CRC Construction Innovation
BUILDING OUR FUTURE

Final Report
Task 2: Design Guidelines for Delivering High Quality Indoor Environments

Research Project No: 2003-028-B-01

The research described in this report was carried out by:

Project Leader
Phillip Paevere

Researchers
Selwyn Tucker
Seongwon Seo
David Johnston
Angela Williams
Pene Mitchell
Phillipa Watson
Delwyn Jones
Otti Newhouse
Michael Ambrose
Peter Lawther
Angela O'Donnell
Philip Crowther
Robin Drogemuller
Mary Hardie
Shahed Khan
Loretta Kivlighon
Graham Miller
Stephen Brown
Mark Luther
John Mahoney
Min Cheng

Project Affiliates
Ken Stickland
Ken Moschner
Dale Gilbert
Michael Griffiths
Mark Luther

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Distribution List

Cooperative Research Centre for Construction Innovation
Authors

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Please direct all enquiries to:

Chief Executive Officer
Cooperative Research Centre for Construction Innovation
9th Floor, L Block, QUT, 2 George St
Brisbane Qld 4000
AUSTRALIA
T: 61 7 3138 9291
F: 61 7 3138 9151
E: enquiries@construction-innovation.info
W: www.construction-innovation.info

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PREFACE

The Cooperative Research Centre for Construction Innovation (CRC CI) is a national research, development and implementation centre focused on the needs of the property, design, construction and facility management sectors. Established in 2001 and headquartered at Queensland University of Technology as an unincorporated joint venture under the Australian Government's Cooperative Research Program, the CRC CI is developing key technologies, tools and management systems to improve the effectiveness of the construction industry. The CRC CI is a seven year project funded by a Commonwealth grant and industry, research and other government support. More than 150 researchers and an alliance of 19 leading partner organisations are involved in and support the activities of the CRC CI.

There are three research areas:

- Program A - *Business and Industry Development*
- Program B - *Sustainable Built Assets*
- Program C - *Delivery and Management of Built Assets*

Underpinning these research programs is an *Information Communication Technology* (ICT) Platform.

Each project involves at least two industry partners and two research partners to ensure collaboration and industry focus is optimised throughout the research and implementation phases. The complementary blend of industry partners ensures a real-life environment whereby research can be easily tested and results quickly disseminated.

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- City of Melbourne for its permission to use results from IEQ assessments of CH1 and CH2
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- Mark Luther and the MABEL team from Deakin University, who conducted the physical comfort IEQ measurements
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EXECUTIVE SUMMARY

This report is for one of the four Tasks of the CRC project ‘Regenerating Construction to Enhance Sustainability’. The report specifically addresses Task 2 ‘Design guidelines for delivering high quality indoor environments’.

‘Regenerating Construction to Enhance Sustainability’ was designed to assist in the delivery of demonstrably superior green buildings in respect of:

- Eco-efficient re-design: achieving a smaller ecological footprint and within budget
- Enhanced indoor environment quality and performance, reflected in improved health, well being and productivity of building occupants
- Waste minimisation (through re-design for dis-assembly).

The project examined both a planned re-life of the City of Melbourne (CoM) Council House 1 (CH1) (project not proceeded with) and a comparable new building CH2 (as an alternative to CH1), with a focus on **four key tasks** as follows:

1. Use of LCADesign Green Star and NABERS as assessment tools for building redesign (original vs refurbished building) to assist industry in benchmarking practice and harmonisation of current Australian assessment tools – and in line with CRC’s role in the Green Space activity (now the Australian Sustainable Built Environment Council (ASBEC)).
2. Developing design guidelines for delivering high quality indoor environments (an industry benefit as well as one tailored via Charette to CoM requirements) and protocols for their measurement.
3. A before vs after survey of the CH1/CH2 building occupant health, well-being and productivity, in order to *value* the benefit of enhanced indoor environments to the CoM and more broadly to industry (see research methodology section). Task 2 and 3 need to be undertaken on occupants common to both CH1 and CH2.
4. A prototype tool developed for use in association with 3D CAD that can assess material selection on the basis of ease of dis-assembly, re-use and recycling (thereby minimising waste generation in subsequent refurbishment or demolition [a beta version only for this specific refurbishment application. If received positively by industry it can be developed as an additional module for LCADesign].

