

The WELL Building Standard (IWBI, 2016) was launched in 2015 in the USA and is primarily aimed at creating healthier work and living spaces. It is primarily performance-based and was developed by integrating scientific and medical research to address the complex issues of human health and wellbeing in relation to the built environment. The standard contains 29 air quality-related areas to be addressed, including relevant standards, ventilation, VOC reduction, filtration, cleaning, monitoring and feedback.

LEED (Leadership in Energy and Environmental Design)

LEED is a building certification programme developed by the US Green Building Council (USGBC, 2016). It includes a set of rating systems for the design, construction, operation, and maintenance of buildings, homes, and neighbourhoods to help building owners and operators be environmentally responsible and use resources efficiently. It includes minimum air quality and ventilation performance requirements to contribute to the comfort and wellbeing of building occupants. Parameters to be monitored for compliance include VOCs, formaldehyde, particles (PM_{10}) and carbon monoxide.

Indoor air quality monitoring

In general, indoor air quality monitoring can often be carried out by using outdoor air quality monitors. Outdoor air quality is highly regulated and therefore outdoor air pollutant measurements require the use of specified reference methods and equipment in order for the results obtained to comply with relevant air quality legislative requirements. In general, the pollutants covered are mainly those regulated as a part of the UK Air Quality Strategy (Defra, 2007). Thus, the assessment mechanisms for both indoor and outdoor environments are the same.

Much of the instrumentation and personal sampling equipment available for indoor monitoring is suited to more industrial-type workplaces. These workplaces generally have more fit and healthy occupants, and so it typically measures airborne pollutants in the occupational range (with concentrations in the ppm or mg m^{-3} range). For office-type and other environments, where occupant fitness and health are closer to that of the general population, instruments operating in the 'environmental' range (with concentrations in the ppb or µg m^{-3} range) are usually more suitable.

Nonetheless, with careful selection there is equipment available that can be used to monitor the indoor environment for a variety of potential airborne contaminants. The results obtained from such IAQ monitoring can then be compared against available air quality standards and guidelines, such as the UK Air Quality Strategy, the World Health Organization Air Quality Guidelines (WHO, 2010), and the Health and Safety Executive Workplace Exposure Limits as appropriate (HSE, 2011a).

There are some measurements, for example, for volatile organic compounds (VOCs) where standards and guidance for indoor monitoring exist (BS, 2011). However, there are few specific methodologies for general IAQ monitoring.

Mitigating air pollutants in the indoor environment

Control strategies

Control strategies for reducing the concentration of air pollutants in the indoor environment depend on the type and location of the source and activity. Ventilation with outdoor fresh air, will dilute and flush out pollutants derived from indoor sources but will not eliminate them completely. In fact, the incoming ventilation air may itself be polluted from outdoor sources, which will place an additional burden on indoor air. Care therefore needs to be taken in selecting the correct mitigation strategy to give optimum indoor air quality for health and wellbeing (Figure 3).

