Environment Australia

Indoor Air Quality

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Preface

Australia: State of the Environment 1996 (the first ever independent and comprehensive assessment of the state of Australia's environment) was presented to the Commonwealth Environment Minister in 1996. This landmark report, which draws upon the expertise of a broad section of the Australian scientific and technical community, was prepared by seven expert reference groups working under the broad direction of an independent State of the Environment Advisory Council. While preparing the report, the Department of the Environment, Sport and Territories, on behalf of the reference groups, commissioned a number of specialist technical papers. These have been refereed and are now being published as the State of the Environment Technical Paper Series. Reflecting the theme chapters of the report, the papers relate to human settlements, biodiversity, the atmosphere, land resources, inland waters, estuaries and the sea, and natural and cultural heritage. The topics covered range from air and water quality to sea grasses and historic shipwrecks.

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This technical paper was prepared under a consultancy agreement between CSIRO Division of Building, Construction and Engineering and the Department of the Environment, Sports and Territories. Within the time available to the CSIRO consultant, Mr. Stephen Brown (Senior Research Scientist) an effort has been made to present a comprehensive picture of the state of the indoor air environment in Australia, the pressures on this environment and the responses to these pressures. Strong emphasis was given to transparency in presenting the issues raised in this paper with the aim of providing information to decision-makers at all levels so that issues can be debated and resolved. The author acknowledges assistance provided by Dr Jeff Symons, CSIRO Division of Building, Construction and Engineering for providing information on ventilation practice in Australian buildings and individuals who made information available for the report (see Appendix 1). Any opinions expressed in the review are those of the consultant and should not be taken to infer the policies of CSIRO, the Department of the Environment, Sports and Territories or any other body.

Abstract

The objective of this paper was ‘the preparation of an analysis of the current state of air quality in a range of indoor environments in Australia, the identification of human-induced pressures on indoor air quality and the assessment of responses to pressures on indoor air quality’. The term indoor air was taken to include the air inside residential buildings and accessible public indoor areas of workplaces. This paper focuses on non-industrial workplaces and industrial workplaces are discussed only in relation to the operation and enforcement of occupational exposure standards for air. The scope of the paper was specified by the State of the Environment Atmosphere Reference Group.

Summary

Poor indoor air quality is widely regarded as a significant health, environment and economic problem. There is no authoritative definition of indoor air quality either in Australia or internationally. This paper uses a broad definition by Wesolowski (1987) which is ‘the totality of attributes of indoor air that affect a person’s health and well-being’. Indoor air quality indicators must thereby determine how well indoor air (a) satisfies thermal and respiratory requirements, (b) prevents unhealthy accumulation of pollutants, and (c) allows for a sense of well-being. While these factors are all considered, most emphasis is placed on the unhealthy accumulation of pollutants, since this is considered more relevant to the paper’s scope.

Overseas studies have established the occurrence of a range of building-related illnesses, many with identifiable and diverse causes. A subset of these illnesses—termed the ‘sick building syndrome’ (SBS)—includes mainly subjective symptoms (mild irritation of eyes, nose and throat, headaches, lethargy). SBS symptoms are believed to arise from multiple causes which, while not clearly understood, are associated mainly with air-conditioned office buildings. Australian studies in these areas have been limited, but suggest a common occurrence of building-related illnesses, SBS-like symptoms and dissatisfaction with office air environments.

A large number of pollutants have been investigated in Australian buildings, some in great detail but, for others, few observations are available. A summary of pollutants, their major sources and current response measures is presented in Table 1. In general, it is considered that many of these pollutants have not been sufficiently researched to determine both exposure levels for the Australian population and the most appropriate strategies to reduce exposure.

The more significant pollutants are considered to be environmental tobacco smoke, house dust mites and nitrogen dioxide—based on the observation of high indoor levels; and respirable suspended particles, microbials and volatile organic compounds—based on their potential for high indoor levels but lack of investigation.

High levels of environmental tobacco smoke have been found in recreational buildings where mechanical ventilation systems are not capable of removing this pollutant, even when these systems comply with Standards requirements. House dust mite allergen levels are very high in residences from coastal areas and may present a particular health problem for Australia. Nitrogen dioxide concentrations have been found to be high in many residences and schools with unflued gas heaters. While rectification programs have commenced for government schools in New South Wales, a vast number of these heaters are used without control in some other States and Territories.

Sectors of the population differ markedly in their sensitivities to pollutants. Infants and children are more vulnerable to respiratory illnesses associated with environmental tobacco smoke, house dust mites and gas combustion products such as nitrogen dioxide. Asthmatics are sensitive to a variety of pollutants which act as inducers and triggers.

Table 1: Pollutants measured in Australian buildings

Pollutant	Indoor concentration range	Major sources	Control
Asbestos fibres	<0.002 f/mL	Friable products	Risk management, removal
Radon	Conventional dwellings: 99.9% <200 Bq/m^3	Soil under building	Siting of building
	Earth-constructed dwellings: ~91% <200 Bq/m^3	Earth walls	Material selection
Environmental tobacco smoke (ETS)	High in recreational buildings	Cigarette smoke	Prohibition, designated smoking area
Respirable suspended particulates	Poorly characterised	ETS, cooking, fuel combustion	Poorly characterised
Legionella spp.	30% of population exposed	Water cooling towers	Maintenance, siting
House dust mites	Coastal areas 10–40 µg/g Der p1	Bedding, carpet, furniture	Removal of habitat (humidity control)
Microbial	100s to 18 000 CFU/m^3	Moist/damp surfaces	Control moisture/ mould
Formaldehyde	Conventional buildings <100 ppb (1–3 days average) Mobile buildings 100–1000 ppb	Pressed-wood products	Source emission control, ventilation
Volatile organic compounds	Poorly characterised	'Wet' synthetic materials	Source emission control, ventilation
Pesticides	Limited data, median <5 µg/m^3	Major sources unknown	Floor structure, inspection, clean-up
Nitrogen dioxide	Up to 1000 ppb	Unflued gas heaters	Source emission control, flued systems ventilation
Carbon monoxide	~10% >9 ppm	Unflued gas heaters	Source emission control, flued systems ventilation
Carbon dioxide	Poorly characterised	Exhaled air	Outdoor air ventilation
Ozone	Poorly characterised	Poorly characterised	Source emission control, ventilation

The question of multiple chemical sensitivity and the possible influence of indoor air pollutants is under debate. The protection of sensitive sectors of the population is considered appropriate when selecting indoor air quality indicators for residential, health and educational building categories. Indicators for other building categories will need to consider the likely access to them by sensitive sectors of the population.

The two major pressures on indoor air pollution are:

(a) (low) building ventilation rates; and

(b) (high) emission from pollutant sources.

Data on ventilation rates in Australian buildings are limited but indicate ventilation rates have become lower in residential buildings constructed in recent years and may be low in mechanically ventilated buildings constructed to the low-ventilation codes of the 1980s. Attention should be given to limiting the impact of energy conservation measures on minimum ventilation rates in residences. Design, operation and maintenance of mechanical ventilation systems have all contributed to indoor air pollution problems in the past and all of these aspects need to be addressed for new constructions and retrospectively for current buildings. Improved ventilation methods and codes are being introduced in other countries. Adoption in Australia has been slow due to inadequate research funding and expertise in the industry.

Major indoor air pollutants typically occur at much higher concentrations than found outdoors, or are completely different pollutants from those outdoors. Pollutants that originate outdoors generally reach indoor air at much reduced concentrations due to deposition losses as outdoor air infiltrates buildings. Unless these pollutants also arise indoors, prevention of exposure requires limitations on outdoor rather than indoor concentrations. Pollutants that originate indoors build to elevated concentrations in response to emission from sources under restrained (even if acceptable) ventilation conditions.

Significant sources of pollutants of indoor air in Australia have been:

(a) asbestos released from friable asbestos products, particularly asbestos ‘fluff’ which was a unique use of raw asbestos to insulate the ceilings of 1100 ACT and 100 NSW residences

(b) radon emitted from some soils in a small proportion of earth-constructed buildings

(c) environmental tobacco smoke from tobacco smoking, particularly in recreational buildings

(d) house dust mite allergens in residences, particularly in coastal climates

(e) formaldehyde in mobile buildings using pressed-wood products and conventional buildings insulated with urea formaldehyde foam insulation

(f) nitrogen dioxide emitted from unflued gas appliances, particularly heaters in residences and schools

(g) termiticides applied to the foundations of buildings with ‘leaky’ floors.

Control of pollutant emission from sources is widely accepted as the optimum response for improving indoor air quality. Examples of control measures that are being used or encouraged and which will reduce exposures to indoor air pollutants in the future are:

(a) prohibition of smoking in buildings or its restriction to appropriately designed areas separate from non-smokers (widely used)

(b) control of *Legionella* by regular maintenance and treatment of cooling towers and their location to prevent aerosol drift into air inlets (assumed to be widely used)

(c) reduction of exposure to house dust mite allergens by removing mite habitats (used by asthmatics) or reducing indoor humidities (recognised need but procedures yet to be developed)

(d) prevention of moist and damp interior surfaces to control microbial contaminants (recognised need for some commercial buildings)

(e) industrial development of low-emission interior products to control indoor concentrations of formaldehyde and volatile organic compounds (becoming used)

(f) use of low-NO_x heaters (used by NSW public schools) or flues and local exhaust (used by few States) to minimise gas combustion products indoors.

Regulatory actions related to indoor air quality are limited, especially in comparison to regulation of outdoor air quality and industrial workplace air—a feature also common overseas. While some guidance has been provided by authorities such as the National Health and Medical Research Council (NHMRC) and the National Occupational Health and Safety Commisssion (NOHSC), there is a need for a more structured approach for evaluation and control of indoor air quality. A severe limitation is the absence of a single government authority with responsibility for indoor air quality. Harmonisation of occupational standards and environmental guidelines is desirable in order to clarify their roles in different indoor environments. Development of improved ventilation codes, voluntary reduction of pollutant emissions from manufactured products, and improved public education should be used to improve indoor air quality, but have been adopted to only a limited extent in Australia.

Indoor air quality indicators should be related to a systematic process of building investigation, should reflect comfort and ventilation of the building air, and be measured in relation to the presence of critical sources rather than applied to all buildings. Building investigation, particularly for commercial buildings, should use the following structured step-wise strategy in Figure 1.

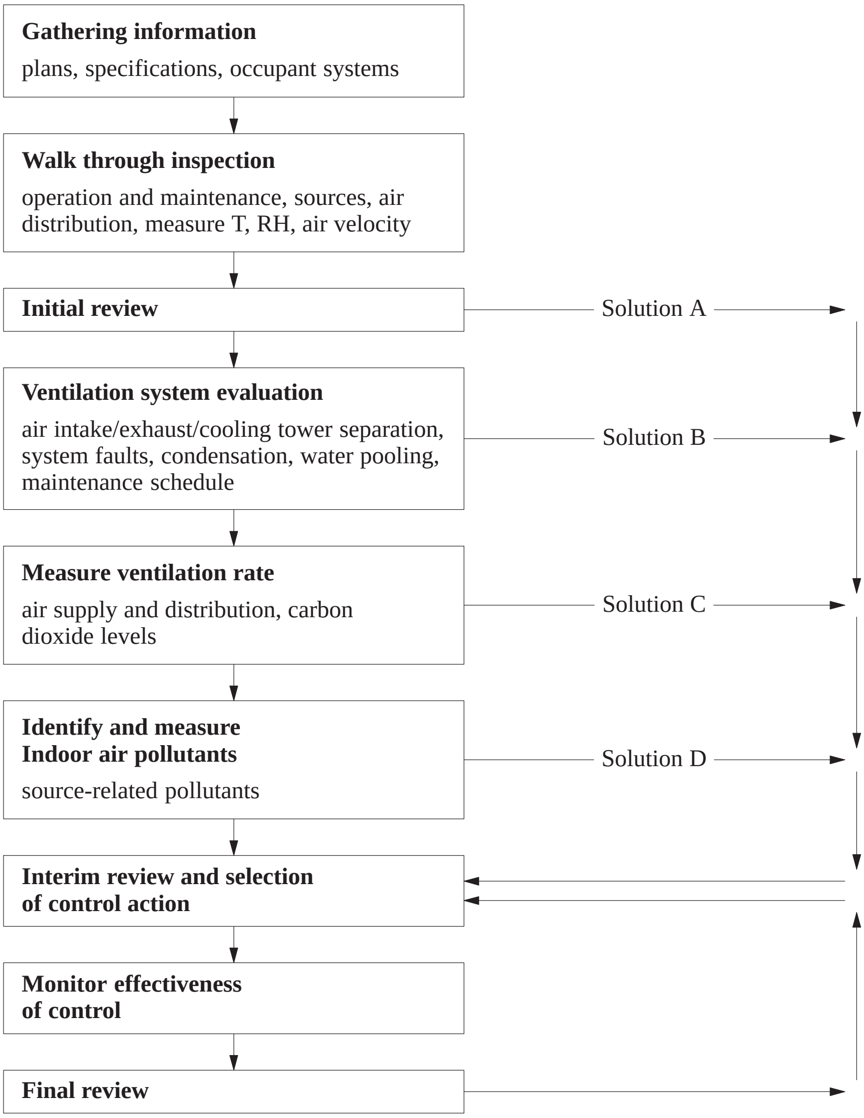

Figure 1: Strategy for investigation of indoor air quality

The following indicators (and their critical sources where applicable) could be used within this strategy:

(a) comfort indicators

- thermal comfort criteria
- optimal humidity range 40–60% relative humidity
- occupant symptom questionnaire

(b) ventilation indicators

- concentration of carbon dioxide under steady-state conditions: residences less than 1000 ppm, commercial buildings less than 800 ppm

(c) source indicators

- asbestos fibres: use applicable codes and regulations for hazard assessment of products
- radon: measure for earth-constructed residences or habitable basements
- environmental tobacco smoke: use nicotine or respirable suspended particulates (RSPs) as indicators for areas with heavy smoking; robust indicator needed for other situations
- RSPs: reserved, pending more knowledge
- *Legionella*: use applicable codes and regulations; retrospective application

- house dust mite: measure allergens in dust to determine if below ten percentile level for particular area
- microbials: moist or damp surfaces with or without visible growths are unacceptable; no presence of confirmed pathogens or toxigenic fungi in air or surface samples
- formaldehyde: measure in new buildings or caravans and mobile buildings with other than small usage of pressed-wood products
- volatile organic compounds: a total VOC concentration above 500 μg/m^3 indicates significant sources; determine concentrations of carcinogens and irritants if potential sources are present
- pesticides: measure concentrations if residues found or building has ‘leaky’ floor, especially for post-construction application of termiticides
- nitrogen dioxide: measure concentrations in all buildings (but particularly residences, schools and hospitals) where unflued gas appliances are used (particularly heaters)
- carbon monoxide: measure concentrations in all buildings with unflued gas heaters (particularly residences, schools and hospitals) and in enclosed parking sites not designed to AS 1668.2–1991
- carbon dioxide: measure concentration in mechanically ventilated buildings under steady-state conditions as an indicator of outdoor air ventilation rates
- ozone: measure concentrations in rooms with heavy-use electrostatic photocopiers, laser printers and other sources, and at outlets from ozone-based air sterilisers.

1 Introduction

Indoor air quality is recognised as a significant environmental and health problem in most countries. Modern populations typically spend 80–90% of their time indoors, whether at home, work or elsewhere. Coupled with the common research finding that pollutants in indoor air occur more frequently and at higher concentrations than in outdoor air, it is clear that indoor air is the major source for environmental exposure to air pollutants. The result of such exposure is a spectrum of illnesses ranging from mild to severe effects (e.g. mild irritation/lethargy, impaired respiratory development, asthma, cancer) that cost communities heavily in suffering and economic loss. For example, US estimates of annual economic loss due to poor indoor air quality are several tens of billions of dollars (Environmental Protection Agency 1994). Similar estimates have not been made for Australia but it can easily be calculated that for a 3% productivity loss by Australian office workers (a figure found in some overseas studies) an annual loss of $3 billion is incurred. The national cost of asthma in Australia is better known and estimated to be $750 million annually, with two million people suffering from the disease (Institute for Child Health Research, pers. comm.) and indoor air being a contributory factor.

There is no universal definition of indoor air quality (Spengler and Samet 1991) nor one accepted in Australia.

The NHMRC (1992) defined indoor air as ‘air within a building occupied for a period of at least one hour by people of varying states of health’. Buildings covered by this definition were homes, schools, restaurants, public buildings, residential institutions and offices, but not premises (e.g. workplaces) or parts of premises otherwise covered by occupational health standards. It did not define indoor air quality. While many definitions have been proposed by researchers, this paper uses a broad definition by Wesolowski (1987) which is ‘the totality of attributes of indoor air that affect a person’s health and well-being’. Under such a definition, indoor air quality indicators must determine how well indoor air satisfies thermal requirements and respiratory requirements, prevents unhealthy accumulation of pollutants, and allows for a sense of well-being. A narrower definition of indoor air quality is the occurrence of pollutants at concentrations affecting occupant health and since this has more relevance to this paper it will receive more emphasis, but not to the exclusion of other factors.

Information was gathered from published reports and conferences up to the end of 1994 and by requesting unpublished information from approximately 100 government bodies, universities, consultants and public groups. Those who provided information are acknowledged in Appendix 1.

2 Air quality in Australian indoor environments

2.1 Subjective symptoms in building occupants

Health effects that are experienced by the occupants of certain buildings range from severe effects (asthma, allergic response, cancer risks) to a series of mild symptoms, generally non-specific in nature, which exhibit an association with the indoor environment, particularly indoor air. Collectively, all such health effects are termed ‘building-related illness’ and many arise from identifiable causes, for example specific pollutants, poor ventilation, humidifier fever, poor thermal comfort, poor lighting, psychosocial factors. However, it has been found that a range of subjective symptoms, termed the ‘sick building syndrome’ by the World Health Organisation (WHO 1982), occur in a high proportion (30% or more) of occupants of specific buildings (generally, but not exclusively, air-conditioned offices) without clearly identified causes. Raw (1992) summarised SBS symptoms as:

- irritated, dry or watering eyes (sometimes described as itching, tiredness, smarting, redness, burning, difficulty wearing contact lenses)
- irritated, runny or blocked nose (sometimes described as congestion, nosebleeds, itchy or stuffy nose)
- dry or sore throat (sometimes described as irritation, oropharyngeal symptoms, upper airway irritation, difficulty swallowing)
- dryness, itching or irritation of the skin, occasionally with rash (or specific clinical terms such as erythema, rosacea, urticaria, pruritis, xerodermia)

- less specific symptoms such as headache, lethargy, irritability and poor concentration.

Despite much investigation into SBS, it is now regarded as probable that it has multifactorial causes with no single cause showing a clear association to the symptoms (Sykes 1989). Raw (1992) summarised the current but limited knowledge on potential causes as follows:

- ventilation rate—in some cases symptoms have been reduced by increasing fresh air intake but there is little evidence that this will be effective where the ventilation rate already meets current guidelines
- ventilation systems—air conditioning is strongly associated with SBS but mechanical ventilation and humidification are not; the association may be due to poor air distribution, poor maintenance, or creation of an environment conducive to growth of micro-organisms and dust mites
- airborne chemical pollution—many pollutants probably contribute
- micro-organisms and particulates—evidence is increasing that an important role is played by a mixture of organic and non-organic dust from poorly maintained air-conditioning systems and furnishings
- temperature—temperatures above 21°C have been shown to increase symptoms but possibly only where humidity is low or under particular conditions of air movement
- humidity—relative humidities below 30% may be associated with symptoms
- lighting—certain symptoms may be promoted by poor lighting, absence of windows or flicker from fluorescent tubes operated at 50 Hz
- personal and organisational factors—symptoms are more frequent among women, workers in routine jobs, those with a history of allergy, workers at video display units, and those who perceive they have poor control over their indoor environment.