This report deals only with the requirements of Task 2. The link between Tasks 2 and 3 is considered in a separate report (Paevere and Brown 2008).

Initially, a review of existing research literature and practices was undertaken, and this led to the consideration of Indoor Environment Quality as consisting of four key **Indicators**:

- Indoor Air Quality
- Thermal Comfort
- Lighting, and
- Noise.

A set of Metrics was selected for each Indicator, these requiring specific methodologies for measurement and criteria for high quality environments. Additionally, a sampling protocol was developed for assessing these metrics in buildings. The application to two office buildings in Melbourne led to the following recommended list of Metrics and sampling:

IEQ Indicator	**Measurement location(s)**			**Sampling Period in Working Shift (h)**	**Criteria for high performance rating (levels not to be exceeded for time averages specified)**
	Number of Levels	**Loc-ations /Level**	**Out-door**		
Indoor Air Quality					
TVOC	3	1	1	1	500 µg/m^3 (1 h)
Benzene	3	1	1	1	10 µg/m^3 (1 h)
Toluene	3	1	1	1	4100 µg/m^3 (1 h)
Formaldehyde	3	1	1	0.5	100 µg/m^3 (0.5 h)
PM2.5	3	1	1	8	25 µg/m^3 (8 h)
CO	3	1	1	8	9 ppm (8 h), 25ppm (1 h)
CO_2	3	1	1	8	800 ppm (1 h)
Microbial	3	20	-	-	none visible/no moisture
Thermal Comfort					
Whole body	3	6+	1	8 (total)	Grade A (PPD<6%), Grade B (<10%), Grade C (<15%)
Draught	3	6+	-	2 min	Grade A (max. 0.10-12 m/s)
RH	3	2	1	8	40-70% (1 h)
Vertical temp. gradient (0.1 – 1.1 m)	3	6+	-	2 min	Grade A (<2 °C)
Floor T	3	6+	-	2 min	Grade A (19 – 29 °C)
Radiant temp. asymmetry	3	6+	-	2 min	warm ceiling < 5 °C, cool wall < 10 °C, cool ceiling < 14 °C, warm wall < 23 °C
Lighting					
General illuminance	3	6+	-	2 min	160 lx (min)
Task illuminance	3	6+	-	2 min	320 – 600 lx (task specific)
Glare	3	4	-	2 min	Daylight Glare Probability Index <0.3
Noise					
Unoccupied office (general areas)	3	6+	-	1 h (total)	40 – 45 dB(A)
Occupied office (general areas)	3	6+	-	1 h (total)	<55 dB(A) average
Reverberation time	3	1	-	<1 h	0.4-0.6 sec
Occupant Comfort Survey					
	3	30	-	4 h	<20% daily+weekly complaint rate

These were applied to CH1 and CH2 office buildings, or were selected following such application, and were found to be:

- appropriate for IEQ assessment, and
- implementable under field conditions.

A number of recommendations were made specifically from these assessments, as follows:

- A key building sampling strategy will be the application of the Office Environment Survey to building occupants on selected Levels; this should be applied prior to adopting an IEQ building sampling strategy and should act to inform such a strategy
- The IAQ sampling strategy may be reduced where pre-assessment inspection shows building Levels are similar in materials used, occupancy type and building services
- The IAQ criteria should be accepted in ‘Regenerating Construction …’ as protective for occupant health and well-being