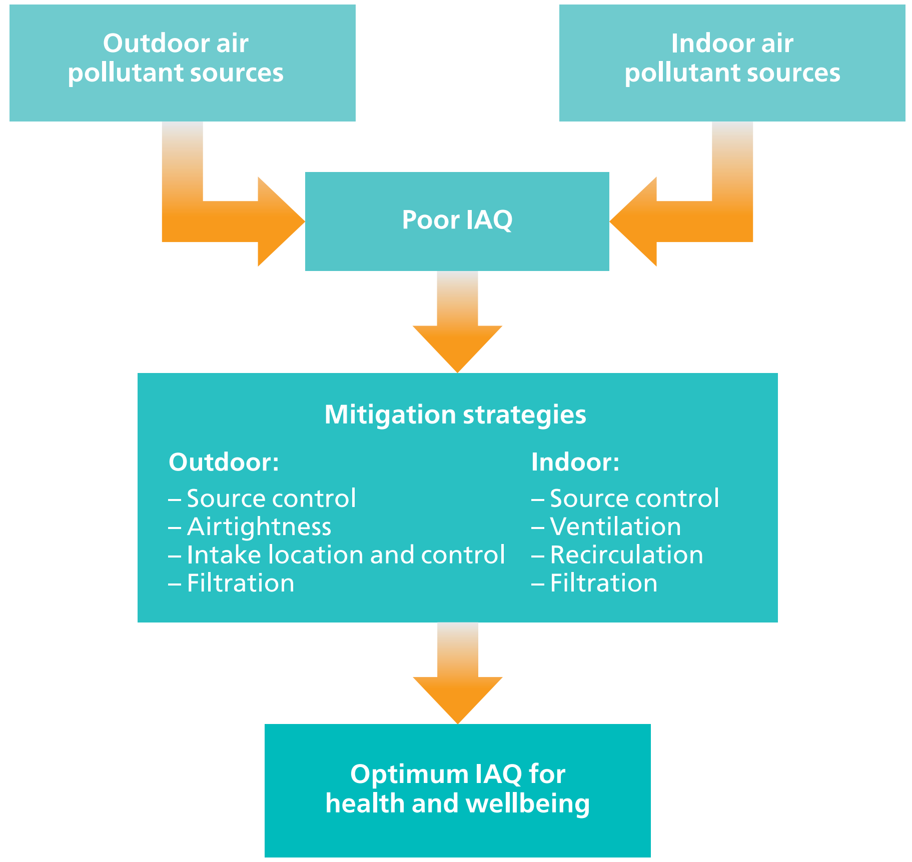


Figure 3. Air pollution mitigation strategies to give optimum indoor air quality

Reducing ingress of outdoor pollutants

Guidance on reducing the ingress of outdoor pollution covers the following main strategies (Liddament, 1996; CIBSE, 1999; CLG, 2010a; Kukadia and Hall, 2011; Cheng et al., 2014; Kukadia and Abela, 2015):

1. **Outdoor air pollution source control**
2. **Building airtightness**
3. **Ventilation air intake position**
4. **Filtration**

Further information on these is covered in the following sections.

Outdoor air pollution source control

Air pollutant emissions from sources, such as vehicles and industrial processes, are controlled by various legislation, regulation and guidance. However, despite such control measures being in place, outdoor air pollution levels in the UK are still relatively high and likely to be so in the foreseeable future. Therefore, additional measures are required to reduce the ingress of outdoor pollutants into the indoor environment (Kukadia and Hall, 2011).

Building airtightness

Once a contaminant from an outdoor source has reached a building, the extent of pollutant ingress will depend on the airtightness of the building envelope and number and size of openings, as well as the ventilation strategy.

Adventitious gaps and cracks in the building envelope contribute to the air permeability of the building, the subsequent uncontrolled infiltration of outdoor air and hence pollutants. Therefore, reducing air permeability by sealing the building envelope, and increasing its airtightness, will help reduce air ingress and so air pollution.

The Approved Document Part L of the Building Regulations in England, requires that the air permeability should not exceed a limiting or worst-allowable value of 10 $m^3/(h.m^2)$ at 50 Pa pressure difference. However, in practice, the actual design air permeability applied to satisfy energy and CO_2 emission targets, is often much lower and may typically be of the order of 5 $m^3/(h.m^2)$ at 50 Pa.

Ventilation air intake position

The effective location of ventilation air intakes is important for reducing the ingress of local sources of air pollution. Guidance available is given by CIBSE (1999), Approved Document Part F (Appendix D) of the UK Building Regulations (CLG, 2010), Kukadia and Hall, 2011 and Cheng et al., 2014.

Recommended guidance includes:

– Ventilation intakes need to be placed away from the direct impact of short-range pollutant sources, such as roads, especially if they are within a few metres of the building. Inlets for mechanical systems can be placed on the roof to avoid ground-based pollutant sources, if no other sources are present at high level.

– If intakes are to be located higher up a tall building then cross-contamination from, for example, exhaust stacks and boiler flues, needs to be considered carefully and avoided.

– Ventilation intakes can be placed in courtyards and enclosed spaces as they can offer protection for air intakes. However, care needs to be taken to ensure that emissions from sources such as loading areas, ventilation extracts, boiler discharges or kitchen odour are not discharged into such spaces directly. In general, pollutants discharged directly into courtyards disperse and clear slowly, therefore posing a potential risk.