Assessment of building-related illnesses in Australia has been very limited and is restricted to studies of office environments. Williams (1992) investigated ventilation system adequacy in 228 suburban, low-rise office buildings in Melbourne and, while illness was not specifically assessed, it was reported that occupants of 62% of buildings experienced unacceptably stuffy, drowsy conditions. Eighty-two per cent of the buildings failed to meet current ventilation guidelines (largely due to changes in these guidelines after the buildings were constructed). A similar incidence has been observed for inadequate ventilation of commercial buildings in Perth (K. Collins, BCA Consultants, Perth). Also it has been reported (D. McKenna, Community and Public Sector Union, unpublished paper) that a multi-State survey of 511 Commonwealth Government office workers in 1990 found that 91% experienced discomfort or illness associated with poor ventilation or temperature control. Complaints included: too hot (72%), too stuffy (72%), drowsiness (48%), headaches (48%), and sore throat (55%).

Rowe et al. (1993) determined sick leave absences from six Sydney office buildings containing a total of 500 occupants and with different design ventilation rates (3.5–11 L/person/second) and no previous evidence of occupant illness. They found no correlation between sick leave absence and design ventilation rate. However, the appropriateness of using sick leave absences as a measure of the occurrence of mild symptoms in the workforce (Sykes 1989) and the small sample size involved limit the significance of this finding. A British study has found an effect on sick leave only when an individual worker experiences several SBS symptoms (Robertson et al. 1990). However, Rowe et al. observed significant differences between the buildings that were consistent over separate study periods, suggesting some role of building-related factors. Rowe and Wilke (1994) investigated occupant perceptions of thermal comfort and indoor air quality vectors in eight office buildings in Sydney and suburbs. They found that more than 45% of occupants of each building were dissatisfied with either vector, the greatest dissatisfaction being found in six buildings that were mechanically ventilated.

Dingle and Olden (1992) investigated a new, four-level office building in Perth where occupants complained of strong chemical odours and SBS-like symptoms. They applied a self-response questionnaire to 44 occupants selected randomly from the building’s 126 office workers. Symptoms and their incidences were: dry eyes (65%), tired and strained eyes (54%), reflection/glare (41%), fatigue (57%), sore throat (28%) and migraine (36%). Factors that were identified as possible contributors to these symptoms were window glare and high indoor temperatures. Kemp and Dingle (1994) described a range of SBS-like symptoms in 20–40% of occupants from a new, eight-level office building in Perth where occupants complained of strong chemical odours. Rabone et al. (1994) found no association between recent occupant mental distress and work-related symptoms in 401 occupants of a 'sick' office building in Sydney. Instead, the symptoms were strongly associated with 'stuffiness' of the air—supporting a role of building factors rather than human factors in the cause of symptoms.

2.2 Concentrations of major pollutants in indoor air

This section will provide a perspective on indoor pollutant concentrations found in Australian buildings as well as relative data found in other countries. It was considered that many of the measurements made in Australia might not have been published and so unpublished data were sought widely from bodies around Australia. Pollutants were selected on the basis of their known occurrence in indoor air and their association with indoor sources. Measurements are compared to indoor air goal concentrations recommended by the NHMRC, provided in Table 2. Pollutants arising from outdoor air and entering buildings by air infiltration and ventilation are discussed in section 3.3.

2.2.1 Asbestos fibres

Asbestos building products have been widely used in Australia (see section 3.1.1) and include friable insulation products that easily release airborne asbestos fibres when physically disturbed. Indoor air concentrations of asbestos fibres have received little investigation in Australia, but it is assumed that overseas findings will be indicative of behaviour in Australian buildings. Overseas investigations of buildings containing asbestos insulation products were extensively reviewed by the Health Effects Institute—Asbestos Research (1991). It concluded that:

Table 2: NHMRC air quality goals for indoor air

Pollutant	Goal concentration	Status
Radon	200 Bq/m^3 (1 year)	Final (action level)
Formaldehyde	100 ppb (ceiling)	Final (residences, schools)
Lead	1.5 µg/m^3 (3 month)	Interim
Carbon monoxide	9 ppm (8 hour)	Interim
Nitrogen dioxide	—	Under review
Total volatile organic compounds	500 µg/m^3 (1 hour)	Level of concern
Single volatile organic compounds	$\leqslant$50% Total volatile organic compounds	Level of concern
Sulphates	15 µg/m^3 (1 year)	Interim
Sulphur dioxide	500 ppb (10 minute) 250 ppb (1 hour) 20 ppb (1 year)	Interim Interim Interim
Total suspended particulates	90 µg/m^3 (1 year)	Interim
Ozone	120 ppb (1 hour)	Interim

Table 3: Exposures to airborne asbestos in buildings and lifetime lung cancer and mesothelioma risk

Exposure scenario— Indoor air concentrations	Lifetime risk per million people exposed
1. Lifetime outdoor exposure	
• 0.00001 f/mL (rural)	4
• 0.0001 f/mL (urban)	40
2. Exposure in asbestos-containing school, age 5–18 years	
• 0.0005 f/mL (average)	6
• 0.005 f/mL (high)	60
3. Exposure in asbestos containing public building, age 25–45 years	
• 0.0002 f/mL (average)	4
• 0.002 f/mL (high)	40
4. Occupational exposure, age 25–45 years	
• 0.1 f/mL (current exposure standard)	2 000
• 10 f/mL (historical industrial exposure)	200 000

(a) activities of general occupants are unlikely to result in elevated asbestos fibre concentrations but routine activities of maintenance workers may lead to localised elevation of concentrations;

(b) damaged friable (see section 3.1.1) sprayed asbestos—particularly with visible debris—has often been associated with elevated asbestos fibre concentrations in indoor air whereas the undamaged product rarely shows this association; and

(c) accessible friable asbestos products have a high probability of being damaged.

The review summarised asbestos fibre concentrations (fibres longer than 5 μm per mL of air (f/mL) from analytical transmission electron microscope (TEM) measurements) in the indoor air of 108 US, 26 Canadian and 64 UK buildings and the risks to occupants as shown in Table 3.

Asbestos fibre concentrations in Australian buildings were reported by Altree-Williams and Preston (1985). They used scanning electron microscope/energy dispersive X-ray analysis for asbestos identification and counting but this method would not detect the fine fibres measured in analytical TEM methods. However their findings for 193 air samples from the occupied areas of 22 office and plant buildings containing asbestos insulation products were:

0.022 f/mL	1 sample (loose asbestos in roof space)
0.003 f/mL	3 samples
0.002 f/mL	5 samples
0.001 f/mL	22 samples
< 0.001 f/mL	162 samples

While these results are numerically similar to the results in Table 3, the different measurement techniques prevent relative assessment of the data sets.

Most asbestos building products other than insulation products are non-friable and release asbestos fibres as a result of intermittent machining processes that break down the product (e.g sawing, grinding and sanding). Asbestos concentrations (by the membrane filter method) in the breathing zone of building occupants carrying out such processes with some non-friable products are summarised in Table 4.

Note that these are short-term concentrations in response to specific work operations and their impact on long-term concentrations such as those presented in Table 3 will depend on the frequency of the operations and build-up of residues.

Table 4: Asbestos fibre concentrations during work with asbestos cement (AC) products and vinyl floor tiles

Work operation	Asbestos fibre concentration (f/mL)
Sawing and hammering AC interior cladding	0.9–1.5
Hand sawing AC sheet and pipe	2–4
Machine sawing AC products	
• without local exhaust ventilation	2–20
• with local exhaust ventilation	< 2
Machine buffing of vinyl floor tiles	0.02–0.3

Sources: AC products (Brown 1981)
Vinyl floor tiles (Martin and Edwards 1993)

2.2.2 Radon

Radon concentrations in Australian buildings have been widely investigated and found to be well below accepted indoor air goals in nearly all buildings. This is in marked contrast to the USA and the UK where large numbers of buildings exceed radon concentration goals. This difference is believed to result from differences in building practice, soil types and the coastal proximity of much of Australian housing.

Radon (radon–222) is an inert gas which is the decay product of radium–226, the fifth daughter of uranium–238. Uranium–238 and radium–226 are present in most soils and rocks, although to widely different levels. Since radon is gaseous it leaves the soil or rock and enters surrounding air or water and hence is ubiquitous in indoor and outdoor air. Radon decay leads to emission of alpha particles which can damage live tissue, such as that of the lung if radon or its daughters are inhaled. Radon has been classified as a Class 1 (human) carcinogen following studies of lung cancer incidence in miners (International Agency for Research on Cancer (IARC) 1993).

Radon entry into building air is generally via the soil under a building but less significant sources such as natural gas for cooking/heating or some building materials are also known (Wadden and Scheff 1983). Radon concentrations in indoor air will exceed those outdoors due to the restricted dispersion of air in buildings. Radium levels in soils can vary over several orders of magnitude and this was considered the critical factor underlying variation in radon concentrations in the air of US buildings rather than different ventilation levels (Samet 1991). Large, non-random surveys of US dwellings have shown that the geometric mean concentration is approximately 55 Bq/m^3 but that three million residences (4% of total) exceeded a USEPA action guideline of 150 Bq/m^3 and one million exceeded an action limit of 300 Bq/m^3.

Figure 2: Geometric mean radon activity concentrations (Bq/m^3) in dwellings from each State or Territory

Source: (Langroo et al. 1990)

A survey of radon levels in 3413 Australian dwellings was carried out in 1988 by the Australian Radiation Laboratory (ARL)(Langroo et al. 1990; Solomon 1990). The dwellings were randomly distributed and were selected from all States with numbers biased for population. It was found that the geometric mean radon activity concentration was 8 Bq/m^3 nationally, which was approximately one-half of the world average. Levels found for each State are presented in Figure 2.

Three of the dwellings (0.09% of survey population) exceeded 200 Bq/m^3, the indoor air quality goal and action limit set by the NHMRC (Table 2). It was estimated that 2000–3000 dwellings across Australia may exceed this level. Further surveys of 1000 West Australian dwellings (Toussaint 1994) and 44 Sydney dwellings (Ferrari et al. 1988a) found similar results to the ARL survey. Another more limited survey compared radon activity concentrations in three typical cavity-brick wall dwellings with concentrations in 11 earth-constructed dwellings (Baggs and Wong 1987). Significantly higher concentrations were found in the latter, reflecting the source in soils and the degree of sealing of internal earth walls—one building exceeding the 200 Bq/m^3 level.

It has been suggested that radon levels in high-rise buildings may become elevated due to stack effects (Persily 1993). Measurements in three low to high–rise office buildings in Melbourne averaged 15 Bq/m^3 (Hocking and Joyner 1994) and 30 Bq/m^3 in two high-rise buildings in Perth (W. Tossaint, WA Radiation Health Branch, pers. comm.). Higher levels (but still below the action limit) were observed in upper floors as well as basements of the buildings.

2.2.3 Environmental tobacco smoke

Environmental tobacco smoke (ETS) is the term used to describe a complex airborne mixture of gases and particles that results from tobacco smoking in buildings. Most measurements of ETS components in Australia have been in recreational buildings, where smoking is still commonly allowed. High levels of ETS components were found in these buildings even where accepted ventilation engineering practice was used. More investigation is needed for other buildings due to the paucity of information available.

ETS from cigarettes is produced primarily by the smoke released at the burning end (sidestream smoke) and smoke exhaled by the smoker (mainstream smoke). The smoke is quickly diluted and dispersed in building air and changes rapidly in its physiochemical properties, especially in the decreased proportion of constituents found in the particle phase relative to the vapour phase. Chemical composition also changes due to the way that constituents respond to ventilation and contact with indoor surfaces (Guerin et al. 1992).

An exposure standard for ETS has not been determined (NOHSC 1994) and several components have been measured as markers of ETS—most frequently combustion-derived particulate matter since a high proportion is of respirable size. US studies have found respirable particle concentrations in the presence of ETS of 40–70 µg/m^3 (24-hour sample) in residences and 200–350 µg/m^3 (<30-minute samples) in public entertainment areas (Samet and Spengler 1991). Typical background levels in non-smoking public buildings have been estimated as a few tens of µg/m^3 while typical levels in smoking public buildings are 120 µg/m^3 or less (Guerin et al. 1992).

Nicotine concentration is a more specific marker of the presence of ETS. Nicotine concentrations in US homes with smoking were found to average 3.7 µg/m^3 compared with 0.3 µg/m^3 in homes without smoking (Henderson et al. 1989). Levels in public buildings were usually 10 µg/m^3 or less and levels in high exposure settings (entertainment areas and poorly ventilated areas) could be 2 to 10 times higher. Difficulties can arise in the use of nicotine as an ETS marker for areas where smoking is intermittent since nicotine deposited previously on surfaces may be re-emitted to the indoor air (Guerin et al. 1992).

Limited measurements of respirable suspended particulates (RSP) from smoking have been carried out in Australian dwellings (Ferrari et al. 1988) and recreational buildings (Bannister et al. 1994). Cummings et al. (1990) and Cummings (1991) measured concentrations of several components of ETS in 80 recreational buildings (mainly clubs, hotels and trains) in Sydney. Significantly elevated levels of nicotine (20–140 µg/m^3), total suspended particulates (16–1600 µg/m^3) and polycyclic aromatic hydrocarbons (20–220 ng/m^3) were observed, indicating that the air cleaning methods in use were inadequate to ensure acceptable indoor air quality. Collins (1994) summarised many measurements in Perth buildings where 30% of occupants smoked and accepted ventilation engineering practice was used. RSP concentrations ranged from 150 to 225 μg/m^3 and nicotine concentrations from 21 to 42 μg/m^3. Gaughan (1990) reported that RSP concentrations in the Adelaide casino during peak occupancy ranged from 110 to 430 μg/m^3 but carbon monoxide concentrations were less than 6 ppm. He determined that installation of electrostatic and activated carbon filtration systems and increased ventilation rates would be necessary to reduce RSP concentations to below 150 μg/m^3.

2.2.4 Respirable suspended particulates

Respirable suspended particulates (RSP) also arise in indoor air from fuel-based heating appliances and cooking stoves although the impact of these on indoor air quality has not yet been well described (Samet and Spengler 1991). Wood-burning heaters and kerosene heaters can elevate RSP concentrations to short-term levels similar to those described earlier for ETS by either leakage or re-entrainment of polluted outdoor air. Airtight wood heaters will limit indoor leakage but still contribute substantially to outdoor air pollution. Ferrari et al. (1988) found an average ‘respirable’ particle concentration of 86 μg/m^3 in eight Sydney dwellings with wood fires compared to 28 μg/m^3 found in four dwellings without wood fires. Short-term concentrations during cooking (fuel unspecified) averaged 420 μg/m^3 in seven Sydney dwellings. Ingress of outdoor respirable particulates into indoor air due to air infiltration may also contribute to indoor particulates but these may vary significantly (e.g. amount of soot and acid aerosols) from those generated indoors (Dockery and Pope 1994).

2.2.5 *Legionella* spp.

The occurrence of Legionnaires’ disease has been well-documented in Australia. It is largely a result of *Legionella* growth in small cooling tower systems and evidence indicates frequent exposure to the population. *Legionella* spp. are pathogenic bacteria that are ubiquitous in soil and water in low numbers, but their numbers can grow significantly in warm environments such as cooling tower water.

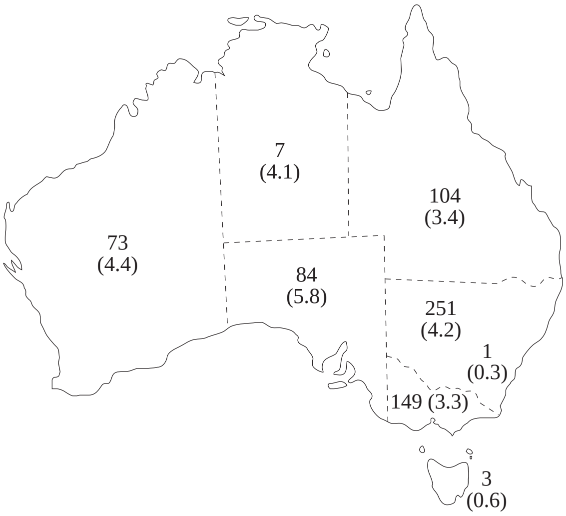

Figure 3: Number of notifications (and incidences per 100 000 population) of Legionnaires’ disease for each State from 1991 to 1994 (Communicable Diseases Network—Australia New Zealand—National Notificable Diseases Surveliance System)

(pers. comm.)

Colonisation of cooling tower water varies with season—probably in response to different *Legionella* growth rates with water temperature changes (Broadbent and Bentham 1992). The combined action of water sprays and air movement in the cooling towers (or other water-containing equipment) produces a droplet aerosol containing the bacteria which may drift into air inlets. Inhalation of the aerosol can lead to development of Legionnaires’ disease, a pneumonia that has a high mortality rate and represents 1% of pneumonia cases in Australia (Office of the Commissioner for the Environment 1992).

Legionnaires’ disease occurs sporadically in Australia but evidence indicates frequent exposure to the bacteria has occurred without illness in healthy people, (e.g. a serological survey of healthy people in South Australia found 31 % had evidence of subclinical infections (Pitt et al., referenced by Munro et al. 1994). It has been estimated that 5% of those exposed to airborne *Legionella* develop the disease, and that the illness is fatal for 10–15% of these people (Denis, referenced by Commission of European Communities (CEC) 1993). Disease outbreaks can be significant and are notifiable in all States and Territories. The number of notifications for each State or Territory from 1991 to 1994 is presented in

Figure 3. While most outbreaks in the US have resulted from *Legionella* in tempered water supplies, most outbreaks in Australia have been associated with cooling towers, particularly small systems operated after a period of shutdown (Broadbent et al. 1994).

Pontiac fever, also caused by a number of *Legionella* spp., is milder and appears as epidemics of non-pneumonic fever which last 2–5 days. Ninety-five per cent of those exposed become ill but no fatalities have been reported and the overall incidence is largely unknown (CEC 1993).

2.2.6 House dust mites

House dust mites (HDMs) are a major source of allergen in common house dust from indoor furniture and furnishings. Allergens in the indoor environment are significant pollutants since they can sensitise various organs such that an inflammatory reaction occurs on repeat exposure. Allergic reaction in the lung leads to asthma; in the nose, to hay fever or allergic rhinitis; in the skin, to dermatitis or a form of eczema. Research in recent years has shown that high levels of HDM allergens occur in dwellings in coastal areas of Australia, and may present a particular health problem in this country (Woolcock 1991). Many other biological materials can act as allergens—for example animal dander, cat saliva, cockroach saliva and faeces, dried urine from rats and mice (EPA 1988). However, these are not discussed here since levels in Australian buildings are unknown. Black (1993) suggested that HDMs were more likely to cause sensitisation than pollens or fungi since HDM exposure is perennial rather than seasonal and the level of allergen exposure can be 20 ng/hour for HDM compared to 1 mg/season for pollen and fungi.

The predominant species in Australia is *Dermatophagoides pteronyssinus* (Tovey 1992) although other species may be common in some buildings (Colloff et al. 1991). Most of the allergen resides in mite faeces which are 10–40 μm in diameter and become airborne when dust deposits are disturbed (e.g. during cleaning, housework or other disruptive activities). Generally exposure to HDM allergens has been difficult to assess using airborne allergen measurements and as alternatives the allergen concentrations (e.g. Der p 1, the allergen specific to *D. pteronyssinus*) or the numbers of mites in accumulated dust (vacuumed from carpet or furniture) have been used. It has been suggested that at allergen levels above 2 μg of Der p 1 per gram of fine dust (equivalent to 100 HDM per gram of fine dust), there is an increased risk of sensitisation, bronchial reactivity and symptomatic asthma; at levels above 10 μg of Der p 1 per gram of fine dust (500 HDM/g) the risk of acute or severe asthma attacks is increased (Platts-Mills and de Weck 1988).