- The ppbRAE instrument should be used for assessing IAQ with caution, and only as a device for determining the absence of VOC pollution rather than for determining the level of pollution and its health significance, the latter requiring GC/MS sampling and analysis
- A sustainable building refurbishment or construction may be expected to meet IAQ criteria for formaldehyde and VOCs soon after construction if low emission materials/contents are utilised
- The thermal comfort sampling strategy was considered to provide a ‘snapshot’ measurement, appropriate for identifying the need for more extensive assessment
- Estimation of whole body thermal comfort in offices should use the ISO default values of 0.5 clo/1.2 met for summer and 1.0 clo/1.2 met in winter, unless actual estimates of occupant clo values are available
- Task illuminance in offices can be achieved by occupants when specific and appropriate task lights are provided. Task illuminance should be assessed with task lights operating if present
- The noise level in an occupied office is an additional metric and a criterion of 55 dBA (averaged from several locations and times) should provide approximately 99% speech intelligibility.

1 BACKGROUND

The CRC for Construction Innovation has initiated a project on “Regenerating Construction to Enhance Sustainability”, with the following characteristics:

Overall Objectives

- to re-life a building to an “A Grade” office standard
- 30 years’ usage
- business case cash flows to be based on a 16-20 year period
- ecologically sustainable design
- delivery method that is cost effective, and
- incorporation of best practice building and design technologies

Specific Objectives

- upgrade the building to satisfy current (and foreseeable future) statutory and regulatory requirements, e.g. fire systems, equity/access requirements and workplace health and safety
- rationalise and improve the indoor office environment to achieve space efficiencies and occupant well-being and productivity improvements – space target of 14m^2/person, productivity targets not defined
- reduce operating costs: targets not defined
- re-life as a “green” building to achieve sustainability outcomes in areas such as energy efficiency, recycling of materials, waste reductions, generic fit-out designs to reduce the future costs of “churn”, etc..

Regenerating Construction to Enhance Sustainability is designed to assist in the delivery of superior refurbished **office** buildings according to a core set of 4 sustainability criteria:

- Eco-efficiency: minimising the ecological footprint of the refurbished building (compared to predecessor) within an agreed budget
- High indoor environment quality (IEQ): where the refurbished building has achieved demonstrable improvement in respect of key IEQ criteria, including thermal performance and indoor air quality
- Healthier and more productive working environment: as measured by the performance of occupants determined pre- vs post-refurbishment
- Waste minimisation by examining how to reduce the generation of waste during construction, i.e. off-cuts, over ordering, etc, and refurbishment, by increasing recycling and re-use. Dual objectives relate to minimisation of construction waste during refurbishment and minimisation of waste generation during next refurbishment (or demolition) phase as a result of designing for dis-assembly during the current refurbishment.

These are all quantifiable elements, the results of which could be employed to estimate the contribution to improved triple bottom line (TBL) performance of the entire built environment achievable via refurbishment of existing stock to prescribed levels.

This report deals with the core sustainability criterion of **high indoor environment quality**. Indoor Environmental Quality (IEQ) design guidelines will be developed in the report via the following steps:

- Identifying *key indicators for high quality indoor environments*, their definition and measurement and inter-connectedness (matrix/model):
    a. These indicators are expected to be encompassed in the following factors: indoor air pollutants, thermal comfort, lighting & noise
    b. Building ventilation rate will significantly impact on these factors if uncontrolled, but since it is currently tightly regulated in BCA via Australian Standard 1668, it will be assumed that that ventilation performance has been optimised for BCA requirements
- Sampling *and measurement protocols for performance measures* of key IEQ indicators
    c. Performance measures may be variable over time, location and season according to changes in exterior impacts (weather, urban air pollutants), occupancy levels, and building

operations. Also, their impacts on occupant will have a temporal factor (e.g. irritant pollutants affect occupants in minutes, carcinogen in years, poor thermal comfort in tens of minutes etc).