Ventilation air intake control

Recommended guidance includes:

– For pollutant sources such as urban road traffic, where concentration fluctuates with the time of day, it is recommended that the flow of external air is reduced, or ventilation intakes are closed, for up to an hour during peak periods such as rush hours. Air intakes located on a less polluted side of the building may then be used for fresh air or, for a short time air can be fully re-circulated within the building.

– The building may be used as a 'fresh air' reservoir (Liddament, 1996) to supply air during short local pollution episodes. The use of atria as a source of 'fresh air' for this purpose may also be an option.

Filtration

Filtration is used to physically remove particles, and in some cases environmental gaseous pollutants, from the ventilation air supply. Virtually all mechanical ventilation systems incorporate some form of filtration, but this is usually primarily to protect the HVAC system rather than to improve air quality. In the UK, filtration performance standards are specified by BS EN 779, BS EN 1822 and BS EN 14387 (BSI, 2012a, 2009, 2008) and CIBSE Guide B (CIBSE, 2004).

It should be noted that filtration systems are selective and are only effective at dealing with the pollutants for which they are designed.

Particle filtration performance

Basic filters are used to remove large particles such as dust but they offer little protection against smaller, respirable particles. These are classified as 'General' or 'G' filters, and in advanced ventilation systems will form part of a pre-filter. In the UK, higher specification particle filters are classified in increasing order of effectiveness as follows:

– Medium ('M' type filters)

– Fine ('F' type filters)

– Efficient Particulate Air (EPA or 'E' type filters)

– High Efficiency Particulate Air (HEPA or 'H' type filters)

– Ultra-Low Penetration Air (ULPA or 'U' type filters)

A full discussion of filtration classification is given in CIBSE Guide B.

Contaminant gas and vapour removal

This is a specialist topic where expert advice needs to be sought, as it is not commonly applied in standard building filtration systems. However, where needed, tertiary adsorption filters (for example activated carbon) may be fitted, taking into consideration the specific contaminants for which they have been designed. An integrated and balanced approach needs to be taken when designing for these systems.

Control of ground pollutants

Pollutants in soil gas, such as radon and organic chemicals emitted beneath the building, can be stopped from entering the indoor environment with impermeable membranes in the floor structure, or by other means. The Building Regulations provide advice on design measures to minimise ingress of both polluted ambient air (CLG, 2010a) and ground pollutants, including moisture, (CLG, 2006a). They also require appropriate works to prevent foul air from drainage systems entering the building (CLG, 2006b) and ensure the adequate generation of air for fuel combustion in heating appliances, and appropriate provision of flues for the removal of fumes (CLG, 2010b).

Reducing indoor pollutant emissions

Guidance on reducing indoor pollution covers the following main strategies:

1. **Indoor air pollution source control**
2. **Ventilation**
3. **Recirculation**
4. **Filtration**

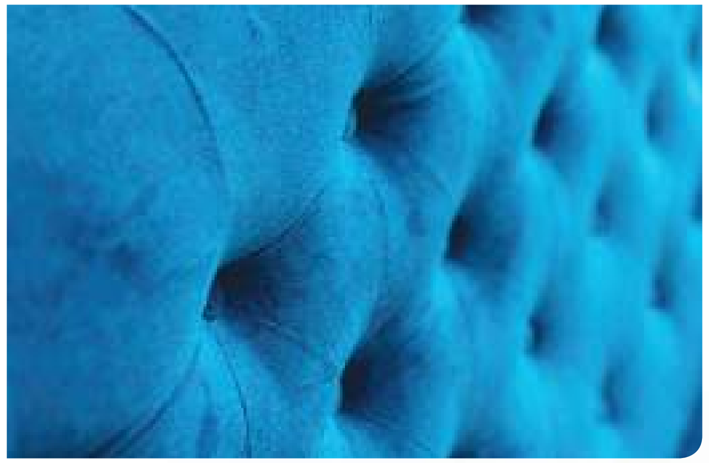
Indoor air pollution source control

There is currently a lack of awareness amongst occupiers of buildings, that certain activities (for example, smoking, using scented candles, painting and decorating) pollute the indoor environment and can cause adverse health effects. It is likely that if occupants were more aware of this they would try to keep such activities to a minimum or ensure that appropriate measures (such as purge ventilation) are used as mitigation.