Since mites require humidities above 40–50% relative humidity for survival at normal indoor temperatures, the level of mite allergens in very dry or cold climate regions (Stockholm, Arizona) is generally less than 2 μg/g, whereas in regions with one season suitable for population growth (coastal Europe and USA) the level has a mean between 2 and 15 μg/g. Regions with a climate suitable for mite populations for much of the year (coastal areas of Australia and South America) have mean allergen levels of 10 to 40 μg/g (Tovey 1992).

A summary of HDM allergen measurements in Australia is presented in Figure 4 and should be regarded only as indicative of distribution since significant variations in assays can lead to 2- to 5-fold variations in field measurements (Tovey 1994). Mite allergen levels appear to be highest in coastal regions, and become lower inland and virtually zero in central Australia.

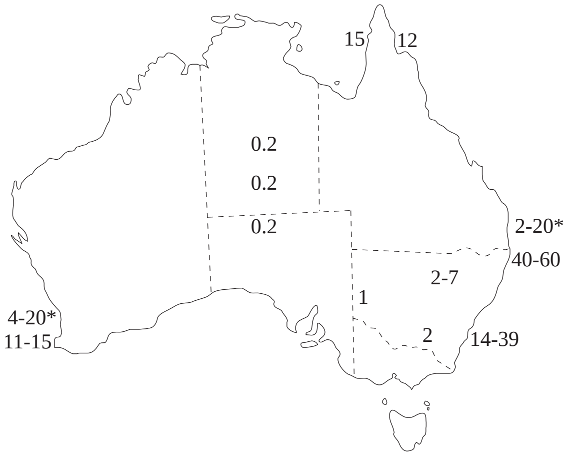

Figure 4: Geometric mean HDM allergen levels (Der p 1 μg/g fine dust) in dwellings from different regions of Australia (*range estimated from mite numbers)

Sources: Domrow 1970, Colloff et al. 1991, Tovey 1992, Peat 1994.

For any region, mite allergen levels fluctuate widely between dwellings for unknown reasons, although indoor humidity is a possible controlling factor (Tovey 1993; Brown et al. 1994). Limited studies of public buildings in Sydney (Green et al. 1992) and Melbourne (Brown 1994) have shown virtually zero HDM levels compared to nearby dwellings. This may be due to greater ventilation rates and lower indoor humidities in public buildings, but these factors have yet to be investigated.

2.2.7 Microbial contaminants

These include viable and non-viable microbiological matter such as viruses, bacteria, fungi, protozoa, insect faeces and pollens. *Legionnella* spp. and house dust mites fall within this classification but have been discussed separately since there is more knowledge of their occurrence and health effects. By comparison, the impact of other microbial contaminants on indoor air quality in Australia has received little investigation.

In order for airborne disease transmission to occur from microbes in buildings, there must be a source or reservoir for the microbes, some means for the microbes to multiply (amplifiers) and a mechanism for their release and dispersion into indoor air (Burge and Feeley 1991). The major reservoir indoors is stagnant water or wet interior surfaces that accumulate microbes which enter the building with outdoor air. Such reservoirs may act as amplifiers for bacteria, while fungi can grow in relatively dry environments (e.g. at relative humidities above 75% (Solomon and Burge 1984)). Airborne dispersion is relatively easy for microbes found in building ventilation systems (e.g. fungal and bacterial spores) or contaminated carpet.

Airborne assessment of microbes is complicated by the selection of appropriate sampling techniques, the variety of species that are present and their temporal fluctuations, the high potential contribution from outdoor sources and the limited knowledge of species-specific health effects (although inflammation and allergic response predominate). Several recent studies suggest that indoor air microbials may have a more common role in the SBS than previously thought (Rylander 1993, 1993a). Specific guidelines were supplied by the American Conference of Governmental Industrial Hygienists (ACGIH 1989). These relied primarily on site inspection for potential sources of microbes, and air sampling was regarded as a secondary or last resort action where occupant illness had occurred. Any indoor air sampling must be performed relative to outdoor air sampling and must determine both taxa and concentrations. The World Health Organization (WHO 1990) guidelines for assessment of hazardous indoor airborne fungi used a similar approach, as summarised in Table 5.

Table 5: Guidelines for assessing airborne fungi

Result of air sampling	Acceptable level
A. Confirmed pathogens (e.g. *Aspergillus fumigatus*) or toxigenic fungi (e.g. *Strachybotrys atra* and toxigenic *Penicillium*, *Fusarium* species)	Not acceptable
B. Only one species other than *Cladosporium* or *Alternaria*	< 50 CFU*/m^3
C. A mixture of species reflective of outdoor flora	< 150 CFU*/m^3
D. Primarily *Cladosporium* or other common phylloplane fungi	< 500 CFU*/m^3

Source: (WHO 1990)
* CFU colony forming units

Published studies in Australian buildings have been limited. Godish et al. (1993) investigated airborne mould and bacteria levels in 40 dwellings in the Latrobe Valley, Victoria. All dwellings had one or more occupants with persistent respiratory symptoms such as asthma or allergy. Seventy-five per cent of the houses had evidence of indoor mould growth, 25% of the houses had one or more rooms where viable mould concentrations exceeded 2000 CFU/m^3 and 13% had concentrations exceeding 10 000 CFU/m^3. Outdoor mould levels contributed to indoor levels but indoor samples had much higher levels of *Penicillium* spp. A current study of 30 dwellings in the same area found indoor viable mould levels up to 18 000 CFU/m^3 with median levels (in different seasons) between 500 and 1150 CFU/m^3 (M. Garrett, Monash University, pers. comm.). Seneviratne et al. (1994) reported measurements in three Sydney office buildings with histories of SBS symptoms. Two buildings exhibited low colony counts which were primarily *Cladosporium*, *Aspergillus* and *Penicillium*. The third, a building found to have damp walls but no visible mould growth, exhibited similar species but at high airborne levels (600–2500 CFU/m^3). Cliff (SIMTARS, Queensland, pers. comm.) determined viable mould concentrations in three office buildings, 7–15 years old and with occupant complaints. Concentrations ranged from 19 to 1230 CFU/m^3 (44 measurements) and averaged 340 CFU/m^3; outside concentrations were 500–1000 CFU/m^3 (3 measurements). Adamczyk (Department of Administrative Services Centre for Environmental Management (DASCEM), pers. comm.) reported total viable species in two office buildings from 9 to 730 CFU/m^3, the 66 measurements averaging 170 CFU/m^3.

2.2.8 Formaldehyde

Formaldehyde concentrations have been found to be low in conventional, established residences and offices but exceeded the NHMRC goal in mobile buildings, probably due to their high content of pressed-wood products and low ventilation rates. Concentrations exceeding the goal have also been observed in residences recently insulated with urea formaldehyde foam insulation (UFFI), although, after several months when the foam has dried, the formaldehyde concentrations are generally below the NHMRC goal. Concentrations in new or renovated buildings have received little investigation.

Formaldehyde is an irritating gas with a pungent odour and readily dissolves in water. Its major industrial application is in the production of different resins which are widely used in indoor materials and in consumer products, particularly pressed-wood and building products such as particleboard and medium density fibreboard. Formaldehyde is also emitted by gas stoves and in tobacco smoke.

Much of the initial concern over formaldehyde in indoor air arose in the early 1980s from the use of UFFI as a wall and ceiling cavity insulation (see NHMRC 1982 in Appendix 4). UFFI was used in 50 000 to 70 000 Australian dwellings and occupant health complaints arose in less than 1% of these. Formaldehyde indoor air concentrations in the 1000 ppb range could occur soon after installation of UFFI although after several months concentrations were typically less than 100 ppb, the indoor air goal recommended by the NHMRC (Brown 1991).

Concentrations in the 1000 ppb range also occurred in US dwellings using pressed-wood products, particularly those using large quantities and low ventilation rates—such as mobile homes and caravans (Marbury and Kreiger 1991). Typical average concentrations in US and Canadian dwellings have been 30–140 ppb for conventional homes and 160–400 ppb for mobile homes. Concentrations found in Australian buildings are summarised in Table 6.

Formaldehyde concentrations in conventional Australian buildings appear somewhat lower than those reported in North America while those in mobile buildings are similar.

2.2.9 Volatile organic compounds

In contrast to other countries, volatile organic compounds (VOCs) have received very little investigation in Australian buildings of any type, although a CSIRO project aims to commence such measurements. Despite this situation, there is an indoor ‘level of concern’ for VOCs established by the NHMRC (Table 2). It is unknown whether Australian buildings comply with or exceed this level.

Table 6: Formaldehyde concentrations in Australian buildings

Building type	Study	Number of buildings	Formaldehyde concentration (ppb)	
			range	mean
Conventional dwelling	Dingle et al. (1992)	100	0–97	26
	Hooper et al. (1994)	40	3–73	23
	McPhail (1991)	39	10–33	26
Caravan	Dingle et al. (1992)	20	20–280	90
Caravan/mobile home	McPhail (1991)	24	80–1200	310
Conventional office	Dingle et al. (1992)	3	15–70	21
	Cliff (Simtars, Qld)	4	20–120	66
	Ruksenas (Noel Arnold & Assoc)	8	10–80	40
Mobile office	Dingle et al. (1992)	12	420–830	710

VOCs are organic compounds with boiling points between 40–60°C and 260°C (excluding pesticides) that arise from the large number of materials, equipment and consumer products used in buildings. Generally, in any building, 50 to 150 of such compounds are found using the sensitive analytical methods (detecting concentrations around 1 $\mu g/m^3$) now available. It has been postulated that the individual compounds have an interactive effect on sensory irritation and should be considered together as a total VOC (TVOC) concentration (Molhave and Nielsen 1992). A common definition for TVOC is lacking, especially one relevant to occupant exposure and health effects, although the European Commission will have examined a guideline definition for TVOC by the end of 1995 (M. De Bortoli, EC Joint Research Centre, Italy, pers. comm.). A review of TVOC measurements overseas (Brown et al. 1994) found that:

(a) mean TVOC concentrations in established residences were 1130 $\mu g/m^3$, greatly exceeding individual VOC concentrations (less than 5 to 50 $\mu g/m^3$);

(b) mean TVOC concentrations in new buildings were approximately 4000 $\mu g/m^3$, indicating the major source was new building products and contents; and

(c) 90 percentile concentrations of TVOC were approximately 4000 $\mu g/m^3$ in established residences and 18 000 $\mu g/m^3$ in new buildings, levels that are comparable to those observed to cause irritation to human subjects (Molhave 1990).

Limited data exist for VOC concentrations in Australian buildings. CSIRO Division of Building, Construction and Engineering, Highett, has a project to characterise VOC concentrations in buildings and preliminary results are presented in Table 7 together with other measurements. Note that differences in analytical methods limit comparison of these data. Further investigation is needed to determine the level of exposure to VOCs for Australian populations.

2.2.10 Pesticides

Indoor air pesticide concentrations have been investigated recently in small samples of Australian dwellings treated with termiticides. No investigation appears to have addressed other pesticide sources. Australian and overseas studies indicate indoor air termiticide concentrations are greater for dwellings treated after construction or with floor constructions conducive to accumulation and ingress of pesticide vapours into living spaces.

Table 7: VOC concentrations in Australian buildings

Data source	Building type	Complaints (yes/no)	TVOC concentration ($\mu g/m^3$)	Major compounds
CSIRO	Dwelling	Yes	32	Limonene, acetone
CSIRO	Dwelling	No	143 (9 outdoor)	Limonene, alkanes, pinene
CSIRO	Library • new carpet • 6 months later	 No No	 210–340 44	 Styrene, 4–phenyl cyclohexene, toluene, xylene
CSIRO	Office	No	69 (outdoor 27)	Limonene, ethanol, toluene
Healthy Buildings International	18 office	Unknown	av. <90 max ~2700	Toluene, xylene, 1,1,1–trichloroethane Dichloromethane, toluene, 1,1,1–trichloroethane
Simtars (D. Cliff, pers. comm.)	3 office	Yes	88–527 av. <190	Toluene, xylene, trichloroethane, chloroform, acetone, dichloromethane, tetrachloroethylene
Noel Arnold & Assoc. (J. Ruksenas, pers. comm.)	3 office	Yes	10–2000	Unknown
DASCEM (Z. Adamczyk, pers. comm.)	1 office	Unknown	20–1250 av. 550	Toluene, hexane

Generally, exposure to pesticides in dwellings is believed to occur through the use of consumer products, intrusion of termiticides from foundations and contamination of house dusts. Exposure can occur by inhalation and by absorption through the skin after contact with treated surfaces and so airborne concentrations are not the only indicators for occupant exposure. Misuse of pesticides is considered to provide the greatest potential for exposure and is an ‘all too frequent’ occurrence (Lewis and Wallace 1987).

There is no Australian guideline for indoor air pesticide concentrations but the US National Academy of Sciences (NAS 1979) set guidelines to indicate the presence of pesticides rather than health effects (Table 8). The US armed forces study of chlordane in over 10 000 dwellings found the guideline was exceeded in 276 dwellings (Wallace 1991). The incidence of contamination was greater in houses built on soil treated after construction rather than before construction (Lillie and Barnes 1987). Wallace also summarised measurements from 200 US houses (Table 8).

Investigations into pesticide levels in Australian buildings are relatively recent. Dingle et al. (1994) reported that pesticides were detected in the indoor air of 19 of 22 dwellings treated with termaticides several years previously. Mean concentrations ($\mu g/m^3$) were chlorpyrifos 2.2, heptachlor 1.2, aldrin 0.4, and chlordane/dieldrin 0.1. Gun et al. (1994) summarised the findings of a two-year study into indoor air and blood dieldren levels after 29 constructed dwellings were treated with aldrin to prevent termite infestation using Australian Standard practice. The airborne aldrin concentrations one to six weeks after the treatment ranged from 0.08 to 51 $\mu g/m^3$, with median concentrations of 0.7 to 2.6 $\mu g/m^3$. Six dwellings exceeded a concentration of 10 $\mu g/m^3$ after one week, two dwellings exceeded this level after six months, and one dwelling exceeded it after one year. Poor sub–floor ventilation and a ‘leaky’ floor were important contributors to indoor air pollution by aldrin (Pisaniello et al. 1993). Blood dieldren levels of occupants showed an increase of borderline statistical significance after the treatment. This was largely due to results from the two most heavily contaminated dwellings where occupants showed clear and sustained increases in blood dieldrin levels.

2.2.11 Nitrogen dioxide

Indoor air concentrations of nitrogen dioxide have received much investigation in dwellings and schools in Australia, particularly in New South Wales (NSW) where unflued gas heaters have been widely used. High concentrations have been found in many of these buildings and while an extensive rectification program is ongoing in NSW government schools, it is expected that similar concentrations will occur in a large number of similar buildings in other States which have not yet been evaluated. Assessment of the significance of indoor nitrogen dioxide concentrations is limited by uncertainties about health effects at low levels and the absence of an NHMRC indoor air goal, although recent child health studies indicate an urgent need for these issues to be clarified.

Nitrogen dioxide and nitric oxide occur in building air due to indoor combustion sources, but nitrogen dioxide is the oxide of principal health concern since it is known to cause lung damage at high concentrations. Nitrogen dioxide is an oxidant gas deposited primarily in the large and small airways of the lung. Other potentially toxic derivatives of nitrogen oxides (e.g. nitric acid and nitrates) may also be generated but their presence in indoor air and potential health effects have not been addressed (Samet and Spengler 1991).

Spengler et al. (1983) measured nitrogen dioxide average concentrations over a one-year period in 137 US dwellings from a rural community where outdoor annual mean concentrations were 20–30 ppb. Annual mean indoor concentrations were higher than outdoors by 100 ppb in kitchens and 60 ppb in bedrooms for dwellings with gas cooking (seldom vented in the US). Ten per cent of the dwellings exhibited concentrations exceeding the US National Ambient Air Quality Standard of 200 ppb. Concentrations in dwellings with electric cooking were lower than outdoor concentrations. A recent study (Brauer and Spengler 1994) identified the high potential exposure that could occur in US ice skating rinks.

For Australia, the NHMRC recommends an ambient nitrogen dioxide goal concentration of 160 ppb (one-hour average) but a goal for indoor air has been under review over many years. In November 1994, the WHO International Program for Chemical Safety Task Group (Review of Environmental Health Criteria for Oxides of Nitrogen) met in Melbourne and set a health-related exposure guideline for nitrogen dioxide in indoor or outdoor air. This guideline is confidential until the criteria document has been published, probably late in 1995. The NHMRC will consider these criteria and all other evaluations in its review process (L. Heiskanen, NHMRC, pers. comm.). Two recent Australian studies have demonstrated statistically significant respiratory symptom increases in children who live in residences with gas stoves or unflued gas heaters (Volkmer et al. 1994) or lives in residences or attend schools with unflued gas heaters that lead to maximum one-hour nitrogen dioxide concentrations greater than 80 ppb (Pillotto et al. 1997, pers. comm.).

Table 8: Average pesticide concentrations in US houses

Pesticide	Average pesticide concentration (µg/m^3)		
	NAS Guideline	Florida	Massachusetts
Chlorpyrifos	10	0.23	0.01
Chlordane	5	0.26	0.12
Heptachlor	2	0.13	0.02
Diazinon	–	0.21	0.03
Propoxur	–	0.30	0.02

Most measurements in Australia have been made in NSW where unflued natural gas space heaters are widely used without restriction. Unflued gas heaters, especially liquefied petroleum gas (LPG), are used in most other States with little restriction (see section 4.2.2) and so NSW findings will have some relevance to these. Twenty per cent of Sydney dwellings are estimated to use unflued gas heaters. Average nitrogen dioxide concentrations in 64 Sydney dwellings for 2–3 hours after unflued gas heaters were lit exceeded 160 ppb in 50% of cases and 300 ppb in 20%. It was concluded that unflued gas heaters were a significant source of indoor air pollution by nitrogen dioxide (Ferrari et al. 1988). Lyall (1993) reported on a 1992 winter nitrogen dioxide survey of 195 dwellings that used unflued gas heaters in Sydney, Adelaide and Perth. Similar to the findings of Ferrari et al., 20% of the Sydney homes exceeded 300 ppb but only 4–5% of Adelaide and Perth dwellings did so (this may have reflected heater size limitations and the requirement for fixed wall vents for the latter (section 4.2.2)). Median (and range) concentrations were: Sydney 200 ppb (30–830 ppb), Adelaide 100 ppb (0–340 ppb) and Perth 100 ppb (30–600 ppb). Evaluation of the 21 Sydney dwellings exceeding 300 ppb found that servicing of radiant heaters and modifying convection heaters could reduce concentrations, although not to levels much below 300 ppb.

A 1989 investigation of over 700 NSW school rooms with unflued gas heaters (most with a window or door open) found the concentrations averaged 145 ppb, exceeding 160 ppb in 23% of cases and 300 ppb in 7% (McPhail and Betts 1992). The major factors affecting these levels were gas leaks in the heaters (causing greater nitrogen dioxide production) and room ventilation levels. In some room trials, creating cross-ventilation by opening windows and doors reduced concentrations from 1000 ppb to 300 ppb, but the practicality of such an approach under winter conditions is open to question. Riley (ACT Government Analytical Laboratory, personal communication) reported that nitrogen dioxide concentrations in ACT schools with unflued gas heaters ranged from 20 to 200 ppb. A summary of all results presented above is provided in Figure 5, which shows that the NHMRC ambient goal for nitrogen dioxide of 160 ppb was commonly exceeded in these buildings.