  d. Protocols must be employed to reliably sample the performance measures according to their impacts on occupants, the central focus of this project.
- Reliable, scientific *procedures by which the indicators can be measured* at any location
- Performance criteria for each indicator
  e. Performance targets for IEQ indicators will be recommended (in the context of international best practice, standards or guidelines) based on a review of the current international literature
  f. Performance targets will have the potential to be linked with occupant satisfaction surveys, acceptable indoor air pollutant levels, and acceptable levels of thermal comfort, lighting and noise
- Design and specification implications of performance targets
  g. There will be a range of implications such as the procurement of low-polluting materials, furniture and office equipment, the use of high performance systems for environmental control, and the operation and design of feedback systems for performance measures
- Document the implementation of the guidelines in a target building by the following
  h. Measure IEQ in target building (where possible) using nominated indicators (eg IAQ, lighting, noise, thermal comfort, ergonomic factors), ideally undertaken over 6 months (duplicate measurements in 2 seasons) prior to refurbishment
  i. Measure IEQ of refurbished building with same nominated indicators on handover to 6 months later (duplicate measurements in 2 seasons)
  j. Provide report that compares IEQ before vs after refurbishment, and comparing both with guidelines for optimised indoor environments.

2 SELECTION OF IEQ INDICATORS

2.1 Indoor Air Quality Indicators

Poor indoor air quality (IAQ) can be a significant health, environment and economic problem, and has become a public health issue and liability for employers and building managers who fail to provide a 'safe' working environment. The meaning of IAQ is often interpreted differently across disciplines, but this report uses a broad definition for IAQ which has been generally accepted in Australia (Brown 1997, Environment Australia 2001, Brown 2005), which is 'the totality of *attributes* of indoor air that affect a person's health and well-being'. IAQ measures must thereby determine how well indoor air (a) satisfies thermal and respiratory requirements of occupants, (b) prevents unhealthy accumulation of pollutants, and (c) allows for a sense of well-being.

International research has 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 have been limited, but indicate similar occurrence to other developed countries for building-related illnesses, SBS-like symptoms and dissatisfaction with office air environments.

Regulatory actions related to indoor air quality are limited in Australia, especially in comparison to regulation of outdoor air quality and industrial workplace air, a feature also common overseas. Some guidance has been provided by authorities such as:

- the National Health and Medical Research Council (NHMRC), which has defined indoor air as the air within any dwelling, office, school or hospital where people spend more than one hour per day; the NHMRC recommends health-based advisory IAQ goals for several pollutants, as presented in Table 2.1;
- the National Occupational Health and Safety Commission (NOHSC 1995), which provides exposure guidelines for a large number of air contaminants in workplaces (only) which are generally called up in OHS regulation; and
- the World Health Organization (2000) which has recommended health-based environmental air quality guidelines for Europe which it stated were applicable to both urban and indoor air exposures.

Table 2.1 provides comparative exposure or IAQ goal/guidelines from the above organizations, and it is seen that there are substantial differences between occupational and environmental requirements (National Health and Medical Research Council, 1996). This arises because:

- occupational exposures occur for approximately 40 hours per week, whereas environmental exposures occur continuously (i.e. 168 hours per week, a factor of 4 higher than occupational exposure)
- the population health demographic of the workforce differs considerably from the general population, which includes sectors with specific 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. The question of multiple chemical sensitivity and the possible influence of indoor air pollutants is under debate.

Thus, the protection of sensitive sectors of the population is considered appropriate when selecting IAQ guidelines for residential, health and educational building categories. Indicators for other building categories, especially office buildings, will need to consider the likely access to them by sensitive sectors of the population; for example, a government office to which the general public has access will need to apply an environmental guideline, while a private office accessible only to employees may choose to apply occupational guidelines depending on the health status of its employees.