A common misconception is that dilution with fresh ventilation air is the only way of removing harmful contaminants from the occupied space. It is more effective to control the source of pollutant, if possible, especially as outdoor air may itself be contaminated. Preventing indoor air quality problems by source control is generally less expensive than identifying and solving them after they occur. The generation of internal pollution can be avoided, for example, by using low-emitting furnishings and carpeting and discouraging pollutant-emitting activities.

The Building Regulations, Approved Document F(F1 Means of Ventilation) 2006, emphasises the need for a complementary strategy of 'source control' by reducing the release of volatile pollutants into the indoor air. Particular sources include formaldehyde and VOCs from building components, fabrics and furnishings.

The Zero Carbon Hub (ZCH, 2012), recommended that particular products or components be banned from use indoors. Examples include asbestos products, lead in interior paint, and prohibiting smoking in enclosed public spaces and workplaces. It further recommended the use of products with low or zero emission of pollutants.



Low-emitting products and labelling schemes

Air pollutants are emitted from materials and products used in construction, decoration and furnishing. A greater use of low-emitting products will help to reduce the pollution load in buildings and the risk of accumulating high pollutant levels.

Low-emitting products will only reduce some types of pollution from some of the wide range of indoor sources. Therefore this approach is only one part of an effective strategy for indoor air quality management. Other pollution sources, such as cooking and heating, people and pets, radon from the ground, water vapour and residual VOC emissions from 'low-emitting' products, also need to be managed. Source control provides substantial benefits, but does not preclude the need for adequate ventilation to achieve a healthy indoor environment.

There are various labelling schemes for products and materials used in the construction and fitting out of buildings. Most of these focus primarily on characteristics such as sustainability and embedded energy use, but some now also cover the emission of chemicals such as formaldehyde and VOCs. However, these schemes are currently voluntary rather than mandatory.

Also, some emissions are expressed in units of $\mu g\ m^{-3}$, and these could be confusing when room concentrations are also expressed in units of $\mu g\ m^{-3}$. A product with emissions of, say 50 $\mu g\ m^{-3}$, could be used but the resulting concentrations in a room could be several hundred $\mu g\ m^{-3}$. This is because emissions are calculated using a standard area in a standard sized chamber, and the application rate in a room could differ from the measured sample area to chamber volume ratio.

Ventilation and recirculation

Ventilation is most suited to providing fresh air for occupants' respiration, and to diluting and removing unavoidable pollutants. These include those generated by occupants themselves (metabolic carbon dioxide and odour), as well as pollutants from activities including cooking and washing. Localised sources of pollutants, such as those generated by cooking, washing, clothes drying and use of office equipment, should be extracted at source by localised or central ventilation extraction. In each case the extract hood location needs to be close to the source. Details of suitable ventilation strategies are given in Part F of the Building Regulations (CLG, 2016).

In mechanically ventilated commercial buildings, 'recirculation' of part of the indoor air almost always occurs, so some form of filtration, especially for particles, is normally required. Sometimes re-circulatory systems are used in the home, often to control allergy-type problems. To be effective, such systems must have a flow rate that is much greater than (typically two or three times) the outdoor air ventilation rate.

Filtration

Indoor air can be cleaned by filtering, and then recycled within the building or room. Filtration systems can range from those that treat air in the mechanical ventilation system of the building, to devices in individual rooms that may be fixed or stand-alone. Also, passive products, such as wall materials with enhanced properties for absorbing some pollutants, are available on the market – though the efficacy of these is as yet unproven.

Case studies

Investigation of a poorly-ventilated office building

BRE investigated an office building where the staff had concerns over inadequate ventilation provision, and the possible health effects of any resulting poor air quality. The building had been significantly modified since its original design and some of the ventilation system components were no longer fully operational.