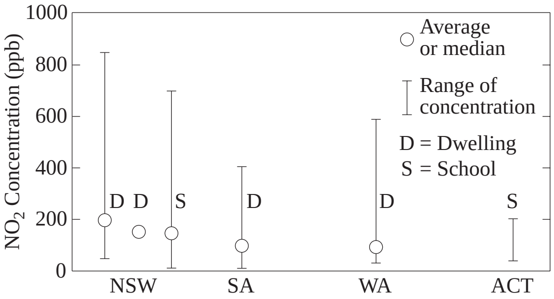

Figure 5: Nitrogen dioxide concentrations during winter periods in Australian buildings with unflued gas heaters and no remediation actions to the heaters

In response to the findings, in 1990 the Department of School Education (NSW) instituted a major program of gas leak rectification in all schools and introduction of low-NO_X heaters (still unflued). McPhail and Betts (1992) reported that subsequent nitrogen dioxide concentrations in 2645 rooms with conventional unflued heaters exceeded 100 ppb in 20% of cases and 300 ppb in 2.5% of cases; for rooms with 437 low-NO_X heaters, the exceedances were 7.6% and 0%, respectively. This program in NSW schools is ongoing and all heaters found to cause nitrogen dioxide concentrations above 300 ppb and heaters in colder areas of the State have been replaced with low-NO_X heaters. To date 17 500 heaters have been replaced which is 38% of unflued heaters in NSW public schools. The intention is to eventually replace all unflued gas convection heaters. Between 1990 and 1994, the program has measured nitrogen dioxide concentrations in schoolrooms with 14 000 unflued gas convection heaters and found the median concentration to be 50 ppb with 11% exceeding 160 ppb and 3% exceeding 300 ppb. (Note that these measurements were subsequent to the gas leak rectification and heater maintenance program for all NSW public schools and an Education Department directive requiring windows to be opened while heaters were operating. This may explain why the concentrations are significantly lower than those measured in 1989 by McPhail and Betts). In the same period, measurements in schoolrooms with 519 low-NO_X heaters (often two to a room) exhibited a median concentration of 40 ppb with 4% of measurements exceeding 160 ppb and 0.5% exceeding 300 ppb. All low-NO_X heaters were fuelled by LPG and preliminary investigation by NSW Public Works indicated some supplies had a non-propane content which caused higher nitrogen dioxide emission (Margaret Rodanska, NSW Public Works, pers. comm.).

2.2.12 Carbon monoxide

Carbon monoxide concentrations have been measured in Australian dwellings with unflued gas heaters but the proportion exceeding the NHMRC indoor air goal is unclear. Concentrations in other buildings have received little investigation, an inadequacy that should be addressed for enclosed carparks and adjacent areas since overseas experience has shown these may experience high concentrations.

Carbon monoxide is produced indoors primarily by fuel combustion (e.g. gas or wood-burning appliances, car exhausts) or infiltration of polluted outdoor air. Outdoor levels in rural areas have been measured to be below 1 ppm (Health and Welfare Canada 1989) but levels as high as 50 ppm, but typically 10–12 ppm, have been measured for vehicle occupants in heavy traffic (Coultas and Lambert 1991). Very high indoor residential concentrations have been measured in poisoning accidents which generally resulted from malfunctioning or misused combustion appliances.

Indoor carbon monoxide concentrations are expected to generally follow outdoor levels except where combustion sources occur in buildings without full venting. The NHMRC indoor (and outdoor) air goal concentration for carbon monoxide is 9 ppm (eight-hour average). Levels higher than this have been experienced overseas in indoor parking areas and building locations attached to these (Coultas and Lambert 1991).

Ferrari et al. (1988) measured carbon monoxide concentrations in 52 Sydney dwellings, mostly with unflued gas heaters and found that three exceeded the NHMRC goal, possibly due to poor building ventilation or appliance servicing. Lyall (1993) measured carbon monoxide concentrations in 195 dwellings in Sydney, Adelaide and Perth-all with unflued gas heating. Median concentrations (and measured range) were Sydney 6 ppm (1–47 ppm), Adelaide 0.6 ppm (0–37 ppm) and Perth 5.3 ppm (0.3–22 ppm). Clearly, a proportion of the dwellings exceeded the NHMRC goal but this proportion was not reported.

Pontin et al. (1994) measured carbon monoxide concentrations in four central-Perth and one suburban office building with no known carbon monoxide sources other than underground parking. The concentrations varied with peak traffic flow outdoors and hourly averages ranged from 1 to 8 ppm, eight-hour averages from 1 to 5 ppm. Cummings et al. (1990) found that carbon monoxide concentrations at 80 sites in recreational buildings with smoking permitted ranged from 0–24 ppm and generally exceeded 9 ppm during peak activity periods, largely due to a significant contribution by outdoor levels.

2.2.13 Carbon dioxide

Humans exhale carbon dioxide and in a building this exhaled gas can be removed only by dilution with outdoor air. The carbon dioxide concentrations generally encountered in buildings have no adverse health effects. However, the concentrations measured, in the absence of other sources (e.g. combustion processes), will be closely related to the ventilation rate relative to the number of occupants and building volume. This relation has been established overseas such that carbon dioxide levels are used as indicators of the adequacy of ventilation for air quality evaluation. However, there has been no investigation into its application in Australian buildings.

Typical outdoor concentrations are 350–450 ppm but concentrations around 3000 ppm can be exceeded in poorly ventilated rooms from exhaled air alone. The occupational exposure standard (ACGIH 1994) is 5000 ppm, to protect against undesirable changes in the acid–base balance of the body. Many studies of occupant perceptions of air quality suggest that concentrations above 800–1000 ppm indicate an inadequate supply of fresh air in mechanically ventilated buildings (Health and Welfare Canada 1987). Consequently carbon dioxide concentration has been used as a surrogate measure of ventilation rate relative to its influence on indoor air quality (see section 3.2.2.1) and may be used as the sensor in demand-controlled ventilation systems (Reardon and Shaw 1993). Carbon dioxide concentrations have also been used to estimate effective ventilation rates for buildings but can only be used in this way under specific building/occupancy conditions. The most important condition is the maintenance of steady-state ventilation conditions—which is difficult to achieve for buildings operating at low ventilation rates (White 1994).

While no research into carbon dioxide concentration–ventilation rate interaction has been carried out in Australia, several consultants have used concentration measurements in office building investigations to determine the adequacy of ventilation. Results submitted by these consultants are presented in Table 9 but have not been related to building ventilation rates, limiting their interpretation.

2.2.14 Ozone

Ozone is a strong oxidiser formed in outdoor air by photochemical reactions and is an irritant that affects the mucous membranes, other lung tissues and lung function. Indoor sources were considered of minor significance 10 years ago (Wadden and Scheff 1983) but this may change with the increased use of electrostatic photocopiers and laser printers in offices, which have been reported to emit substantial quantities of ozone (Cutter Information Corporation 1992a). Many of the suppliers of such equipment limit ozone emissions by use of charcoal filters on exhausts—but these must be replaced regularly. The NOHSC (1989) noted that a combination of heavy use, poor maintenance and inadequate ventilation could result in excessive ozone levels. Little research into ozone exposure in modern office buildings appears to have been carried out as yet, but emission limits have been proposed for office equipment (see section 4.4). Riley (ACT Government Analytical Lab, pers. comm.) reported that ozone concentrations measured in ACT offices were typically less than 10 ppb.

2.3 Sensitive sectors of the population

Some sectors of the population are known to exhibit greater sensitivity to airborne pollutants. These sectors commonly include the very young, the old and the infirm, and examples of these will be cited. However, other sectors to be discussed will be asthmatics and individuals who have become sensitised to specific pollutants, resulting in an immunologic response even at very low concentrations.

Table 9: Carbon dioxide concentrations in office buildings investigated by Australian consultants

Consultant	Building	Number of measurements	Concentration (ppm)	
			range	mean
Z. Adamczyk (DASCEM)	A	75	350–600	440
	B	44	700–1250	1000
J. Archibald (ACS)	C	20	400–600	430
D. Cliff (SIMTARS)	D (complaint)	64	300–600	420
	E (complaint)	22	300–650	450
	F (non–complaint)	20	300–500	410
J. Ruksenas (Noel Arnold & Assoc.)	9 complaint	–	360–1210	–
	18 non–complaint	–	360–1130	–

In their first few months of life, infants appear to be more vulnerable and sensitive to pollutants. Consistent with this is evidence that induction of asthma occurs as a result of specific allergen exposure in the first years of life (Hurry et al. 1988; Landau 1993). Similarly, parental smoking has been found to increase significantly the frequency of bronchitis and pneumonia during the first year of life and chest illness in older children (Samet et al. 1991), and exposure of a large population of Australian pre-school children to unflued gas appliances has been found to increase symptoms of respiratory illness (Volkmer et al. 1994).

Groups at particular risk from exposure to carbon monoxide are those with cardiovascular, cerebovascular and peripheral vascular disease, foetuses, the newborn, pregnant women and people living at high altitudes (Health and Welfare Canada 1987). Nutritional status is another factor—for example, individuals with diets deficient in selenium or vitamin E may undergo greater lung damage from ozone exposure (Maroni 1994). Studies of the mortality effects of particulate pollution in outdoor air have found the strongest effects in the elderly (Dockery and Pope 1994).

Asthmatics are clearly at risk from pollutant exposures. Landau (1993) defined asthma as an episodic cough or wheeze in a clinical setting where asthma is most likely and other serious conditions have been excluded. He noted that predisposition to asthma was genetically determined and was probably present in up to one-third of the Australian population. The disease asthma is present once the pathological process responsible for altered airways responsiveness has developed. In Australia, it is estimated that 8–9% of the population suffers from asthma, with asthma being experienced at some time by one in four children, one in seven adolescents and one in ten adults (Asthma Foundation of Victoria, pers. comm.). A range of inducers and triggers have been identified—such as environmental tobacco smoke (ETS), grass pollens, house dust mite and cat dander. Ostro et al. (1994) reported that adults with moderate to severe asthma exhibited increased morbidity associated with several domestic combustion sources (gas and wood stoves, fireplaces, ETS). In general, the incidence of asthma in the developed world has increased markedly in recent decades and it has been estimated by some that 90% of asthma has indoor origin, whether it be in the home or workplace (Green 1994).

Sections of adult populations appear to exhibit unusual sensitivity to some indoor pollutants. Hypersensitivity pneumonitis (HSP) can exhibit as an acute or chronic form, the former being easier to recognise. Shortly after inhaling an offending agent, the person experiences chills, fever and shortness of breath and their chest X-rays mimic pneumonia. In the indoor environment, a broad range of inhaled antigenic materials (mostly complex organic particles) can cause HSP. Fungi such as *Alternaria*, *Penicillium* and *Aspergillus* spp. and avian proteins from pet birds and simple reactive chemicals (e.g. toluene diisocyanate, diphenylmethane diisocyanate) have been documented as causative agents (Weissman and Schuyler 1991). HSP is not common in the UK but has been well described in the US from mechanical ventilation systems (Pickering 1994), where it has been suggested to be quite common but unrecognised (Rose 1994).

Evidence indicates that a portion of modern populations may develop ‘multiple chemical sensitivity’ (MCS) although the existence of this effect remains a matter of dispute among medical bodies (Collins 1993; Brooks 1992; Hodgson 1993). Cullen (1987) defined MCS as an acquired disorder characterised by recurrent symptoms from multiple organs in response to demonstrable exposure to many unrelated chemicals at doses far below those established as harmful to the general population (e.g. less than 1% of occupational exposure standards). Ashford and Miller (1991) identified four clusters of people with heightened chemical reactivity:

(a) industrial workers

(b) occupants of ‘sick’ buildings

(c) communities whose air or water is contaminated by chemicals

(d) individuals who have had unique exposures to various chemicals.

The incidence of MCS has been estimated to be as high as 15% in the US (Collins 1993) but this must depend on definition and diagnosis of the condition (which are uncertain factors at the moment). In contrast to Ashford and Miller, Cullen differentiated MCS from sick building syndrome on the basis of the pattern of dose-related symptoms that are observed in co-workers with the latter.

Miller (1994a) called for greater knowledge of MCS and its development so that strategies to prevent sensitising events could be developed rather than ‘over-regulation’ of environmental exposures to protect the sensitised individual.

3 Human-induced pressures and trends

3.1 Major indoor pollutant sources

For each of the major indoor pollutants described earlier, one or more major sources of pollutant emission are known. The identity of these sources, their changes in the past and possible changes in the future will be described in this section.

3.1.1 Asbestos fibres

Asbestos fibres were used widely in many building products in Australia up to the early 1980s and much of these remain in place in the current building stock. The major building products manufactured (Brown 1981) were asbestos-cement (AC) sheet products for interior and exterior cladding, flooring products (high density underlay sheets, vinyl-asbestos floor tiles, ‘cushion’ vinyl flooring) and fire, thermal or acoustic insulation products (asbestos millboard, sheet and pipe pre-formed insulation panels, sprayed asbestos insulation). These products varied greatly in the types and amounts of asbestos and binders that were used and in consequence exhibit large differences in their physical integrity (particularly friability). Friability is the ability of the material to be broken down to dust. Most insulation products are considered friable, many sprayed asbestos insulation products being highly friable such that minor disturbance can result in a large airborne release of asbestos fibres.

Sprayed asbestos insulation products were widely used in commercial and industrial buildings in Australia and can act as a major source of asbestos fibre exposure if the products are damaged or deteriorated—particularly during building maintenance activities (Brown 1981). Local State regulations and guidance from the NOHSC (1988) are in place to manage risks from such products in workplaces. It has been estimated that $300 million is spent annually removing asbestos insulation products from Australian buildings (Rogers 1991). It is clear from recent overseas studies that removal must encompass stringent precautions and that it can lead to elevated indoor asbestos concentrations for a prolonged period after removal (Kominsky et al. 1994).

Australia experienced a unique source of indoor asbestos which was used as a domestic ceiling space insulation. A specific ACT contractor installed unbound asbestos ‘fluff’, largely amosite but also crocidolite in some (five to ten) cases, in the ceiling spaces of approximately 1100 ACT houses and approximately 100 houses (Rist 1993) from nearby NSW towns (e.g. Queanbeyan, Finley). The installations were carried out between 1968 and 1979 and are believed to be localised to this area of Australia.

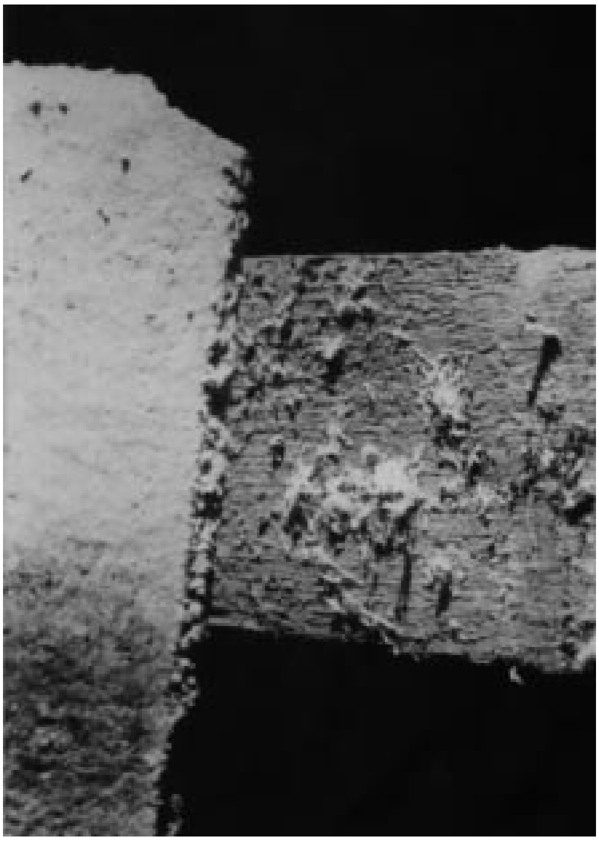

Figure 6a: Asbestos fluff contaminating roof tile battens of ACT house

Source: (S. Brown, CSIRO Division of Building, Construction and Engineering)

Asbestos concentrations (by the membrane filter method, NOHSC 1988) were reported to be less than 0.01 f/mL in the living spaces of 16 ACT houses where measurements were made (W. Riley, ACT Board of Health, pers. comm.).

In 1988 the Federal Government decided to remove the asbestos fluff from the ACT houses in a $100 million Domestic Asbestos Program which operated from 1989 to 1993. In a review of the Program (Brown and Martin 1991) it was found that:

(a) large amounts of asbestos fibres had moved from the ceiling space and contaminated most building cavities (roof, wall and sub-floor) prior to removal, as shown in Figure 6;

(b) dwellings from which asbestos had been removed prior to the Asbestos Program still contained significant quantities of asbestos (these were later recleaned under the Program); and

(c) the stringent requirements of the Program (no visible or accessible asbestos to remain) were met in most locations with the exception of internal walls and the unsealed undersides of some roof timbers (work procedures were modified to ensure full sealing of all timbers; no action was taken on residues in internal walls).

Figure 6b: Asbestos fluff contaminating sub-floor area of ACT house

Source: (S. Brown, CSIRO Division of Building, Construction and Engineering)

Figure 7: Proportion (%) of private dwellings in each State in 1981 with asbestos cement sheet external walls

Source: (ABS 1981 Census of Population and Housing)

It is believed that no removal program is planned for the nearby NSW houses also insulated with asbestos fluff. Queanbeyan Shire has advertised for homeowners to supply insulation samples and this has led to seven positively identified cases. It has provided advice on procedures to isolate the insulation from living spaces by the sealing of gaps and openings and avoiding entry into the roof space. The insulation must be removed by a licensed asbestos contractor if the building is altered or demolished (R. Whitworth, Queanbeyan Shire, pers. comm.).

Another aspect of Australian building practice that is different from other countries is the widespread use of AC sheet products. It has been estimated that, until production ceased in 1983, 1300 million square metres of AC building sheets were produced (Brown 1994a). Approximately one-half of this produce, if still installed in buildings, is over 30 years old. These products contained chrysotile, with lesser quantities of amosite or crocidolite (the latter until the late 1960s). The sheets were used for exterior cladding (roofing and walls) and interior lining of buildings of all types. Usable statistics on specific applications are only available for external walls of private dwellings, as presented in Figure 7—but these demonstrate the wide usage of these products (the total number of private dwellings with AC external walls was 680 000). Environmental emission of asbestos from AC products is more likely to occur from outdoor products (particularly roofing) than indoor products, due to surface degradation of the former (Brown 1987). Asbestos concentrations around such buildings are generally extremely small and little different from ambient levels in other urban areas, although they are persistent over time (Felbermayer and Ussar 1980; Western Australian Advisory Committee on Hazardous Substances 1990).

3.1.2 Radon

The major source of radon in indoor air is the soil under buildings. For the USA, it is believed that variation of radium levels in soils is the critical factor underlying radon concentrations in indoor air rather than ventilation differences (Samet 1991). Such information is currently being gathered by the Australian Geological Survey Organisation and is available for approximately one-half of rural areas across Australia (Ian Hone, AGSO, pers. comm.). This information may aid siting of future buildings to limit radon ingress or the selection of materials for earth-constructed buildings.

3.1.3 Environmental tobacco smoke

Clearly, the major source of environmental tobacco smoke (ETS) is tobacco smoking within an indoor space and ETS can be effectively prevented by use of a smoking prohibition policy (Cummings 1991). Presently, approximately 80% of large workplaces in Victoria (Mullins and Gibbs 1994) and over 70% in other States (ASH 1995) are smoke-free. A recent guidance note by the NOHSC (1994) considered that since ETS is a carcinogen, the principle of elimination, whenever practicable, applies. Alternatively it recommended that smoking be isolated to ‘designated smoking areas’ within internal areas of workplaces which have separate mechanical ventilation and operate under negative pressure (unspecified) compared to adjacent areas of the building. An evaluation of ETS pollutants in US offices with five smoking policies lends support to the use of designated smoking areas as an optimum strategy next to the prohibition of smoking (Hedge et al. 1983).