Table 2.1 IAQ, environmental and occupational exposure goals for air contaminants

Pollutant	**NHMRC IAQ goals**		**NOHSC Occup. Exposure Stds.** **(exposure period)**	**NEPM Ambient Air Standards (exposure period)**	**WHO Air Quality Guideline** **(exposure period)**
	µg/m^3 or ppm	**meas. period**			
Carbon monoxide (CO)	9 ppm	8 h	30 ppm (8h)	9ppm (8 h)	9 ppm (8 h) 25 ppm (1 h)
Nitrogen dioxide	-	-	3 ppm (8 h)	0.12 ppm (1 h) 0.03 ppm (1 y)	0.11 ppm (1 h) 0.02 ppm (1 y)
Lead	1.5 µg/m^3	3 mo	150 µg/m^3 (8 h)	0.5 µg/m^3 (1 y)	0.5 µg/m^3 (1 y)
Ozone	0.1 ppm	1 h	0.1 ppm (peak)	0.1 ppm (1 h)	-
	0.08 ppm	4 h	-	0.08 ppm (4 h)	0.06 ppm (8 h)
Radon	200 Bq/m^3	1 y	-	-	(100 Bq/m^3)
Sulphates	15 µg/m^3	1 y	-	-	-
Sulphur dioxide (SO_2)	0.25 ppm	10 min	2 ppm (8 h)	0.20 ppm (1 h)	0.18 ppm (10min)
	0.20 ppm	1 h		0.08 ppm (24 h)	0.04 ppm (24 h)
	0.02 ppm	1 y		0.02 ppm (1 y)	0.02 ppm (1 y)
Total Suspended Particulates	90 µg/m^3	1 y	-	-	-
PM2.5	-	-	-	25 µg/m^3 (24 h) 8 µg/m^3 (1 y)	Dose-response
Formaldehyde	120 µg/m^3 0.1ppm	peak	1 ppm (8 h)	50 µg/m^3 / 0.04 ppm (24 h)	100 µg/m^3 (30 min)
Total Volatile Organic Compounds	500 µg/m^3 (no VOC > 0.5 TVOC)	1 h	-	-	-
Benzene	-	-	1 ppm (8 h)	0.003 ppm / 10 µg/m^3 (1y)	carcinogen
Toluene	-	-	50 ppm	1 ppm (24 h) 0.1 ppm (1 y)	0.07 ppm / 260 µg/m^3 (1 week)
Xylene isomers	-	-		0.25 ppm (24 h) 0.2 ppm (1 y)	0.20 ppm / 870 µg/m^3 (1 y)
1,4-Dichlorobenzene	-	-	25 ppm	-	0.02 ppm / 134 µg/m^3 (1 year)
Dichloromethane	-	-	50 ppm	-	0.5 ppm / 3000 µg/m^3 (24 h)
Ethylbenzene	-	-	100 ppm	-	5 ppm / 22,000 µg/m^3 (1 year)
Styrene	-	-	50 ppm	-	0.06 ppm / 260 µg/m^3 (1 week)
Tetrachloroethylene	-	-	50 ppm	-	0.04 ppm / 250 µg/m^3 (24 h)
1,3,5-Trichlorobenzene	-	-	-	-	0.005 ppm / 36 µg/m^3 (1 year)
1,2,4-Trichlorobenzene	-	-	5 ppm	-	0.001 ppm / 8 µg/m^3 (1 year)

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 the pollutants, their major sources and the available control measures is presented in Table 2.2. Many of these pollutants have not been sufficiently researched to determine exposure levels for the Australian population or the most appropriate strategies to reduce exposure (Brown 1997).

Table 2.2 Pollutants measured in Australian buildings (some relative to NHMRC goals)