Measurements were made of the building ventilation rate, and the concentrations of various potential air pollutants including carbon monoxide, carbon dioxide, VOCs, formaldehyde and particles. With the exception of carbon dioxide, the results showed that no significant concentrations of air pollutants were present. However, the carbon dioxide measurement results showed that the building was very poorly ventilated, with concentrations at levels that would have potentially significant effects on occupant performance and productivity. Recommendations were made on how the ventilation system could be adapted and improved to enhance the air quality in the building, in both the short and longer term.

The effects of cooking in an airtight home

Measurements of ventilation rate and various air quality parameters were carried out under relatively controlled conditions in a modern, airtight home (built to meet the Code for Sustainable Homes – 'Level 6'). The aim was to investigate the effect of different types of fuel (electricity and gas), cooking (boiling, frying) and ventilation rate.

Findings included the following:

- frying food produced more air pollutants than boiling,
- the use of gas as a cooking fuel produced more nitrogen oxides (NO_x) and fine particles,
- the ventilation system in the house did not provide a significant change in ventilation rate when operated in the 'boost' mode as compared with the 'normal' mode,
- with the ventilation system off (to simulate a potential failure), many of the air pollutants remained in the house for long periods of time.

The ventilation system in the house had been very poorly installed and maintained (despite the high-profile nature of the development), rendering it incapable of delivering the required background (purpose-provided) and purge ventilation when required. This highlights the need for checking that building ventilation rates specified at the design stage of a project are actually delivered in practice, both post-construction and post-occupancy.

Indoor air quality investigation at a school

Following health-related concerns from staff at a newbuild school, BRE was commissioned to evaluate the environmental conditions in the school. A comprehensive four-week programme of surveys, inspections, monitoring and testing was carried out by BRE in order to fulfil the requirements of a detailed tender specification document, with over-arching objectives, including investigation of factors that may have led to ill health of building occupants, assessment of occupant comfort, and verification of whether the school building complied with Building Regulations and contractual and statutory requirements in terms of air quality and environmental conditions.

A full programme of inspections, snap-shot measurements and continuous monitoring was undertaken, including:

- Thermal comfort assessment (temperature and relative humidity).
- Inspection of heating and air handling systems (including controls).
- Air quality monitoring (CO, CO_2, particulate matter, SO_2, NO_2, VOCs, formaldehyde).
- Airtightness and air change rate measurements.
- Lighting assessment (daylight; electric lighting; glare; task-based lighting).
- Background noise assessment.

BRE's findings were presented in a full technical report, and later in person to senior educational officers at the local authority. The main findings and recommended remedial actions were also presented in layman's terms to school staff and to maintenance staff working for the school's contracted facilities management organisation. This included guidance on use of features such as trickle vents and HVAC controls.

BRE was later commissioned to undertake follow-up monitoring to verify that remedial actions had been effective.

Appendix

Table 4.1. Guideline concentrations for Total Volatile Organic Compounds (TVOCs)

	Total Volatile Organic Compounds (TVOCs)	
	Guideline concentration µg m^{-3}	Averaging time
UK Building Regulations, Approved Document F	300	8 hours
European	200 to 500	
	Guideline concentration µg m_{-3}	Comment
Mølhave, L	<200	Comfort range
	200-3,000	Multifactorial exposure
	3,000-25,000	Discomfort
	>25,000	Toxic
Seifert, B	300	Target guideline value. No individual compound should exceed 10% of target value
Finnish Society of IAQ and Climate	<200	Target values of indoor climate; best air quality; 90% of occupants satisfied
	<300	Room may have a slight odour
	<600	Minimum requirement

Table 4.2. Guideline concentrations for formaldehyde

	Formaldehyde	
	Guideline concentration µg m^{-3}	Averaging time
World Health Organization	100	30 minute mean based on effects other than cancer or odour/annoyance
COMEAP	100	30 minutes
UK HSE Workplace Exposure Limits	2,500	8 hour mean
	2,500	15 minute mean (short-term exposure limit, STEL)
INDEX	30	Non-carcinogenic no-effect level