It might be thought that mechanical ventilation to AS1668.2–1991 will control ETS by dilution ventilation (see section 3.2.2.1). Measurements in Australian buildings (section 2.2.3) show this is not the case. An analysis of such a strategy by Repace and Lowrey (1984) found it required impractically huge ventilation rates or uneconomically expensive filtration equipment to control ETS. Cain et al. (1983) found that for odour control of ETS alone, dilution ventilation incurred a heavy energy penalty. Recent legislation in the ACT—*The Smoke-free Areas (Enclosed Public Places) Act 1994*—appears to have ignored the above findings by exempting restaurants and licensed premises from smoking prohibition ‘provided they are fitted with equipment capable of maintaining air quality in accordance with Australian Standard 1668.2’.

3.1.4 Respirable suspended particles

Respirable suspended particles (RSPs) have many potential sources in buildings—none clearly outstanding relative to others. Sources include tobacco smoke, cooking and cooking appliances, wood heaters and kerosene heaters.

3.1.5 *Legionella* spp.

Most Australian outbreaks of Legionnaires’ disease have been traced to cooling towers (especially small units) and to a lesser extent spa baths. This differs somewhat from overseas experience where large hot water systems in hotels and the like have been the major source of the bacteria (Broadbent et al. 1994). Many overseas bodies have recommended that such hot water systems operate at a temperature above 60 °C, be designed to minimise dead legs in lines, or be replaced by smaller, instantaneous type systems (Broadbent 1987).

3.1.6 House dust mite

The major sources of house dust mite (HDM) allergens in indoor air have been bedding, carpets and furniture in dwellings located in coastal rather than central areas of Australia (see Figure 4). Peat (1994) found that the risk of HDM-sensitised children in NSW having current asthma correlated strongly with Der p 1 levels sampled from mattresses. Limited evidence from public buildings indicates these are not a normal source of HDM allergen exposure (Green et al. 1992; Brown 1994). It is unknown what the trends are in HDM allergen levels in Australian dwellings, but Denmark was reported to experience a large growth in allergen levels following reduction of building ventilation levels in response to the energy crisis of the 1970s (Korsgaard 1992).

3.1.7 Microbial contaminants

Overseas research has shown that microbial contamination of indoor air resulted from moisture problems (past or present) in buildings (e.g. leaks to porous materials, stagnant water in ventilation systems, condensation on building surfaces). Careful visual inspection and surface sampling is considered the most effective method to identify microbial sources and deal with indoor air quality problems (Nevalainen et al. 1994).

3.1.8 Formaldehyde

The major source of formaldehyde in indoor air has been pressed-wood products such as particleboard, plywood and medium density fibreboard which use formaldehyde-based resins. The amount of products used indoors and the level of building ventilation are significant factors in concentrations achieved. Manufacturers in Europe and the USA have been reducing formaldehyde emission from these products for several years. Similar activity has occurred in Australia, steered by the Australian Wood Panels Association (Bruce Steenson, AWPA, pers. comm.), so that 85–90% of current products meet European low-emission limits with all products targeted to meet the limits by June 1995. Indoor air concentrations when such products are first installed may reach 500 ppb in poorly ventilated spaces (CSR Wood Panels 1993) but concentrations found in typical new buildings using these products are unknown. Use of imported products from countries without these product emission controls are expected to result in higher indoor formaldehyde concentrations, but this aspect has not been investigated in published literature.

3.1.9 Volatile organic compounds

The major sources of volatile organic compounds (VOCs) in indoor air are believed to be wet construction products (paints, adhesives, sealants) in new buildings and a mixture of wet household products and other materials in established buildings (Brown 1994b). The major reduction of VOC emissions from new materials overseas has been for carpets in the US where a ‘Carpet Dialog’ was established between government and industry (Carpet

Policy Dialogue Group 1991). This led to industry-wide testing of carpet, reduction of emissions and the establishment of a ‘green’ carpet labeling scheme in 1992. Formal programs for other materials are unknown but VOC emission limits for a wide range of materials have been specified in the State of Washington (Black 1993a) and Germany (Cutter Information Corporation 1992b) and have been called for in Australia (Gilbert 1993) (see Section 4.4).

3.1.10 Pesticides

Since limited research has been carried out into pesticide levels in indoor air, there is little information on major sources. Meaklin (1992) recommended the following measures to reduce exposure to pesticides, suggesting termiticides can be a major source:

(a) new buildings in termite prone areas should be treated **before** construction;

(b) buildings should be vacant for at least one day and preferably longer when liquid termiticide treatments are used in existing buildings (also, the building sub-floor space should be well ventilated and low-volatility chemicals should be used);

(c) site inspection and clean-up should be undertaken for each treatment; and

(d) buildings should be ventilated after some indoor pesticide applications and the use of certain pesticide products avoided.

3.1.11 Nitrogen dioxide

It is clear from Australian investigations (section 2.2.11) that the major source of nitrogen dioxide in the indoor air of a large number of dwellings and schools is unflued gas heating appliances and probably cooking appliances as well. (US studies suggest that gas cooking appliances (seldom vented in the US) are a major source in that country). Nitrogen dioxide concentrations have been lowered in schools where traditional unflued gas heaters have been replaced with low-NO_x unflued heaters.

3.1.12 Carbon monoxide

Major indoor sources of carbon monoxide are unflued gas heating appliances in dwellings and enclosed car parking sites in commercial buildings, although the extent to which these lead to goal concentrations being exceeded is unknown. Enclosed carparks constructed since introduction of AS 1668.2–1991 ‘Mechanical ventilation for acceptable indoor air quality’ have specific requirements for natural or mechanical ventilation. It is optional for the latter to be controlled to maintain concentrations of carbon monoxide (from petrol engines) or nitrogen dioxide (from diesel engines) below 80% of occupational exposure standards.

3.1.13 Carbon dioxide

In the absence of unvented combustion processes, building occupants are the major source of indoor carbon dioxide and the concentrations attained are largely a function of building ventilation rates and occupancy levels.

3.1.14 Ozone

Potential indoor sources of indoor ozone are electrostatic photocopiers, laser printers, electrostatic precipitators for air cleaning and ozone-based air sterilisers, but the contribution from these sources has received little attention.

3.2 Building ventilation rates and trends

Ventilation rates of buildings (whether domestic or commercial) have varied greatly in recent decades due to a range of factors such as energy conservation practice, changes to building regulations and building practices, and variations in ventilation standards and codes. Limited evidence now indicates that air infiltration rates in some new Australian dwellings are below levels considered overseas as essential for good indoor air quality. Also, commercial buildings constructed in the 1980s may not meet current standards (see section 2.1, Williams 1992). Moves to introduce new ventilation methods and codes to improve indoor air quality have commenced overseas but not in Australia where practical research into building ventilation has been lacking in recent years.

3.2.1 Air infiltration into Australian dwellings

The Building Code of Australia (1990) requires that all buildings have adequate ventilation and air quality by providing permanent openable windows or mechanical ventilation to Australian Standards. With windows closed or ventilation systems off, air enters buildings by infiltration. Infiltration is the leakage of air through cracks, spaces and ventilators in the building envelope. The rate of infiltration is determined by pressure differences between the inside and outside of the building. These pressure differences drive air through the building envelope either into or out of the building. Pressure differences can be caused by wind flowing over the building, which creates regions of higher pressure (usually on the windward side of the building) and low pressure (on the leeward side), or they can be caused by thermal effects. For these reasons, air infiltration will vary markedly over time—depending on outdoor meteorological conditions and operating conditions of the building. Additionally, the building ventilation rate will vary markedly, depending on window and door openings and/or operation of ventilation systems. Infiltration rate is the minimum air change rate that can occur in a building. Generally, it is desirable to minimise the infiltration rate of mechanically ventilated buildings in order to minimise the energy losses from the building. However, for other buildings with low infiltration rates, odours, vapours, carbon dioxide and other gases which are released into the building will not be adequately removed when windows and doors are shut.

The rate of infiltration can be measured in an individual room of a home using tracer gas techniques. A gas is introduced into the building at a controlled rate, and the rate of change of the concentration of the tracer gas is measured and related to infiltration rate. An alternative technique is to pressurise or depressurise the building and measure the air flow rate required to maintain the indoor to outdoor pressure difference at a fixed level, usually 10 or 50 Pa. This latter technique can be performed on single rooms or complete houses and provides a well-controlled and repeatable experiment for comparison of infiltration differences between houses. However, it leads to air change rates that are much larger than are experienced due to normal infiltration.

New building materials, alternative construction techniques, and changing standards (such as the removal of the requirement for wall vents) have had a significant influence on the resultant infiltration rate of Australian dwellings. Biggs et al. (1986) measured the pressurised infiltration rates of a variety of Australian house designs, ranging from those more than 30-years-old to contemporary ones. The designs included brick veneer, cavity brick, weatherboard cladding, fibre-cement sheet cladding, suspended timber floor and concrete slab floor. Infiltration rates were very high in older style houses with fixed wall vents, being approximately double that for houses without wall vents. Houses without wall vents had similar infiltration rates to those reported in New Zealand, Netherlands and UK, but three times higher rates than for houses reported from Canada and Sweden.

Table 10: Infiltration rates (air changes hour) through houses for 50 Pa pressure difference

Country	Number of houses	Mean air change/hour
Australia (Sample 1)	10	26.3
Australia (Sample 2)	12	12.2
New Zealand	10	11.0
Netherlands	130	12.0
United Kingdom	19	13.9
Canada	60	4.4
Sweden	205	3.7

(Biggs and Bennie 1988)

Biggs et al. (1987) measured pressurised infiltration rates in unoccupied houses in Melbourne, and correlated the results with wind speed. They estimated that the background infiltration (for no wind) was 0.33 air changes per hour (ACH) on average, which increased with increasing wind speed. The empirical equations and wind data were used to estimate the average natural infiltration rate for the test houses if they were located in major Australian cities. Their estimates were 0.44 ACH in Canberra, 0.55 ACH in Sydney and Hobart, and 0.57 ACH in Melbourne. These values were higher than the 0.2–0.4 ACH in Sweden where building practices had led to very tight construction for energy conservation, but lower than the 0.7 ACH reported in the UK and USA.

Biggs and Bennie (1988) summarised previous measurements on 32 dwellings in Sydney and Melbourne. They concluded that infiltration rates were approximately halved as a result of combined effects of eliminating fixed wall vents, using sliding aluminium windows, weather-stripping exterior doors and using concrete slab floors. A comparison between pressurised infiltration rates in Australian dwellings and those from other countries is shown in Table 10. Note that these should not be confused with the normal infiltration rates discussed above.

The Australian Sample 1 houses exhibited higher infiltration rates than Sample 2 houses primarily due to the use of fixed wall vents in the former. More recent unpublished results from Energy Victoria indicate even lower infiltration rates for houses with and without wall vents.

Harrison (1985) measured infiltration rates for nine new houses in Perth using the tracer gas technique. The houses were of brick veneer, tile roof, concrete slab floor and single storey construction and did not use fixed wall vents. They were not significantly different from the houses selected for study by Biggs. Infiltration rates ranged from 0.05 to 0.41 ACH and are substantially lower than the results from Biggs's studies. Pressurisation measurements at 50 Pa by Harrison were in the range 10–15 ACH, which are in good agreement with the results of Biggs (Table 10, Sample 2 houses). This good agreement suggests that the Perth and Eastern States houses have similar infiltration rates.

Ferrari (1991) reported the infiltration rates (by tracer decay) of the living rooms of 41 Sydney dwellings in winter, generally measured during evening heating by unflued gas heaters and with windows and doors generally closed. Air change rates varied from 0.2 to 2.3 ACH and averaged 0.9 ACH. Significantly, a subset of dwellings less than five years old exhibited an average infiltration rate of 0.33 ACH.

The average ventilation rates actually achieved in an occupied house will be somewhat higher than the above findings since:

(a) it has been shown (Kvisgaard 1985) that the infiltration rate is about three times larger for occupied than for unoccupied dwellings (most of the above data was for unoccupied dwellings);

(b) mechanical ventilation and fixed vents were disabled during the field measurements;

(c) induced ventilation through flued heating appliances will increase the effective building ventilation; and

(d) Swedish measurements show that infiltration rates increase by 70% after the first year of occupancy due to timber shrinkage and the movement of timber windows and doors after initial usage.

While there are no minimum air change rates required in Australian houses, the measured infiltration rates should be compared with the minimum ventilation rates either suggested or implemented throughout Europe. The proposed rates are 0.5 air changes per hour in Norway, Sweden, Finland, Denmark and Iceland, 0.8 in Germany, and 0.5–1.0 in the UK. Based on our limited data for Australian dwellings, it appears that some new dwellings may exhibit minimum ventilation rates lower than these levels when windows and doors are closed.

3.2.2 Mechanical ventilation of buildings

3.2.2.1 Codes

The Building Code of Australia (1990) (and current and previous State building regulations over recent decades) requires that all occupied rooms have 'adequate flow-through or cross-ventilation and air quality'. This must be provided by natural ventilation from permanent, openable windows, doors or other devices with an aggregate openable size of not less than 5% of the floor area of the room to be ventilated, or a mechanical ventilation system conforming to AS 1668.2 and AS 3666 (see Appendix 4).

Table 11: Ventilation requirements for various versions of ASHRAE Standard 62

Occupied Space	Outdoor Air Ventilation Requirement (L/sec/person)				
	1973 version		1981 version		1989 version
	minimum	recommended	non-smoking	smoking	ventilation rate
Dance venues	7.5	10–13	3.5	18	12.5
Bars	15.0	18–20	5.0	25	15.0
Beauty shops	12.5	15–18	10.0	18	12.5
Classrooms	5.0	5–8	2.5	13	7.5
Dining areas	5.0	8–10	3.5	18	10.0
Hospital patient rooms	5.0	8–10	3.5	18	12.5
Conference rooms	10–13	13–20	3.5	18	10.0
Offices	7.5	8–13	2.5	10	10.0
Residences	2.5	4–5	5.0	5	0.35 ACH
Retail stores	3.5	5–8	2.5	13	1.0–1.5L/sec/m^2
Smoking lounges	–	–	–	–	30.0
Spectator areas	10.0	13–15	3.5	18	7.5
Theatres	2.5	3–5	3.5	18	7.5
Transport waiting rooms	7.5	10–13	3.5	18	7.5

Generally, residences in Australia rely on natural infiltration and openable windows for ventilation while commercial buildings rely on mechanical ventilation. However, there is no restriction for either class of building on the selection of ventilation methods. At present, there is an increasing trend for new dwellings to use ducted central heating or refrigerative cooling systems. For example, approximately 85000 dwellings now use such systems (Leon Condon, Honeywell Australia, pers. comm.) although these are recirculation systems with no outdoor air intake and represent a very small proportion of Australia's four million residences.

Generally, mechanical ventilation is the norm for large commercial buildings in Australia, without humidity control since this is regarded as unnecessary in the largely temperate climate. Australian standards have taken guidance from the US code of the American Society of Heating and Refrigerating Airconditioning Engineers (ASHRAE), Standard 62, and so the history of this code should be reflected in changes to the Australian Standard.

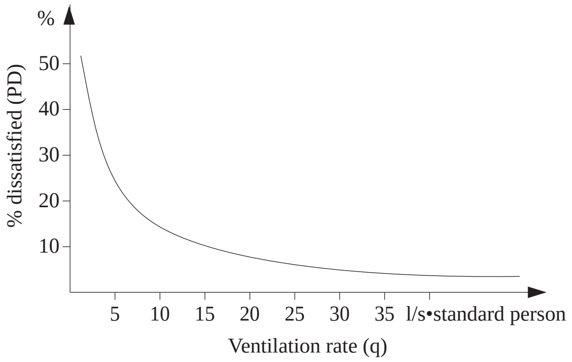

Figure 8: Perceived air quality (% dissatisfied) by a standard person at different ventilation rates

Source: (CEC 1992, Appendix 3)

Comfort air-conditioning first became widely used in the US in the 1920s for picture theatres and gradually spread to other building types (Ludwig and Turner 1991). Ventilation rates from the 1940s were influenced by the research of Yaglou and Witheridge (1937) who evaluated the outdoor air dilution ventilation rates necessary for an occupied room such that 80% of visitors to the room did not find body odours in the room objectionable. They determined that a minimum outdoor air ventilation rate of five litres per second per person was required. More recently, Fanger (1988) has found a somewhat similar ventilation requirement using different methods, as presented in Figure 8.

ASHRAE Standard 62–1973 specified minimum and recommended ventilation requirements for most buildings. These were believed to have worked well until the energy crisis in the late 1970s when building operators lowered the amount of outdoor air brought into buildings (Ludwig and Turner 1991). The Standard was revised in 1981 to Standard 62–1981 to deal with indoor air quality as well as odour issues and was revised again in 1989. AS 1668.2 (1991) reflects this last revision. Standard 62–1981 recommended outdoor air ventilation rates for smoking-permitted and smoking-prohibited conditions but these proved to be confusing and were removed from Standard 62–1989, which recommended single rates allowing for ‘reasonable’ smoking levels. A comparison of the ventilation requirements for the different versions of Standard 62 (Meckler 1991) is shown in Table 11. Generally, these show that minimum mechanical ventilation rate specifications for buildings designed during the 1980s were somewhat reduced from those of other times. Fisk (1994) suggested that Standards primarily affect the average minimum ventilation rates in the building stock. However, for individual buildings there would be poor control and measurement, casual adjustments by building operators and poor understanding of operation—so that for any Standard there could remain buildings with low rates of outdoor air ventilation.

Similar to Standard 62–1989, AS 1662–1991 specifies the quality of outdoor air for use in ventilation of buildings, as presented in Table 12. If these levels are exceeded, the outdoor air must be treated to bring it within the levels. Similarly, recycled air should not exceed these levels.

Table 12: Recommended maximum accepted concentration of pollutants in outdoor air used in AS 1668–1991

Pollutant	Concentration (µg/m3)		Reference
Total suspended particulates	90 260	(1 year) (24 hour)	NHMRC USEPA
Suspended matter	40	(1 year)	WHO
Acid gases	60	(1 year)	WHO
Sulphur dioxide	365 60	(24 hour) (1 year)	USEPA NHMRC
Sulphates	15	(1 year)	NHMRC
Carbon monoxide	40 000 9 900	(1 hr, max) (8 hour)	WHO/USEPA WHO/USEPA
Nitrogen dioxide	340 100	(1 hour, max) (1 year)	NHMRC USEPA
Ozone	240	(1 hour, max)	NHMRC/USEPA
Non-methane hydrocarbons	160	(3 hour, max)	USEPA
Lead	1.5	(90 day)	NHMRC/USEPA

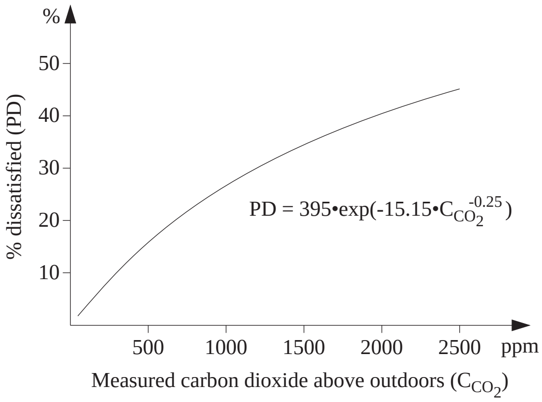

Figure 9: Perceived air quality (% dissatisfied) as a function of carbon dioxide concentration in buildings

Source: (CEC 1992)

One of the major changes evident in Standard 62–1989 and AS 1668.2–1991 is the need to maintain a minimum outdoor air ventilation rate, which was increased from 2.5 litres per second per person in 1981 to 7.5 litres per second per person currently. The rationale for the current ventilation rate was to maintain levels of indoor carbon dioxide exhaled by occupants below 1000 ppm (see Section 2.2.13), this being used as a surrogate for unacceptable body odours to 20% of visitors entering an occupied space, as shown in Figure 9. Odours from other sources require greater ventilation rates, particularly in the case of environmental tobacco smoke which was found to require an outdoor air ventilation rate of 50 litres per second per smoking person (Cain et al. 1983). It has been recommended that local exhaust ventilation is the preferred method for environmental tobacco smoke odour control (Bearg and Turner 1987).