Pollutant	**Indoor concentration range**	**Major sources**	**Control**
Asbestos fibres	< 0.002 f/mL	Friable asbestos products	Risk management, removal
Radon: conventional dwellings	99.9% < goal of 200 Bq/m^3	Soil under building	Siting of building
Radon: earth-constructed dwellings	~9% > goal of 200 Bq/m^3	Background radiation of earth walls	Material selection
Environmental tobacco smoke (ETS)	High in recreational buildings	Cigarette smoke	Prohibition of smoking, designated smoking area
Respirable particulate matter	Poorly characterized	ETS, cooking, fuel combustion	Poorly characterized
Legionella spp.	30% of population exposed	Water cooling towers	Maintenance, site selection
House dust mites	10 – 40 µg/g Der p1 allergen in house dust	Allergen build-up in bedding, carpet, furniture	Removal of habitats, humidity control
Microbiological species	100 – 18000 CFU/m^3	Moist/damp surfaces	Control moisture/ mould
Formaldehyde: conventional buildings	< 100 ppb (1 – 3 day average) (goal 100 ppb ceiling)	Reconstituted wood-based products	Source emission control, ventilation
Formaldehyde: mobile buildings	100 – 1000 ppb	Reconstituted wood-based products	Source emission control, ventilation
Volatile organic compounds (VOC): established buildings new buildings	Total VOC < 500 µg/m^3 Total 2000 – 20 000 µg/m^3 (goal 500 µg/m^3)	'Wet' synthetic materials (adhesives, paints), office equipment, printed matter, furniture	Source emission control, ventilation
Pesticides	Limited data, median < 5 µg/m^3	Major sources unknown	Floor structure, clean-up, inspection
Nitrogen dioxide	Up to 1000 ppb	Unflued gas heaters and stoves	Source emission control, flued appliances
Carbon monoxide	~10% > goal of 9 ppm	Unflued gas heaters and stoves	Source emission control, flued appliances
Carbon dioxide	Poorly characterized	Exhaled air	Ventilation to Standards
Ozone	Poorly characterized	Office equipment, ozone deodorizers	Source emission control, ventilation

In Australia, the most significant IAQ pollutants are considered (Brown 1997) to be:

- environmental tobacco smoke, house dust mites and nitrogen dioxide (all based on the observation of high indoor levels) and
- respirable particulate matter, micro-organisms and volatile organic compounds including formaldehyde (based on their potential for high indoor levels under specific conditions).

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 in 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 heater rectification programs have commenced for government schools in New South Wales, a vast number of these heaters are used without control in many States and Territories.

The following IAQ indicators (and their critical sources where applicable) were recommended (Brown 1997) for IAQ assessment and control:

- Comfort indicators
  - thermal comfort criteria.

  - optimal humidity range 40 – 60% RH, and
  - occupant symptom questionnaire (Raw 1995).
- Ventilation indicators
  - concentration of carbon dioxide under steady-state conditions: residences < 1000 ppm, commercial buildings < 800 ppm (Nathanson 1995), and
  - operation of mechanical ventilation system to AS 1668 air supply requirements.
- Source indicators
  - asbestos fibres: 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 particulate matter (RPM) as indicators for areas with heavy smoking; use combustion derived particulates (ASTM 2002) for all smoking levels,
  - RPM: compare to National Environmental Protection Measures (NEPM) for $PM_{2.5}$ and PM_{10},
  - Legionella spp.: use applicable codes and regulations, applied retrospectively,
  - house dust mite: measure allergens in dust to determine if below ten percentile level for particular area (Brown 1997),
  - micro-organisms: moist or damp surfaces, with or without visible growths present, 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 reconstituted wood-based products,
  - VOCs: a total VOC concentration > 500 $\mu g/m^3$ indicates significant sources to be present; determine concentrations of carcinogens and irritants if potential sources are present,
  - pesticides: measure concentrations if visible residues are found or if 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, and
  - ozone: measure concentrations in rooms with heavy use of electrostatic photocopiers, laser printers and other sources, and at outlets from ozone-based air sterilizers.

Based on the above discussion, key IAQ metrics (Table 2.3) are recommended for CH1 and CH2. Note that an order of priority has been assigned to each, according to the level of quality of indoor air that is likely to be achieved by their application in this particular building. Also, since CH1 and CH2 are Local Government offices which may be accessed by members of the general public with particular sensitivities to air pollutants (the elderly and the young, people with pre-existing cardio-respiratory illness), IAQ indicators relevant to environmental exposures of the general public are selected rather than NOHSC occupational exposure standards.