Table 4.3. COMEAP guideline concentrations for benzene and benzo[α]pyrene

Pollutant	Guideline concentration	Averaging time
Benzene	5.0 µg m^{-3} (1.6 ppb)	Annual mean
Benzo[α]pyrene	0.25 ng m^{-3}	Annual mean

Table 4.4(a). Guideline concentrations for carbon dioxide, CO_2

	Carbon dioxide, CO_2	
	Guideline concentration mg m^{-3} (ppm)	Averaging time
UK HSE Workplace Exposure Limits	9,150 (5,000)	8 hour mean
	27,400 (15,000)	15 minute mean (short-term exposure limit, STEL)
CIBSE Guide A	~1,000 ppm	Performance standard to indicate 'adequate ventilation'

Table 4.4(b). Recommended guideline concentrations for CO_2 levels (BS EN 13779:2007) in rooms

	Carbon dioxide – level above level of outdoor air in ppm	
	Typical range	Default value
IDA 1	<=400	350
IDA 2	400-1,000	500
IDA 3	600-1,000	800
IDA 4	>1,000	1,200

Table 4.5. Guideline concentrations for nitrogen dioxide, NO_2

	Nitrogen dioxide, NO_2	
	Guideline concentration µg m^{-3} (ppb)	Averaging time
World Health Organization (WHO)	200 (105)	1 hour mean
	40 (21)	Annual mean
COMEAP	200 (105)	1 hour mean
	40 (21)	Annual mean
UK Building Regulations, Approved Document F	288 (150)	1 hour mean
	40 (21)	Long-term
UK Air Quality Strategy	200 (105) with a maximum of 18 exceedances allowable within any 12 month period	1 hour mean
	40 (21)	Annual mean

Table 4.6. Guideline concentrations for carbon monoxide, CO

	Carbon monoxide, CO	
	Guideline concentration mg m^{-3} (ppm)	Averaging time
World Health Organization (WHO)	100 (85)	15 minute mean*
	35 (30)	1 hour
	10 (9)	8 hours
	7 (6)	24 hours**
COMEAP	100 (90)	15 minutes
	60 (50)	30 minutes
	30 (25)	1 hour
	10 (10)	8 hours
UK Building Regulations, Approved Document F	100 (90)	15 minutes
	60 (50)	30 minutes
	30 (25)	1 hour
	10 (10)	8 hours
UK Building Regulations, Approved Document F	35 (30)	8 hour occupational exposure
UK Air Quality Strategy	10 (10)	8 hours
UK HSE Workplace Exposure Limits	35 (30)	8 hour mean
	232 (200)	15 minute mean (short-term exposure limit, STEL)

*Assuming light exercise and that such exposure does not occur more than once per day.

**Assuming that the person is awake and alert, but not exercising. It is recognised that someone would not be expected to be awake and alert for the whole 24 hour period.

Table 4.7. Guideline concentrations for ozone, O_3

	Ozone	
	Guideline concentration µg m^{-3} (ppb)	Averaging time
World Health Organization (WHO)	100 (50)	8 hour mean
UK Building Regulations, Approved Document F	100 (50)	Performance criteria – buildings other than dwellings
UK Air Quality Strategy	100 (50)	8 hour mean concentration not to be exceeded more than 10 times a year
UK HSE Workplace Exposure Limits	400 (200)	15 minute short-term exposure limit (STEL)

Table 4.8. Guideline concentrations for sulphur dioxide, SO_2

	Sulphur dioxide, SO_2	
	Guideline concentration µg m^{-3} (ppb)	Averaging time
World Health Organization (WHO)	20 (8)	24 hour
	500 (188)	10 minute
UK Air Quality Strategy	350 (130)	1 hour mean concentration not to be exceeded more than 24 times a year
	125 (47)	24 hour mean concentration not to be exceeded more than 3 times a year
	266 (100)	15 minute mean concentration not to be exceeded more than 35 times a year

Table 4.9. Guideline concentrations for particles

	Particles		
	PM_{10} µg m^{-3}	$PM_{2.5}$ µg m^{-3}	Averaging time
World Health Organization (WHO)	20	10	Annual mean
EU Ambient Air Quality Directive and current UK Air Quality Standard	50	25	24 hour mean
	50		24 hour mean

References

BREEAM (2014a). UK New Construction. Non-Domestic Buildings United Kingdom. Technical Manual SD5076: 5.0 2014. http://www.breeam.com/BREEAMUK2014SchemeDocument/

BREEAM (2014b). UK Refurbishment and Fit-out. Non-Domestic Buildings United Kingdom. Technical Manual SD216: 1.1 2014. http://www.breeam.com/ndrefurb2014manual/

BS (2007). BS EN 13779:2007, "Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems".