New approaches to mechanical ventilation codes have been developed in Europe (CEC 1992, Clausen 1994) and are under development in the USA (Fisk 1994) and will be discussed in Section 4.3.

3.2.2.2 Measurements in Australian buildings

While not systematically investigated, limited measurements indicate that a large proportion of commercial buildings in Australia do not comply with AS 1668.2–1991. Williams (1992) investigated the ventilation system adequacy of 228 low-rise office buildings in suburban Melbourne and found 82% failed to meet the Australian Standard. A similar incidence has been indicated for Perth offices (K. Collins, BCA Consultants pers. comm.). Investigation of 102 commercial buildings, some with subjective complaints by occupants, found that 9% had no outdoor air intake and 42% were ventilated below the Standard requirement (J. Robertson, Healthy Buildings Australia, pers. comm.). These findings are not surprising in view of the recent increases in ventilation requirements by Standards since they do not apply retrospectively to existing buildings.

3.3 Impact of outdoor air pollutants

Outdoor pollutants are those that arise predominantly outdoors and so typically occur at greater concentrations in outdoor air than indoor air (Wesolowski 1987). Such pollutants will occur in indoor air due to air infiltration and ventilation by outdoor air, but pollutant deposition on interior surfaces generally leads to partial reduction in concentrations. Dockery and Spengler (1981) showed that the average concentration of a stable pollutant during a sufficiently long sampling period t, $[I]_t$, is related to its average outdoor concentration $[O]_t$ by:

$$[I]_t = m[O]_t + b$$

$$m = PA/\mathrm{x}A + k$$

$$b = S_t/V\mathrm{x}a + k$$

where P is the penetration of the outdoor pollutant ($0 \leq P \leq 1$), A is the ventilation rate, k the indoor deposition rate, V the interior volume and S_t the time-varying rate for pollutant emission from indoor sources; m is referred to as the pollutant infiltration factor since it is the indoor/outdoor pollutant ratio in the absence of indoor sources. Lewis and Zweidinger (1992) used this approach to apportion indoor aerosol, VOC and aldehyde species in ten US dwellings. They found that m equalled 1 for several volatile organic compounds (VOCs) indicating no deposition or source emission occurred indoors, while other VOCs exhibited large source values. Fine particle concentrations for several metal species, including lead, showed the infiltration contribution was dominant but with $m = 0.66$. Indoor aldehyde concentrations exceeded outdoor concentrations for virtually every measurement pair demonstrating a dominance of indoor sources, particularly for formaldehyde and acetaldehyde. Overall, the study showed that the relative importance of indoor and outdoor sources to indoor pollutant concentrations varied greatly between pollutants and between dwellings.

Yocom (1982) reviewed indoor–outdoor pollutant relationships and distinguished between pollutants and their sources according to the three groupings shown in Table 13. His review concentrated on Groups I and II pollutants for which meaningful indoor–outdoor relationships could be discussed. A summary of his review findings is presented in Table 14, from which Yocom concluded that indoor air quality is substantially different from outdoor air quality and that standards for the latter did not adequately serve the goal of protecting human health.

Table 13: Classification of pollutants according to source

Pollutant group	Pollutants	Sources
I. Predominantly outdoor sources	Sulphur oxides	Fuel combustion, nonferrous smelters
	Ozone	Photochemical reactions
	Pollens	Plant life
	Lead, manganese	Automobiles
	Calcium, chlorine, silicon, cadmium	Suspension of soils or industrial emissions
	Organics	Petrochemicals, natural sources
II. Indoor and outdoor sources	Nitrogen oxides, carbon monoxide	Fuel combustion
	Carbon dioxide	Human exhalation, fuel combustion
	Particles	Resuspension, condensation of vapours and combustion products
	Water vapour	Perspiration, combustion, evaporation
	Organics	Synthetic materials, evaporation, combustion
	Spores	Fungi, moulds
III. Predominantly indoor sources	Radon	Soil, water, construction materials
	Formaldehyde	Pressed-wood products, tobacco smoke, gas stoves, furnishings
	Asbestos and mineral fibres	Insulation products
	Organics	Synthetic materials
	Ammonia	Metabolic products, cleaning products
	Polynuclear aromatic hydrocarbons, nicotine, acrolein	Environmental tobacco smoke
	Mercury	Fungicides in paints
	Viable organisms	Infectious agents
	Allergens	House dust mites, cat dander

Source: (Yocom 1982)

Table 14: Relationship between indoor/outdoor (I/O) pollutant concentrations

Pollutant	I/O Ratio	Comment
Sulphur dioxide	0.1–1.0	Lowest ratios observed when [O] highest—in winter when ventilation minimised
Total particulate matter	0.1–3.5	Dependent on ventilation system and indoor activities; in absence of latter, ratios tend to range 0.1–1.0
Carbon monoxide	1.0	Long-term average in the absence of indoor sources; short-term ratios may be >1 due to transient outdoor levels
	1.2–4.8	Buildings with gas stoves, unflued heaters or smoking
Nitrogen dioxide	~1.0	In the absence of indoor sources
	>1–5.0	Presence of unvented gas stoves
Ozone	0.1–0.7	No indoor sources in use at times of studies
Hydrocarbons	1.5–2.3	Dominated by indoor sources
Lead	0.6–0.8	Typical non-air-conditioned houses
	0.3–0.5	Air-conditioned buildings
Respirable suspended particulates	1.1–5.0	High ratios associated with tobacco smoke
Sulphates, nitrates	0.5–1.0	Homes with gas stoves can show nitrate I/O ~7
Formaldehyde	5.0–30	Related to indoor products

Source: (Yocom 1982)

3.4 Future potential for exposure to indoor air pollutants

It is likely that future exposure to indoor pollutants will be reduced as a consequence of:

(a) greater knowledge about the sources of indoor air pollutants (Section 3.1);

(b) industry initiatives to reduce pollutant emissions from sources (Section 4.4);

(c) development of new approaches to building ventilation (Section 4.3); and

(d) introduction of advisory goals for critical indoor air pollutants (Sections 4.2.2, 5.3, 5.6).

The timeframe for this reduction is difficult to predict but it is observed that the process of exposure reduction has already commenced for several pollutants (e.g. asbestos, ETS, *Legionella*, formaldehyde, nitrogen dioxide) and may soon commence for others (e.g. house dust mites, VOCs, microbials).

The achievement of health-related indoor air goals for residential, school and hospital exposures should be the prime aim of pollutant reduction in order to protect sensitive sectors of the population.

4 Response to pressures on indoor air quality

There have been a range of responses to indoor air quality in Australia, such as State Government activities, development of standards and guidelines, changes to ventilation codes and pollutant sources and improved building design or community education. It will be seen that in contrast to workplace and ambient air environments, there have been no regulations developed specifically for indoor air (non-workplace) environments—a feature also common overseas. It is believed there are several reasons for this lack of regulation:

(a) private indoor environments such as residences are regarded by the public as sacrosanct, requiring minimum imposition of regulations;

(b) enforcement of regulation in residences would be impossible due to their large number;

(c) no single government authority has responsibility for indoor air quality; and

(d) indoor air quality involves a complex set of factors (e.g. building and ventilation system design, construction, operation and maintenance; outdoor climate/pollutant sources; a diverse range and mixture of pollutants; multiple indoor pollutant sources; diverse health effects; protection of a variable population).

Rather than develop indoor air regulations, the United States Environmental Protection Agency (EPA) stated a clear preference to control indoor air quality by research and development, technical assistance and education (Spengler and Samet 1991). In Canada, it was decided that indoor air quality control should be determined on the basis of non-regulatory guidelines which define a quality of air that is conducive to good health and comfort (Tobin et al. 1993). Australia appears to be in the process of adopting a similar but less structured approach.

4.1 State Government activities

Health and environmental regulations in Australia are the responsibility of specific State Government departments, which also may undertake advisory and public education roles. Most have specific health and safety acts such as the Victorian *Occupational Health and Safety Act 1985*. This defines a workplace as ‘any place, whether or not in a building or structure, where employees or self-employed persons work’. Occupational exposure standards from NOHSC (1991) are adopted by most State Governments and some States develop specific regulations—for example, Victoria has produced regulations for asbestos whether present in buildings or in industrial processes (Department of Labour 1992).

State Environmental Protection Authorities have probably been the most active in indoor air quality issues, although the approach has been non-regulatory. The NSW State Pollution Control Commission was the only environmental authority to carry out research into indoor air quality (Ferrari 1991). The Commission was later subsumed by the NSW Environmental Protection Authority which does not have indoor air quality within its area of responsibility (S. McPhail, NSWEPA, pers. comm.). The Victorian EPA has responsibility under the State Environment Protection Policy (The Air Environment) only for the external environment but reviewed indoor air quality in residential buildings (Victorian EPA 1993) in response to recommendations by Streeton (1990). Also in Victoria, the Office of the Commissioner for the Environment (OCE) was established in 1986 to identify key environmental indicators and produce State of the Environment reports. It produced a consultant’s report ‘A Review of Air Quality Indicators and Monitoring Procedures in Victoria’ (OCE 1992) which addressed both indoor and outdoor pollution. The OCE has since been abolished.

4.2 Standards and guidelines

4.2.1 Overseas

A large number of standards and guidelines have been developed overseas. Those from international bodies, or with specific interest to this review, are summarised in Appendix 3.

4.2.2 Australia

Exposure of building occupants to pollutants in workplace air, whether industrial or non-industrial, falls within the requirements of occupational health and safety legislation that is set at State level, as described earlier. Exposure to pollutants in outdoor air is controlled by environmental regulations. Exposure to pollutants in residences is controlled by no specific legislative requirements and it has been suggested such legislation would be considered by the general public as unacceptable interference. However, performance-based regulations are enforced for some aspects of residences and will influence indoor air pollution. Often these refer to Standards and codes and a summary of those relevant to indoor air quality is presented in Appendix 4.

State occupational health and safety practices are influenced by the activities of the National Occupational Health and Safety Commission (NOHSC), Worksafe Australia, established in 1985 to develop, facilitate and implement a national health and safety strategy. The NOHSC (1991) declares national occupational exposure standards and to date has done so for over 600 substances. These serve as guides and have no legal status until incorporated in Commonwealth, State or Territory legislation. The Occupational Medicine Unit within NOHSC is currently studying indoor air quality in 'sick' office buildings in a research capacity, with emphasis on its influence upon stress, psychosocial problems and pollutant exposures (particularly microbial pollutants). Standards related to indoor air may be included in 1995–96 work environment standards (S. Rabone, NOHSC, pers. comm.). The application of different exposure standards to essentially similar workplace populations in offices and industries is a matter of contention, which Lunau (1993) suggested requires a management rather than legislative solution. Emmett (1994) noted that the boundary between indoor air goals and occupational exposure standards became blurred in buildings which acted as one person's workplace and another's public place, and that indoor air goals must consider somewhat different exposure factors, critical health end-points and acceptable risk levels. A need was noted for a harmonisation between these standards and the use of transparent processes in standards setting.

Thel National Health of Medical Research Council (NHMRC) advises the Commonwealth Government on matters in relation to health and directs research funding. The NHMRC has made recommendations for indoor air pollutants which are presented in Table 2.

The Australia and New Zealand Environment Council (ANZEC 1990) produced a discussion paper on indoor air quality that has not been formally approved by the ANZEC Ministerial Council. It concluded that indoor air quality was not being adequately addressed in Australia and recommended a strategy comprising three broad approaches:

(a) community education and awareness;
(b) control of sources of indoor air pollutants; and
(c) reduction of potential for indoor air pollutant problems in the future.

The National Buildings Health Environment Task Group was active from 1988 to 1992 and consisted of representatives from all State Government departments of Public Works and Health and Community Services. Its goal was to establish codes of practice to ensure healthy, energy-efficient and cost-efficient public buildings. A report by Gilbert (1993) and establishment of a Built Environment Unit in the Queensland Administrative Services Department arose from this activity. The Building Owners and Managers Association have produced draft guidelines for the control of indoor air quality which are believed to have just been published.

Building regulations and related activities impinge on indoor air quality. The Building Code of Australia (1990) has specific ventilation requirements by the provision of openable windows or the installation of a mechanical ventilation system conforming to AS 1668.2–1991. The Australian Gas Association (AGA) produces codes for installation of gas appliances which are generally adopted in State Government regulations. AGA Code 601–1992 refers to the installation of unflued natural gas space (UNGS) heaters in buildings and has no general requirement for provision of building ventilation. The code has been adopted by all States except:

(a) Victoria, which effectively prohibits UNGS heaters in dwellings by requiring they be at least 2.5 m above floor level (this allows commercial/industrial heaters to be installed); and
(b) South Australia and Western Australia, which limit the size of heater and require installation of fixed wall vents in the heated room.

The Australian Liquid Petroleum Gas Association nominally refers to AGA Codes but these are seldom enforced and it is believed that unflued LPG gas heaters in rural Australia are common but not effectively regulated, even in Victoria where it has been estimated that over 100 000 have been installed (C. Fong, Gas and Fuel Corporation of Victoria, pers. comm.).

Energy labelling schemes are currently under development by Energy Victoria and the Department of Primary Industry and Energy for application to both residential and commercial buildings. It is believed that these will not specify minimum ventilation rate requirements for naturally ventilated buildings and do not address the impact of energy conservation on indoor air quality.

4.3 Development of improved ventilation codes

There appear to be no actions in Australia directed at specifying minimum ventilation (infiltration) rates in residential buildings. In fact, the removal of requirements for fixed wall vents (which occurred in Victoria in 1984 and in NSW somewhat earlier), the improvement of construction methods and materials and the move to energy conservation in buildings appear to have reduced minimum ventilation rates to levels (Section 3.2.1) that are in the lower range of those recommended for countries with somewhat colder climates than Australia. Most of these reductions have resulted from the removal of wall vents and the use of sheet and concrete slab flooring. Further reductions are considered unlikely from current and future activities in relation to energy conservation (J. Symons, CSIRO, pers. comm.).

Conventional building air-conditioning systems are designed as mixing (dilution) ventilation systems. Conditioned air is introduced into the occupied space and mixes with room air to provide uniform temperature throughout the room. Exhaust air is returned to the air-conditioning plant for recooling and mixing with approximately 10–30% outdoor (fresh) air make-up to dilute polluted air from the building. In this way, pollutants are circulated through the building many times. Computational fluid dynamics modelling, such as that developed at CSIRO Division of Building, Construction and Engineering, can be used to predict air and pollutant flows in building spaces, and to identify areas with poor distribution or recirculation of stale air. It has also demonstrated the advantages of systems other than dilution ventilation.

A new, alternative building ventilation system has emerged from Scandinavian countries. The technique is called displacement ventilation and is designed to provide simultaneously, energy-efficient cooling and improved ventilation of the building. Displacement ventilation introduces cool fresh air at low velocity at floor level. External surface heat loads and internal heat sources within the room warm the air which rises and thermally stratifies. The fresh air rises without mixing with the stale air in the occupied region, and pushes the room pollutants upwards to be exhausted to the atmosphere. The advantages of displacement ventilation include:

(a) the heat generated in the building is exhausted to the atmosphere;

(b) cooling energy consumption can be reduced by up to 50% in some installations (Chen and van Der Kooi 1990; King and Clements 1993);

(c) fresh air ventilation is vastly improved because all supply air is fresh and mixing with return air is avoided; and

(d) the elimination of return air ducting and fans reduces installation costs.

Displacement ventilation is now installed in Scandinavian countries in 25% of commercial buildings and 50% of industrial buildings (Svensson 1989). It is particularly effective in tall building spaces, theatres, atria, restaurants, supermarkets, warehouses, factories and in some office environments. While this emerging technology has potential for improving indoor air quality for many buildings, it has clear limitations. The process can only be used for cooling, it may not provide thermal comfort conditions with high internal heat loads, and it is most effective in tall buildings. In buildings with low ceiling heights, cool draft problems can be encountered.

While there is good environmental potential for this technology, it has been slow to be taken up locally. There has been no Australian research because there is a lack of funding, the existing computerised design tools used by consulting engineers are not appropriate, and there is limited expertise in the industry.

AS 1668.2–1991 is unlikely to be revised for some years. In contrast, ventilation codes overseas are being revised and strengthened with respect to improvement of indoor air quality. Commission of European Communities (1992) produced ‘Guidelines for ventilation requirements in buildings’ which acknowledged that not only the occupants but the building itself could be a major pollutant source and that ventilation must be proportional to this total pollutant load. Procedures were provided to estimate ventilation rates based on pollutant emissions from sources. The guidelines have two goals: there should be negligible health risks to occupants and the occupants should perceive the air as fresh and pleasant rather than stale, stuffy and irritating. Currently the guideline has no regulatory status but is likely to enter the European standard processes in the near future (Clausen 1994).

It has been reported that ASHRAE Standard 62 is in the process of revision and that it too will emphasise the control of indoor air pollution sources (Levin 1992). The revision may require ‘additional ventilation rates’ to be added to the current minimum rates if the building designer does not minimise pollutant emission from sources in the building. The aim of this approach is to encourage the use of low emission materials in order to maintain current minimum levels of ventilation.

4.4 Reduction of pollutant emissions from indoor sources

Many indoor air pollutants have clearly identifiable sources and it is now widely accepted that source emission control is the most important strategy for achieving improved indoor air quality (Tucker 1990; CEC 1992; EPA 1990). Modest-size cross-sectional surveys of commercial buildings in the US have shown that indoor pollutant concentrations show no correlation to ventilation rates (Turk et al. as described by Fisk 1994, see Figure 10). This finding reflects the much greater variation in source emission rates (e.g. over several orders of magnitude, Brown et al. 1992) in comparison to the variations in ventilation rates.

Emphasis on source control is currently growing in the US and Europe and to a small extent in Australia. Tucker (1990) described US activities and provided source emission limits (Table 15) to prevent increments of total volatile organic compound (TVOC) concentrations above 500 µg/m^3 per source or of ozone concentrations above 20 µg/m^3.

The State of Washington (Black 1993a) established criteria for pollutant emissions from interior materials, manufactured products and other pollutant generators in commercial buildings. The emission criteria were required to prevent building air concentrations after 30 days that were greater than:

formaldehyde 50 ppb

TVOC 500 µg/m^3

4-phenylcyclohexene (carpet only) 6.5 µg/m^3

The TVOC requirement was considered a ‘generalised’ VOC control mechanism and there were additional requirements for the emission rates and predicted building concentrations to be reported for compounds (a) listed as carcinogens or teratogens, (b) predicted to exceed 1/10th of occupational exposure standards, or (c) listed as primary or secondary pollutants in National Ambient Air Quality Standards.