Table 2.3 Key indicators for indoor air quality in CH1 and CH2

Indoor air pollutant	Possible sources	IAQ criterion	Priority
Formaldehyde	Partitions, furniture, shelving, flooring	100 μg/m^3 (peak)	High
Total VOC	Building materials, furniture, office equipment,	500 μg/m^3 (1 h)	High
VOC: benzene	As for TVOC, auto exhausts	10 μg/m^3 (1 y)	High
VOC: toluene	As for TVOC, auto exhausts, adhesives, printed matter	4100 μg/m^3 (24 h)	High
VOC: xylenes	As for TVOC, auto exhausts	1200 μg/m^3 (24 h)	Low
PM2.5	Auto exhausts, office equipment	25 μg/m^3 (24 h)	High
Carbon monoxide	Auto exhausts	9ppm (8 h)	High
Carbon dioxide	Exhaled breath	800 ppm (1h)	High
Ozone: at equipt exhausts	Copiers, printers	0.1 ppm	Low
Micro-organisms	Persistently damp surfaces, mechanical ventilation system	Absent on inspection	High
Asbestos	Insulation, sheeting, flooring	Inspection & risk evaluation	Low-Medium

2.2 Thermal Comfort Indicators for Office Workers in Mechanically Conditioned Spaces

Thermal comfort is commonly defined as that ‘condition of mind which expresses satisfaction with the thermal environment’ (International Organization for Standardization, 1994). Since people vary greatly in physiological and psychological factors, it is accepted that it is impossible to satisfy the thermal comfort of all occupants. However, based on existing data it is possible to statistically define conditions that a specified proportion of office occupants will find thermally comfortable. As well as physical parameters - air temperature, radiant temperature, air speed, humidity - a person’s activity levels and the insulation received from clothing will also influence thermal comfort but these are accepted here at typical levels for office environments (and in any case, these are not factors for environmental control).

A significant factor to thermal comfort is whether a space is mechanically conditioned or naturally conditioned – these are known to require different conditions for thermal comfort since occupant expectations in the latter are shifted due to different thermal experiences and availability of individual control. This section will deal only with mechanically conditioned spaces, presenting the physical environmental parameters that must be controlled (ASHRAE 2004).

2.2.1 Air Temperature

For given values of humidity and air speed, the thermal comfort zone can be defined in terms of operative temperatures or in terms of combinations of air temperature and mean radiant temperature. These parameters are defined as follows:

- Operative temperature: the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. In most practical cases, the operative temperature can be calculated as the mean of the air temperature and the mean radiant temperature. Also, in the absence of radiant heating/cooling panels, heat generating equipment, envelope insulation and large window solar heat gain (as specified in ASHRAE 2004), the assumption that operative temperature equals air temperature is acceptable;
- air temperature: the temperature of air surrounding the occupant;

- mean radiant temperature: the uniform surface temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual non-uniform space.

The operative air temperature for buildings recommended by ISO (1994) was between 20 °C and 24 °C (22 °C ± 2 °C) for winter conditions and between 23 °C and 26 °C (24.5 °C ± 1.5 °C) for summer conditions, and these values were endorsed by the Australian Government, 1995. The recent American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard 55 recommends the operative air temperature according to two procedures that produce equivalent results: a simplified graphical method or a computer program based on a heat balance model; only the former will be presented here (ASHRAE 2004).

The graphical method may be applied to spaces where the occupants have activity levels between 1.0 – 1.3 met, where clothing provides 0.5 – 1.0 clo of thermal insulation, and air speeds are not greater than 0.2 m/s, conditions that occur in most office spaces. The range of operative temperatures presented in Figure 2.1 (ASHRAE 2004) are for 80% occupant acceptability (based on 10% dissatisfaction for whole body comfort and 10% for partial body).