BS (2009). BS EN 1822-5:2009 High efficiency air filters (EPA, HEPA and ULPA). Determining the efficiency of filter elements. BSI. http://shop.bsigroup.com/ProductDetail?pid=000000000030176856

BS (2011). BS ISO 16000-6:2011, Indoor air Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA® sorbent, thermal desorption and gas chromatography using MS or MS-FID. The British Standards Institution. ISBN 978 0 580 68997 0

BS (2012e). BS EN 779:2012: Particulate air filters for general ventilation. Determination of the filtration performance. BSI. http://shop.bsigroup.com/ProductDetail/?pid=000000000030200845

BS (2008). BS EN 14387: 2008. 'Respiratory protective devices. Gas filter(s) and combined filter(s). Requirements, testing, marking'

Cheng H., Hall D. J., Kukadia V., (2014). 'Location of ventilation inlets to reduce ingress of external pollutants into urban buildings: a new methodology'. BRE Information Paper in June 2014 IP 9/14, ISBN 978-1-84806-375-4

Chartered Institute of Building Services Engineers (CIBSE). Guide B: Heating, Ventilating, Air Conditioning and Refrigeration. ISBN 978 1 903287 583. London, CIBSE, 2005.

Chartered Institute of Building Services Engineers (CIBSE). Guide A: Environmental design (7th Edition, Issue 2). ISBN 978 1 903287 66 8. London, CIBSE, 2007.

CIBSE (2011). Indoor air quality and ventilation. CIBSE Knowledge Series: KS17. The Chartered Institute of Building Services Engineers, September 2011. ISBN 978-1-906846-19-0

CIBSE (2016). Ventilation'. Chartered Institution of Building Services Engineers (CIBSE) Guide B2 – in publication.

CLG (2006a). Approved Document C Site preparation and resistance to contaminants and moisture. Reprinted December 2010. ISBN 978 1 85946 202 7

CLG (2006b). Approved Document H Drainage and waste disposal. Reprinted December 2010. ISBN 978 1 85946 208 9

CLG (2010a). Approved Document F - Ventilation (2010 edition), reprinted December 2010. ISBN: 978 1 85946 370 3, Published by NBS, part of RIBA Enterprises Ltd.

CLG (2010b). Approved Document J Combustion appliances and fuel storage systems. Reprinted December 2010 ISBN 978 1 85946 371 0

CLG (2010c). Approved Document L1A and 1B: Conservation of fuel and power (New dwellings) (2010 edition), republished December 2010 ISBN: 978 1 85946 324 6 and ISBN 978 1 85946 325 3. Published by NBS, part of RIBA Enterprises Ltd.

COMEAP (2004). "Guidance on the Effects on Health of Indoor Air Pollutants" COMEAP 2004. webarchive.nationalarchives.gov.uk/20140505104658/http://www.comeap.org.uk/images/stories/Documents/Reports/Effects_on_Health_on_Indoor_Pollutants.pdf

Crump D., Brown V., Rowley J., and Squire R.(2004). Reducing ingress of organic vapours into homes situated on contaminated land. Environmental Technology, 25 p443-450.

Crump D, Dengel A, Swainson M. (2009). Indoor air quality in highly efficient homes – a review. NHBC Foundation. July 2009. ISBN 978-1-84806-104-0

Defra (2007a). The Air Quality Strategy for England, Scotland, Wales and Northern Ireland. Volume 1 & 2. July 2007. Department of the Environment, Food and Rural Affairs. PB 12654 & PB 12670.