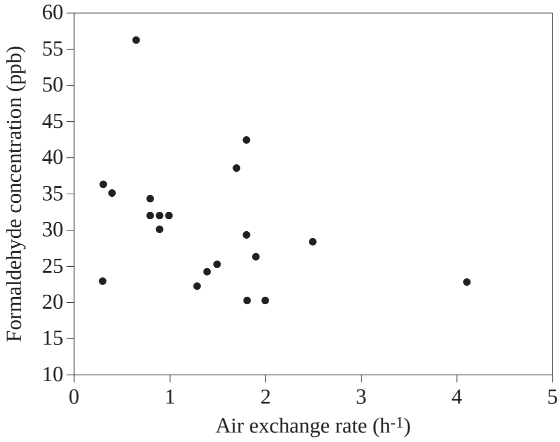

Figure 10: Formaldehyde concentration versus ventilation rate measurements in 20 commercial buildings in the US

Source: (Fisk 1994)

Table 15: Recommended emission limits for low-emitting materials and products for commercial buildings

Material or product	Maximum emission
Floor materials or coatings	600 µg TVOC/m^2/hour
Wall materials or coatings	400 µg TVOC/m^2/hour
Movable partitions	400 µg TVOC/m^2/hour
Office furniture	2500 µg TVOC/hour/workstation
Office machines (central)	250 µg TVOC/hour/m^3 of space 10 µg ozone/hour/m^3 of space
Office machines (personal)	2500 µg TVOC/hour/m^3 of space 100 µg ozone/hour/m^3 of space

Source: (Tucker 1990)

In a voluntary program by the Carpet and Rug Institute (Carpet Policy Dialogue Group 1991), the majority of US manufacturers periodically submit product samples for determination of emission rates of TVOC, styrene, 4-phenylcyclohexene and formaldehyde. Each manufacturer is able to attach a certified 'green label' to their product if emission rates are below specified limits.

In Europe, the Commission of European Communities (McLaughlin and Knoppel 1994) has an ongoing project to develop procedures for evaluating pollutant emissions from building materials. It is worth noting that this type of work is well-advanced in Europe with regard to formaldehyde emission from pressed-wood products (see Appendix 3), and current emphasis is towards VOC emissions. An example is seen in a Danish research group's approach to evaluate the health significance of building products based on emission testing (Nielsen et al. 1994).

Several German regulations (Cutter Information Corporation 1992b) aim to prevent public exposure to carcinogenic VOCs from building materials by future development of product emission goals and current imposition of bans on:

(a) import of wood products (or furniture containing wood products) that emit more than 100 ppb formaldehyde in a test chamber;

(b) import of cleaning products containing more than 0.2% formaldehyde;

(c) use of substances containing more than 0.1% 4-aminodiphenyl or 1% benzene;

(d) production of dyes that contain more than 1% 2-naphthylamine or 4-nitrodiphenyl; and

(e) production, use or import of substances containing more than 1% carbon tetrachloride, 1,1,2,2- or 1,1,1,2-tetrachloroethane or pentachloroethane.

In Australia there have been recommendations to control pollutant emissions from sources by ANZEC (1990), Brown et al. (1992), Gilbert (1993) and NHMRC (1993). Voluntary initiatives by industry have been undertaken for formaldehyde emission from pressed-wood products (see Section 3.1.8) for several years (B. Steenson, Australian Wood Panels Association, pers. comm.) and it is understood that future Australian Standards for these products will include formaldehyde emission limits (Chinam Si, Standards Australia, pers. comm.). CSIRO Division of Building, Construction and Engineering has recently developed environmental chambers and analytical facilities for research into formaldehyde and VOC emissions from indoor materials. It is interacting with researchers using similar facilities in the US, Canada and Europe, and is in the process of discussions with Australian manufacturers on applications to low-emission materials (author's note).

Similarly, voluntary initiatives by the gas industry have reduced nitrogen dioxide emissions from new unflued gas heaters. Current AGA emission rate limits—5 ng/J (previously 15–30 ng/J) for unflued heaters and 15 ng/J for stoves—have been set with the aim of preventing indoor nitrogen dioxide concentrations above 300 ppb, a design level set by AGA (Campbell and Saxby 1994). At present, a nitrogen dioxide indoor air goal does not exist in Australia but has been 'under review' by the NHMRC for some years (see Section 2.2.11). The NHMRC's ambient air goal for nitrogen dioxide is 160 ppb (hourly average)—not to be exceeded more than once a month. Recent child health studies have observed effects even at this concentration (Section 2.2.11). The NSW Department of School Education has a large program of unflued gas heater replacement with low-NO_x heaters and this has reduced indoor concentrations considerably (Section 2.2.11). However, large numbers of unflued gas heaters are used in other buildings throughout Australia (Section 4.2.2) and so in agreement with Ferrari (1991), it is considered prudent that the use of unflued combustion heaters and cookers should be discouraged, and the use of flued heaters and low-NO_x heaters and externally vented cookers encouraged.

4.5 Improved building design

Several activities in recent years have been directed to specifying aspects of the design of buildings so as to minimise indoor air quality problems in the future. An example is the use of several methods in the UK under a voluntary scheme called BREEAM (Building Research Establishment Environmental Assessment Method). The most successful has been the method for new offices, and a method for existing offices has been recently introduced (Prior 1993; Baldwin et al. 1993). The methods identify design issues and criteria for environmental design of buildings in regard to global, local and indoor issues. Similar activities are in process in several European countries, USA, Canada, South Africa and New Zealand.

The CSIRO Division of Building, Construction and Engineering has sought industry support for such methods in Australia and currently has a watching brief on the activities overseas. Less detailed building design schemes have been promoted in Australia such as the Breathe Easy™ home design (Geraldine Elliott, Asthma Foundation of Victoria, pers. comm.) and the 'Green Home' by the Australian Conservation Foundation.

4.6 Public education

Public education is an important tool for improving indoor air quality, especially in residences. It should be based on information derived from research findings in Australia or overseas that demonstrate where indoor air quality problems may occur, their causes and how to remedy the problems. This will be necessary in order to avoid unnecessary (and wasteful) actions by the public in the complex indoor air quality scenario. Ferrari (1991) recommended public education as the first action to be encouraged for improving indoor air quality but noted it had not been successful to that time in Australia. Past examples of public education are:

(a) an 8–page booklet 'Reducing indoor air pollution' by the California Environmental Protection Agency (Headings were: Evaluating the risk, What is indoor air pollution?, Health effects, Sensitive groups, Economic costs, What can you do about indoor air pollution?);

(b) an educational campaign over two years from 1986 by the Commonwealth Department of Health. Over 60000 copies of two documents were circulated. These were titled 'How healthy is the air in your home?' and 'Pollution—is your home safe?' Also, a video 'Indoor Air Pollution' was made by Film Australia (video no. 86157) and was circulated to schools and doctors' surgeries. While the campaign and its products were immensely popular, no subsequent actions have been taken (L. Heiskanen, Deputy Director, Environmental Health, Commonwealth Department of Human Services and Health);

(c) a 1989 brochure from the State Pollution Control Commission titled 'How clean is the air in your home?' (Headings were: Indoor air pollution, Sources, Which pollutants are common in Australia, How to tell if you're being affected, How to improve the air quality in your home);

(d) a 1994 brochure titled 'Reducing allergens which can cause asthma in your home' and 'Specification for an asthma friendly house' from the Asthma Foundation of Victoria (Headings were: Major allergens, Choosing furnishings, How can the design of your home affect asthma?, External environment); and

(e) information sheets (1–2 pages) produced by the CSIRO Division of Building, Construction and Engineering (Examples are: Asbestos in the home, Improving home acoustics, Condensation in houses, Hints on curing a smoking fireplace, Improving sub-floor ventilation, Prevention and control of termite attack, Static electricity in buildings, How safe is CCA-treated timber?).

5 Indicators of indoor air quality

As described in the Introduction, indoor air quality indicators must determine how well indoor air satisfies thermal requirements and respiratory requirements, prevents unhealthy accumulation of pollutants, and allows for a sense of well-being. The indicators need to be applied to a large and complex range of environments. The way an indicator is selected and applied will be an important factor for evaluation and control of indoor air quality and so this factor is also considered in this review.

5.1 Categories of indoor environments

Overseas surveys have usually found that people spend 70–90% of their time indoors, whether at home, work or recreation. Australians behave similarly and have been found to spend 50–80% of their time at home (Australian Bureau of Statistics 1988). This raises questions about the relevance of outdoor pollutant exposures to indoor pollutant exposures and there is universal agreement that the greatest source of exposure to airborne pollutants is the indoor environment. However, the indoor environment consists of a range of categories according to the type of building and the activities within it. This review excludes industrial workplaces from the indoor air environment since these utilise a well-defined population of workers with exposure to specific pollutants over what is generally a predictable period.

Occupational exposure standards and specific guidance on their application exist to protect the health of industrial workers (NOHSC 1991).Other indoor environment categories are:

- residential
- commercial (private, public)
- retail
- health
- educational
- recreational
- transport.

Occupational regulations generally apply to all workplaces and these are defined as 'any place, whether or not in a building or structure, where employees or self-employed people work' (Victorian *Occupational Health and Safety Act 1985*). Essentially, occupational regulations could apply to all of the above environments (depending on their practical occupancy) and yet all could have occupants who are either residents, workers, or non-workers (visitors). A different portion of each of these populations is likely to fall within a category considered sensitive to pollutant exposure (see Section 2.3). Emmett (1994) noted that while occupational standards are applicable by regulation to all workplaces, non-mandatory environmental goals may be required in practice to protect the non-workers who enter some workplaces.

This leaves a somewhat complex picture of environment–occupant–health effect interaction and raises questions about the practicality of selecting indoor air quality indicators to protect the sensitive in **all** indoor air locations. It is believed that indicators should be selected on such a basis for residential, health and educational categories since greater protection for the sensitive is warranted for these. Indicators for other categories could be judged on a case-by-case basis, the prime considerations being the likely access by the sensitive and the presence of indoor pollutant sources.

5.2 Interactive effects of pollutants

The Norwegian Health Directorate (1990) noted that there was an almost complete lack of information regarding interactive effects of pollutants on health. This situation still largely prevails, although several studies have identified interactive effects while others suggest such effects may occur. These effects are significant for two reasons:

(a) they will complicate and limit the outcome of epidemiological investigations of the effects of single pollutants; and

(b) since indoor air pollutant species vary significantly from those outdoors, interactive effects may limit transposing findings from one environment to the other (Peterson 1988).

Examples of interactive effects are:

(a) the synergistic effects on lung cancer of tobacco smoking and exposure to asbestos (Selikoff et al. 1968) or radon (Pershagen et al. 1994);

(b) synergistic effects on odour from exposure to formaldehyde with air extracted from a 'sick' building (Ahlstrom et al. 1986);

(c) interactive effects of exposure to a VOC mixture and different air temperatures and their influence on nasal volumes, sensory irritation and comfort (Jorgensen et al. 1993);

(d) Feron et al. (1992) summarised possible mechanisms for synergism/interactions and gave examples of effects, such as synergistic toxicities to sprayers of some pesticide combinations and synergistic effects on lung damage by ozone or nitrogen dioxide and sulphuric acid aerosol; they noted that indoor air pollutants that occurred below 'minimum-observed-adverse effect levels' with a large safety margin would probably not exhibit interactive effects;

(e) additivity of nasal pungency (irritation) by VOC mixtures as observed in many experiments by Molhave (1990) and supported mechanistically by Cometto-Muniz and Cain (1993);

(f) Miller (1994) summarised interactions between inorganic and microbiological pollutants and noted that: (a) pre-exposure to ozone reduced the amount of antigen required to induce a response in house dust mite–sensitive asthmatics by three times (Devlin et al. 1994); (b) exposure of rats to 5 ppm nitrogen dioxide significantly increased serum IgE and inflammatory lung effects from immunisation with house dust mite antigen (Gilmour 1994); (c) exposure to bacterial endotoxin and house dust mites exhibited significant interactions in effects on lung function, and clinical and immunological criteria (Michel et al. 1991); and

(g) Burge and Feeley (1991) noted that nitrogen dioxide and ozone exposures have been shown to increase the rate of infection and decrease the survival time of mice exposed to pathogenic bacteria and that effects on humans were under investigation.

5.3 Selection of indoor air quality indicators

5.3.1 Relevance of outdoor air pollutants

In general it is considered that indicators of outdoor air pollution will be of little use as indicators of indoor air pollution since:

(a) indoor air contains a complex range of pollutants, most of which originate indoors and differ considerably from the pollutants found outdoors (see Sections 2.2, 3.1 and 3.3);

(b) some indicators of outdoor air pollution have been selected on criteria irrelevant to indoor air and human health—for example, total suspended particulates in relation to visibility reduction, non-methane hydrocarbons in relation to photochemical smog reduction (Peterson 1988);

(c) unless also generated indoors, levels of outdoor air pollutants are generally reduced to lower levels indoors due to deposition and other losses of the pollutants from outdoor air as it infiltrates or ventilates buildings (see Section 3.3);

(d) indoor air quality and outdoor air quality cannot be considered as a continuum of the air environment because of the substantial differences in pollutants, their concentrations and temporal variations and the proportion of time people spend in each environment; and

(e) it is logical to control pollutants in the environments from which they are generated, and so pollutants generated outdoors that reach unacceptable indoor concentrations are indicative first and foremost of poor outdoor air quality (Peterson 1988).

5.3.2 Previous approaches to indoor air quality indicators

A discussion paper by the Australia and New Zealand Environment Council (1990) identified contributors to reduced indoor air quality. These are:

- **Homes:** significant contributors are formaldehyde, nitrogen dioxide and inadequate ventilation
- **Homes:** possible contributors are carbon monoxide, radon, particles/PAHs, ETS, asbestos, dust mites, ozone, pestisides and VOCs
- **Offices:** contributors are formaldehyde, VOCs, microbials, ETS, asbestos, ozone
- **Public places:** contributors are ETS, traffic pollutants and nitrogen dioxide.

The Office of the Commissioner for the Environment (1992) identified two types of indicators:

(a) core indicators—representative of air quality in all types of buildings; and

(b) indoor specific indicators—unique to certain types of indoor environments.

Core indicators were further divided into three sub-groups:

- ventilation core indicators: temperature, humidity; carbon dioxide as surrogate for outdoor air ventilation rate
- single pollutant core indicators: carbon monoxide; formaldehyde; nitrogen dioxide; ozone
- multi-pollutant core indicators: VOCs; microbials; ETS; respirable particulates.

Indoor-specific pollutants recommended as indicators were:

- acid gases
- lead
- fibrous particles
- non-methane hydrocarbons
- class 2 & 3 indicators under Victorian SEPP
- PAHs
- radon
- sulphur dioxide
- pesticides.

Various bodies have recommended indoor air quality goal concentrations for specific pollutants, generally on a health-related basis. These are summarised in Table 16.

Table 16: Comparison of indoor air quality guideline concentrations for pollutants

Indoor air pollutant	**Goal concentrations (µg/m^3 unless specified)**			
	NHMRC (1993) (indoor)	**H&W Canada (1987) (residential)**	**NHD (1990)^a (indoor)**	**WHO (1987)^b (indoor)**
Asbestos	–	–	Source control	carcinogen
Synthetic mineral fibres	–	–	No free fibres	–
Radon	200 Bq/m^3(1y)^d	800Bq/m^3(1y)	200–800 Bq/m^3	carcinogen
ETS	–	–	Prohibited	–
RSP	TSP90(1y)	PM100 (1h)	40 (8h)	100
Legionella	–	2.5	–	–
HDM	–	–	1µg/g Der p 1	–
Microbes	–	–	No pathogens or odour	–
Formaldehyde	120 (ceiling)^d	60–120	60	100
VOC	TVOC 500 (1h)^d VOC 250 (1h)^d	–	Irritants, TVOC 400	Some VOCs^c
Pesticides	–	–	–	–
Nitrogen dioxide	Review	480 (1h)	200 (1h)	400 (1h)
Carbon monoxide	9 ppm (8h)	11 ppm (8h)	9 ppm (8h)	9 ppm
Carbon dioxide	–	3500 ppm	1000 ppm (max)	1000 ppm
Ozone	240 (1h)	240 (1h)	–	150 (1h)
Sulfur dioxide	700 (1h)	1000 (5 min)	–	–
Lead	1.5 (3mo)	–	–	0.5–1.0
Mercury	–	–	–	1.0 (1y)
Rel. Hum.%	–	30–80	–	–

a Values averaged over 24 hours unless specified.

b Short-term exposure averages.

c 1,2 dichloroethane 700, dichloromethane 3000, styrene 800 (70 odour), tetrachloroethylene 5000, toluene 8000 (1000 odour)

d Final goals for radon and formaldehyde; level of concern for TVOC and VOC; other goals are interim goals using ambient air goals.

5.3.3 Types of indicators

Many authorities around the world recommend a structured step-wise strategy for indoor air quality investigations (Brown 1992), especially for commercial buildings (see Figure 1).

It is seen that indoor air pollutant measurements commence with some broad indicators early in the strategy (e.g. temperature, humidity, air velocity, carbon dioxide or ventilation rate) and progress to specific air pollutant indicators if needed within the particular investigation. This approach is both sensible and conserving of resources since there will be little use from measurement of a range of pollutants in a building while it is operating to below acceptable ventilation rates. Also, prior inspection of the building and investigation of occupant complaints should provide direction on what pollutants should be measured (e.g. according to observed sources) and where they should be measured.

Indoor air indicators should be compatible with this strategy and so there is a need to consider two types of indicators: (a) comfort/ventilation indicators; and (b) source indicators.

5.4 Comfort indicators

Comfort indicators will be generally relevant to non-residental buildings. For mechanically ventilated buildings, it is recommended that comfort indicators include factors such as thermal comfort criteria and occupant symptoms reported by questionnaire.

While thermal comfort criteria are well known and widely applied in building air-conditioning designs, the degree to which they are met in practice is not clearly known. A large field study in the US found that 22% of indoor conditions in winter and 50% in summer were outside ASHRAE’s thermal comfort zone (Schiller et al. 1988). Apart from thermal comfort criteria, temperature, humidity and air velocity may have further significance to occupant comfort. Low humidities below 30% may dry out eyes and nasal membranes, causing discomfort particularly for wearers of contact lenses (Bruenis and de Groot 1988). Such humidities may also contribute to greater rates of infection by infectious aerosols, especially under low ventilation conditions (Burge and Feeley 1991) and may aggravate skin itching and redness (Guest 1991). Humidities in this range are common for buildings in inland Australia such as in Canberra (Percival 1992). High humidities (above 70–80%) may lead to microbial problems in buildings. Overall, 30–70% is viewed as the thermal comfort zone for humidity but 40–60% is considered the optimal range for indoor air quality.

Local air velocities also are important to occupant perceptions. ASHRAE Standard 55–1981 ‘Thermal Environment Conditions for Human Occupancy’ recommended the optimal winter condition at 22°C to be an air velocity less than 0.15 m/sec and for summer at 24°C, less than 0.25 m/sec. Limited findings have indicated that feelings of ‘stuffiness’ can occur in buildings where air velocities are very low (Raw 1992).

5.5 Ventilation indicators

As discussed previously (Section 3.2.2.1), indoor carbon dioxide concentrations provide a measure of the adequacy of outdoor air supply to occupied buildings in the absence of other carbon dioxide sources. This is strictly true under steady-state conditions of building ventilation and these must persist for several hours for measurements at low ventilation rates (Bearg et al. 1993). Also, outdoor concentrations must not be elevated. Under these conditions, a carbon dioxide concentration of 1000 ppm or less is regarded as an acceptable ventilation indicator for residential buildings and 800 ppm or less for other building types (T. Nathanson, Public Works Canada, pers. comm.). However, caution is needed in using the above figure for residential buildings since most of the data on this indicator have come from non-residential buildings with different ventilation systems and occupancy rates from residences (Tobin et al. 1993; Lunau 1993).

5.6 Source indicators

These are indicators for indoor air quality that should generally be measured in response to inspection of a building and identification of possible pollutant sources by the strategy described in section 5.3.3. The selection of some of these indicators will be straightforward while for others it will be more complex, particularly where the pollutants are less source-specific than others (e.g. VOCs and microbials).

Note that this approach is advisable for all indoor non-industrial environments and that discrimination according to the category of environment may need to be made by assigning different exposure guidelines for a pollutant. The selection of an indicator for assessment should be made on the basis of observed pollutant sources rather than category of indoor environment.

5.6.1 Asbestos fibres

Asbestos concentration in indoor air is not useful as an indicator since it will be a less reliable measure of exposure potential from friable products than product inspection and hazard assessment. These products are most likely to give rise to hazardous concentrations when damaged. A guidance note for inspection and assessment of friable asbestos products has been available for some years (NOHSC 1988). It is believed it would be strengthened if it incorporated recent developments in specifications for encapsulants (ASTM 1992; Brown 1990) and, more particularly, procedures for visual inspection of abatement sites (ASTM 1993).

5.6.2 Radon

Experience has shown that radon concentrations in virtually all Australian buildings are low compared to exposure guidelines, except in some earth-constructed residences. Radon is useful as an indicator only for earth-constructed residences or for basements that serve as residences. A map of soil uranium concentrations that is being assembled by the Australian Geological Survey Organisation should be used to provide guidance on areas of high radioactivity and the siting of buildings or their design to minimise radon ingress by methods described by ASTM (*ASTM Standardization News*, March 1991, 18–19).

5.6.3 Environmental tobacco smoke

If smoking is permitted in a building, environmental tobacco smoke (ETS) indicators may be necessary to evaluate the effectiveness of ventilation systems or designated smoking areas in preventing exposure of building occupants. ETS is a complex mixture of pollutants that changes rapidly with time, preventing most of them from being used as indoor air quality indicators. Nicotine and RSP may be adequate for environments with heavy smoking but will underestimate (2- to 5-fold) and overestimate (2-fold), respectively, environments where smoking is moderate to light (Eatough 1993). Robust indicators for other smoking environments are yet to be developed (Guerin 1993) although measurements of ultraviolet-absorbing particulate matter and fluorescing particulate matter show promise for selective determination of ETS-derived particulate matter (Guerin et al. 1992). Repace and Lowrey (1993) modelled lung cancer mortality risk from ETS exposure and derived an ‘acceptable risk’ indoor air quality exposure standard of 7.5 ng/m^3 nicotine in workplace air for a working lifetime of 40 years. This might prove a useful indicator of the effectiveness of control strategies if measured over long time periods to minimise the influence of deposition/re-emission on measurements.

In conclusion, an indicator for ETS exposure is available only for indoor environments with heavy smoking (e.g. public recreation places). Generally, the principle of elimination of ETS should be followed using NOHSC (1994) as a guide. Alternative indicators for ETS exposure need to be developed for indoor environments not using NOHSC guidance and where smoking is less than heavy.

5.6.4 Respirable suspended particles

Apart from ETS, respirable suspended particles (RSPs) may arise from a range of sources and so vary physically and chemically and in their influence on health. Since these particles are by their definition deposited deeply in the lungs where they may have toxic effects, their presence in indoor environments requires attention. However, there are current inadequacies in:

(a) knowledge of the physical properties and chemical composition of these particulates;

(b) knowledge of their health effects (assuming effects of outdoor RSP are not applicable to indoor RSP because of physical and chemical differences); and

(c) methods for measuring RSP accurately at guideline levels established elsewhere (e.g. NHD 1990 recommended a guideline of 40 μg/m^3).

It is recommended that an indoor air quality indicator for RSPs be reserved until these inadequacies are addressed.

5.6.5 *Legionella* spp.

There are several guidelines and codes for control of *Legionella* in cooling towers and other sources (see Appendix 4). Use of these guidelines and codes is expected to be a better indicator for *Legionella* control than routine air or water sampling for the bacteria. Such sampling is resource-intensive and may be a poor predictor of *Legionella* entering buildings. However, sampling is useful in explaining disease outbreaks to ensure remedial action at responsible sites and for correct diagnosis of the disease to ensure appropriate medical treatment (CEC 1993). One of the prime requirements of guidelines is the siting of cooling towers relative to building air inlets to prevent ingress of aerosol drift into building air. A minimum separation of six metres is specified but this may be difficult to realise in buildings constructed prior to the guidelines, due to space limitations.

5.6.6 House dust mites

House dust mites (HDMs) are considered a significant health and indoor air problem in Australian residences where HDM allergen levels are often significant. Limited data from Australia (Green et al. 1992) and overseas (CEC 1993) indicate HDM allergen levels are small in office buildings while information for types of buildings other than residences is practically non-existent. CEC (1993) recommended HDMs be considered an indoor air pollutant for residences, schools and hotels. Air sampling for HDM allergen will be relevant to measurement of allergen exposure but has been seldom used (Price et al. 1990) since it requires long sampling periods (2–24 hours) and may be unrepresentative of the short periods of exposure to high allergen concentrations that are clinically important (CEC 1993).

The indicator for HDM exposure (CEC 1993) should be the allergen levels in accumulated dust vacuumed by standard methods from mattresses, carpets and furniture and analysed by an immunochemical assay, preferably enzyme-linked immunosorbent assay (ELISA) for Der p 1.

The indicator could be evaluated against hygienic threshold limits (HTL) proposed by Platts-Mills and de Weck (1988) or categories (based on measured values in residences rather than health risk evaluation) recommended by CEC (1993), both of which are presented in Table 17.

Table 17. Evaluation of measurements of Der p 1 in accumulated dust

Category	Der p 1 (µg/g dust)
CEC—very low	< 0.5
HTL for sensitisation	2
CEC—low	< 5
HTL for acute attacks of asthma	10
CEC—intermediate	<15
CEC—high	<20
CEC—very high	>20

Tovey (1992) suggested that a level <0.2 µg/g may be regarded as ‘safe’ although ambitious for many residences. He proposed a more practical interim goal would be to achieve the ten percentile level for residences in a particular community.

5.6.7 Microbial contaminants

The impact of other microbial contaminants on indoor air quality in Australia has received little investigation. However, moisture and moulds may be common in Australian houses. A national survey of occupants of 3046 houses in 1993 found that 33% of houses had visible mould (26% reported mould in bathrooms, 8% in bedrooms) (Dulux Australia, unpublished data). Engineering consultants have reported substantial contamination associated with moisture in poorly designed and maintained mechanical ventilation systems. This mirrors experience overseas, although the prevalence of such problems is unknown.

While WHO (1990) has provided guidelines for assessing hazardous airborne fungi indoors (see section 2.2.7), CEC (1993) concluded that no health-based airborne guidelines could be adequately set for biological particles. It was also concluded that sampling and analysis methods were not well-standardised but could enable sources and their relative importance to be assessed. Consistent with the present approach to indoor air quality indicators, it was recommended that a walk-through inspection by specialised investigators should be made before considering sampling for microbial contaminants. Visible mould growth was regarded as unacceptable.

Nevalainen et al. (1994) noted that microbial growth was not always visible in a building and that concentrations of fungi in indoor air were not necessarily high even when mould was visible. Holt (1994) found that airborne microbial concentrations varied widely in the same building on a daily basis and concluded their usefulness was suspect; he recommended building inspection instead. While differences between problem and normal houses could be found by careful analysis of fungal concentrations and genera, Navalainen et al. recommended the following as indicators of potential indoor air microbial exposure:

(a) careful inspection of buildings for the presence of moist or damp surfaces or visible moulds; and

(b) sampling of surfaces with sterile swabs where moisture or mould was suspected.

In summary, the following indicators for unacceptable microbial contamination of indoor air are recommended:

(a) the presence of moist or damp surfaces with or without presence of visible mould; and

(b) the presence of confirmed pathogens or toxigenic fungi (see Table 5) in airborne or surface samples.

Attention is drawn to recent suggestions for measuring microbial ‘biomass’ in indoor air (Miller 1994) that may prove to be better indicators in the future.

5.6.8 Formaldehyde

Measurements have shown that formaldehyde concentrations in conventional, established residences and offices seldom exceed 100 ppb measured over several days. However the NHMRC indoor air goal is 100 ppb as a ceiling concentration and few measurements appear to have been made on this basis except those of Hooper et al. (1994) and Cliff (SIMTARS, unpublished). Also, concentrations in buildings at first occupancy are not known even though manufacturers suggest these could reach 500 ppb (see Section 3.1.8).

Formaldehyde concentrations in caravans, mobile homes and mobile offices have clearly been shown to exceed the NHMRC goal but it is not known how to interpret these findings relative to ‘low-emission’ products currently manufactured in Australia.

It is recommended that until these issues are resolved, formaldehyde concentration should remain as an indoor air quality indicator in buildings using other than small quantities of pressed-wood products.

5.6.9 Volatile organic compounds

Since little is known about volatile organic compounds (VOCs) in indoor air in Australia, it is recommended on the basis of overseas studies that:

(a) TVOC be used as an indicator for the presence of significant VOC sources;

(b) a definition for TVOC be developed that is relevant to occupant exposure, possible health effects and practical analytical parameters (a working group will have addressed this issue at Healthy Buildings ‘95 (Milan); also, CEC (Ispra) has proposed to develop a definition by late–1995 (M. De Bortoli, CEC Joint Research Centre, pers. comm.); and

(c) concentrations of specific VOCs that are carcinogens or are irritants at low levels should be determined when potential sources are present.

5.6.10 Pesticides

Pesticide concentrations should be measured as indoor air quality indicators to assist site clean-up when building inspection identifies pesticide residues in or around the building, especially for the post-construction application of termaticides at buildings with ‘leaky’ floors.

5.6.11 Nitrogen dioxide

Nitrogen dioxide concentrations should be measured as indoor air quality indicators in all buildings (but particularly residences, schools and hospitals) which use unflued gas appliances, particularly heaters.

5.6.12 Carbon monoxide

Carbon monoxide concentrations should be measured as indoor air quality indicators in all buildings using unflued gas heaters—particularly residences, schools and hospitals—and in enclosed car parking sites without ventilation to AS1668.2–1991.

5.6.13 Carbon dioxide

Carbon dioxide concentration should be measured as an indoor air quality indicator in mechanically ventilated buildings when operated under steady-state conditions and as a measure of the adequacy of outdoor air ventilation rate relative to the number of building occupants (see section 5.5.).

5.6.14 Ozone

Ozone concentrations should be measured as an indoor air quality indicator in rooms with heavy use of electrostatic photocopiers, laser printers or other sources, and in the air outlet from ozone-based air sterilisers.

5.7 Emerging issues

This review identified a number of issues related to indoor air quality which are either poorly understood or areas of rapidly developing knowledge that could not be reviewed. The intent in this section is to flag merely these issues for further consideration.

Limited surveys of occupant health have been performed in Australia to determine the prevalence of building-related illnesses. Symptom questionnaires offer a means to gather more easily information in relation to environmental factors, particularly in relation to sick building syndrome. However, the questionnaires must be well-designed and applied if they are to gather useful information. Many different questionnaires have been used by researchers internationally, making interpretation of findings difficult. A need for a ‘standardised’ symptom questionnaire was determined during working sessions of ‘Indoor Air: An Integrated Approach’, 26 November – 1 December, Gold Coast. The International Society for Indoor Air Quality and Climate has undertaken to coordinate this activity.

Questions have arisen about the adequacy of ventilation rates of Australian buildings, especially for mechanically ventilated buildings constructed in the 1980s and residential buildings constructed in recent years. The interaction of energy conservation measures and the ventilation levels of the building stock needs to be better understood and coordinated.

Many pollutants may interact in their health effects and the understanding of this interaction is limited and may remain so for complex pollutant mixtures. It has been reported that a mouse bioassay (measuring sensory and pulmonary irritation according to decrements in respiration rates) can be used to quantify the irritancy of building air samples associated with human complaints (Anderson and Coogan 1994). Further studies to verify these findings are needed.

Smoking in public recreation buildings continues largely unchecked in Australia, although it is believed a NOHSC code of practice is to be developed. Unless smoke-free or designated smoking areas are included in this code, the adequacy of ventilation systems to remove ETS from building air will become an issue.

Lead in old paint from houses presents health risks to occupants, especially children, due to flaking and chalking of the paint, and also to homeowners during renovations. The Select Committee upon Lead Pollution (1994) identified lead abatement in public housing, child-care centres and lower socio-economic housing as target areas. Penny (1994) discussed the issues from the paint industries’ perspective and recommended the products be managed in-place by using purpose-designed encapsulants rather than removal. The adoption of abatement strategies and the specification of these encapsulants and their effectiveness will be important factors in these activities.

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47. Maurizio De Bortoli, European Commission, Joint Research Centre, Italy.
48. Aino Nevalainen, National Public Health Institute, Kuopio, Finland.
49. Tedd Nathanson, Public Works Canada, Ottawa.
50. Richard Gammage, Oak Ridge National Laboratories, USA.

Appendix 2: List of Initialisms and Measurement Units

ABS	Australian Bureau of Statistics
AC	asbestos cement
ACGIH	American Conference of Governmental Industrial Hygenists
ACH	air changes per hour
ACT	Australian Capital Territory
AGA	Australian Gas Association
AGSO	Australian Geological Survey Organisation
AIRAH	Australian Institute of Refrigeration Air Condition and Heating (Inc.)
ANZEC	Australia and New Zealand Environment Council
ARL	Australian Radiation Laboratory
ASHRAE	American Society of Heating and Refrigerating Airconditioning Engineers
ASHVE	American Society of Heating and Ventilation Engineers
ASTM	American Society for Testing and Materials
AWPA	Australian Wood Panels Association
Bq/m^3	Becquerel per cubic metre of air
BREEAM	Building Research Establishment Environmental Assessment Method
CEC	Commission of European Communities
CFD	computational fluid dynamics
CFU	colony-forming units
CIBSE	Chartered Institution of Building Services Engineers
CO	carbon monoxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DASCEM	Department of Administrative Services Centre for Environmental Management
Der p 1	Dermatophagoides pteronyssinus serogroup 1
EDXA	energy dispersive X-ray analysis
EPA	Environmental Protection Agency
ETS	environmental tobacco smoke
f/mL	fibre per millilitre of air
HDMs	house dust mites
IAQ	indoor air quality
IARC	International Agency for Research on Cancer
LPG	liquefied petroleum gas
MCS	multiple chemical sensitivity
NHD	Norwegian Health Directorate
NHMRC	National Health and Medical Research Council
NOHSC	National Occupational Health and Safety Commission
NSW	New South Wales
OCE	Office of the Commissioner for the Environment
PAH	polyaromatic hydrocarbon
ppb	parts per billion (10^{-9})
ppm	parts per million (10^{-6})
RH	relative humidity
RSPs	respirable suspended particulates
SAA	Standards Association of Australia
SBS	sick building syndrome
SEPP	State Environment Protection Policy
SIMTARS	Safety in Mining Testing and Research Station
SMF	synthetic mineral fibre
TEM	transmission electron microscopy
TVOC	total volatile organic compounds
UFFI	urea formaldehyde foam insulation
UNGS	unflued natural gas space
USEPA	United States Environmental Protection Agency
VOCs	volatile organic compounds
WHO	World Health Organization
µg/m^3	microgram (10^{-6} gram) per cubic metre of air
ng/m^3	nanogram (10^{-9}gram) per cubic metre of air

Appendix 3: International Standards, Codes and Guidelines

World Health Organisation

1979—Health aspects related to indoor air quality. Report on a WHO working group. EURO Reports and Studies 21

1983—Indoor air pollutants: exposure and health effects. Report on a WHO meeting. EURO Reports and Studies 78

1986—Indoor air quality research. Report on a WHO working group. EURO Reports and Studies 103

1986—Indoor air quality: radon and formaldehyde. Report on a WHO working group. Environmental Health Series No. 13

1987—IARC Environmental Carcinogens. Methods of analysis and exposure measurement. Vol. 9. Passive smoking. IARC Sci. Pub. No. 8

1987—Indoor air quality: organic pollutants. Report on a WHO meeting. EURO Reports and Studies 111

1987—Air quality guidelines for Europe. European Series No. 23

1989—Formaldehyde. Environmental Health Criteria No. 89, Copenhagen

1990—Indoor air quality: biological contaminants. European Series No. 31

Commission of European Communities *(CEC Concerted Action—Indoor air quality and its impact on man):*

1989—Radon in indoor air. Report No. 1

1989—Formaldehyde emission from wood–based materials: guideline for the determination of steady state concentrations in test chambers. Report No. 2

1989—Indoor pollution by NO_2 in European countries. Report No. 3

1989—Sick building syndrome—a practical guide. Report No. 4

1989—Strategy for sampling chemical substances in indoor air. Report No. 6

1990—Indoor air pollution by formaldehyde in European countries. Report No. 7

1991—Guidelines for the characterization of volatile organic compounds emitted from indoor materials and products using small test chambers. Report No. 8

1991—Effects of indoor air pollution on human health. Report No. 10

1992—Guidelines for ventilation requirements in buildings. Report No. 11

1993—Biological particles in indoor environments. Report No. 12

1993—Determination of VOCs emitted from indoor materials and products. Interlaboratory comparison of small chamber measurements. Report No. 13.

Canada

Health and Welfare Canada (1989). Exposure guidelines for residential indoor air quality. A report of the Federal–Provincial Advisory Committee on Environmental and Occupational Health, Department of National Health and Welfare, Ottawa.

Norway

Norwegian Health Directorate (1990). Guidelines for Indoor Air Quality. Report 6–90, IK–2322, Norwegian Health Directorate.

England

House of Commons Environment Committee (1991). Indoor Pollution. HMSO, London.

USA

Environmental Protection Agency (1989). Report to Congress on Indoor Air Quality. EPA/400/1–89/001C. Office of Research and Development, USEPA, Washington.

Appendix 4: Standards and Codes in Australia

Standards Australia

AS1668.2(1991)—Mechanical ventilation for acceptable indoor air quality.

AS1837(1976)—Code of practice for application of ergonomics to factory and office work.

AS4073(1993)—Urea formaldehyde foam thermal insulation. In situ set foam.

AS4074 (1993)—Methods of testing raw materials

AS4075(1993)—Urea formaldehyde foam thermal insulation. Installation requirements for in-situ set foam

AS3660(1993)—Protection of buildings from subterranean termites—Prevention, detection and treatment of infestation.

AS3666(1989)—Air-handling and water systems of buildings-microbial control.

SAAHB23(1992)—Control of microbial growth in air-handling and water systems in buildings.

AS2985(1987)—Workplace atmospheres—methods for sampling and gravimetric determination of respirable dust.

AS3580—Methods for sampling and analysis of ambient air.

AS2986(1987)—Working atmospheres—Organic vapors—Sampling of solid adsorption techniques.

NHMRC

1982—Urea formaldehyde foam insulation. Report of 93rd Session, June.

1988—Australian guidelines for the control of Legionella and Legionnaires' disease. AGPS, Canberra.

1988—Asthma in Australia-strategies for reducing morbidity and mortality. NHMRC, Canberra.

1989—Code of practice for the safe use of termaticides. Approved by 108th Session, November.

1989a—Indoor–air quality. Report of 108th Session, November.

1990—Radon in houses. Report of the 109th Session, May.

1993—Volatile organic compounds in indoor air. Report of 115 Session, June.

NOHSC

1988—Guide to the control of asbestos hazards in buildings in buildings and structures.

1988—Code of practice for the safe removal of asbestos.

1988—Guidance note on the membrane filter method for estimating airborne asbestos dust.

1989—Legionnaires' disease and related illnesses. AGPS, Canberra.

1991—Exposure standards for atmospheric contaminants in the occupational environment. AGPS, Canberra.

1994—Guidance note on passive smoking in the workplace [NOHSC:3019], AGPS, Canberra.