Defra (2007b). Air quality and climate change: A UK perspective – Summary. Air Quality Expert Group. Department of the Environment, Food and Rural Affairs. ISBN 0 85521 173 3. www.defra.gov.uk

DETR (2000a). The Air Quality Strategy for England, Scotland, Wales and Northern Ireland. Department of the Environment, Transport and the Regions in partnership with the Scottish Executive, The National Assembly for Wales and the Department of the Environment In Northern Ireland. (http://www.legislation.gov.uk)

DETR (2000b). The Pollution Prevention and Control (England and Wales) Regulations 2000. ISBN 0-11-099621-6. Available from the Stationery Office.

European Concerted Action (1992). Guidelines for Ventilation Requirements in Buildings. ECA Indoor Air Quality and its Impact on Man, Report No. 11. Commission of European Communities, Luxembourg, Report EUR 14449 EN, 1992.

HMIP (1993). Guidelines on Discharge Stack Heights for Polluting Emissions. Technical Guidance Note D1 (Dispersion). ISBN 0 11 752794 7.

References

HoC (2016b). Parliamentary Early Day Motion. www.parliament.uk/edm/2016-17/733

HSE (1974). Health and Safety at Work Act, 1974. http://www.hse.gov.uk/legislation/hswa.htm

HSE (2002). Control of Substances Hazardous to Health Regulations 2002. http://www.legislation.gov.uk/uksi/2002/2677/regulation/7/made

HSE (2011a). EH40/Workplace Exposure Limits: Containing the list of workplace exposure limits for use with the Control of Substances Hazardous to Health Regulations 2002 (as amended). Updated annually. Health and Safety Executive. ISBN 9780717664467.

INDEX (2005). Kotzias D et al. The INDEX project final report; critical appraisal of the setting and implementation of indoor exposure limits in the EU. EC JRC report EUR 21590 EN, Ispra, Italy, 2005.

IWBI (2016). THE WELL Building Standard v1. International Well Building Institute, February 2016. New York. (www.wellcertified.com)

Kukadia V, Hall D (2011b). Ventilation for Healthy Buildings – Reducing the Impact of Urban Air Pollution. BRE Trust, Report No FB30, 2011. ISBN 978-1-84806-147-7.

Liddament M.W. (1996). A Guide to Energy Efficient Ventilation Air Infiltration and Ventilation Centre (AIVC) ISBN 0-946075-85-9

NHBC (2013). Assessment of MVHR systems and air quality in zero carbon homes. NHBC Foundation, Report NF 52, August 2013. ISBN 978-1-85806-340-2.

Säteri J and Hahkala H (2000). 'New Target Values for IAQ and Climate in Finland'. Proceedings of Healthy Buildings 2000, Vol 4, 531-6, 2000.

WHO (2010). Guidelines for Indoor Air Quality – Selected Pollutants (2010). The WHO European Centre for Environment and Health, Bonn Office, WHO Regional Office for Europe coordinated the development of these WHO guidelines. ISBN 978 92 890 0213 4.

United Nations (2014). Department of Economic and Social Affairs, Population Division. World Urbanization Prospects: the 2014 Revision, Highlights. (ST/ESA/SER.A/352). United Nations, New York. ISBN 978-92-1-123195-3

USGBC (2016). LEED (Leadership in Energy and Environmental Design). U.S. Green Building Council LEED Code. www.usgbc.org/leed

Zero Carbon Hub (2012).

Epidemiology, vol. 28, Nº 1, January 2017

http://www.bmj.com/content/350/bmj.h1111, 2015

http://webarchive.nationalarchives.gov.uk/20140505104658/http://www.comeap.org.uk/images/stories/Documents/Reports/Effects_on_Health_on_Indoor_Pollutants.pdf

http://www.jrc.cec.eu.int/pce/documentation/eur_reports/INDEX%20%20EUR%2021590%20EN%20report.pdf.

http://www.un.org/en/development/desa/population/publications/pdf/urbanization/the_worlds_cities_in_2016_data_booklet.pdf

https://www.bre.co.uk/filelibrary/pdf/87741-Cost-of-Poor-Housing-Briefing-Paper-v3.pdf

http://www.building4change.com/article.jsp?id=2781#.WUjw4-srKUl

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