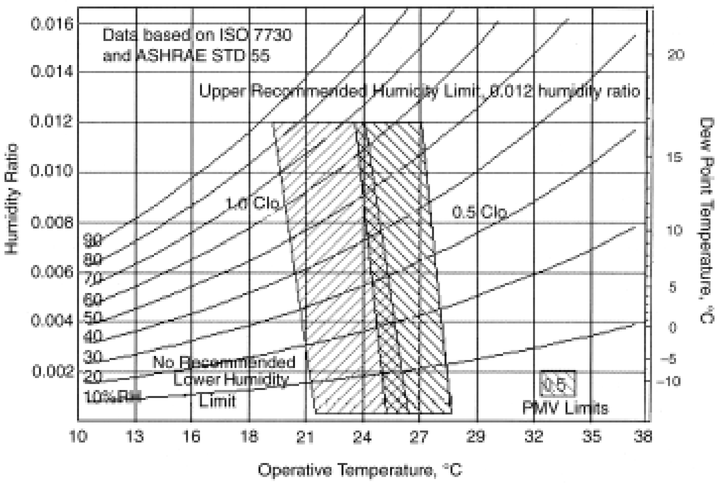


Figure 2.1 Acceptable ranges for operative temperature and humidity in 'typical' office spaces

Zones are shown for two levels of clothing, 0.5 clo and 1.0 clo, which are typical of clothing worn when the outdoor environment is warm and cool, respectively. Note that the thermal comfort zone extends across operative T from 19 °C to 28 °C, the specific T depending on clothing and humidity levels. On the basis of an optimum humidity range of 30 – 70%RH (see next section), for warm outdoors (0.5 clo) the operative T range for 80% occupant acceptability is 24 – 27 °C and for cool outdoors (1.0 clo) 21 – 23 °C.

Relative humidity (RH) is the ratio of the amount of water vapour in air to the maximum amount of water that the same volume of air can hold at the same temperature, expressed as a percentage. Relative humidity that is too high or too low can lead to skin, eye and respiratory irritation (American Society of Heating and Refrigerating and Air Conditioning Engineers, 1992). ISO (1994) recommended that the relative humidity should be 30 % to 70 % for summer and winter conditions. ASHRAE (2004) considered that there was no lower humidity limit for thermal comfort but noted that there were non-thermal comfort factors to consider: skin drying, dry eyes, mucosal irritation and static electricity generation. The ISO lower limit (above) is considered appropriate to limit these factors.

ASHRAE (2004) specified an upper humidity limit of a humidity ratio of 0.012 (water vapour pressure of 1.91 kPa or dew-point T of 16.8 °C). As shown in Figure 2.1, this corresponds to upper RHs of 55 – 85 %RH for acceptable thermal comfort, depending on operative T and clothing.

However, it is important to consider that relative humidities above approximately 70 % can cause microbial growth and damage to surfaces within buildings, especially when condensation on surfaces occurs (Brown 2005). Hence we recommend that relative humidity in buildings should not exceed 70 % RH because of these factors other than thermal comfort.

2.2.2 Air Speed

An increased air speed can be useful as a means for decreasing body temperature although it needs to be sufficiently low so that it is not perceived by the individual as a draught. Also, a minimum air speed is needed so that localised accumulation of indoor air pollutants is prevented. Indoor air spaces have been found to have air speeds between 0.05 to 0.3 m/s (Christiannson *et al* 1989). ISO (1994) recommended that the mean air speed be less than 0.1 m/s, while ASHRAE (1992) recommended an air speed of less than 0.2 m/s for summer conditions. On this basis, we recommend the air velocity in CH1 be within the range 0.05 – 0.2 m/s.

ASHRAE (2004) has specified that air speed may be increased above 0.2 m/s to increase the maximum temperature for acceptability *if occupants are able to control the air speed.* The amount of increase is shown in Figure 2.2 for a lightly clothed person (0.5 – 0.7 clo) in sedentary activity.

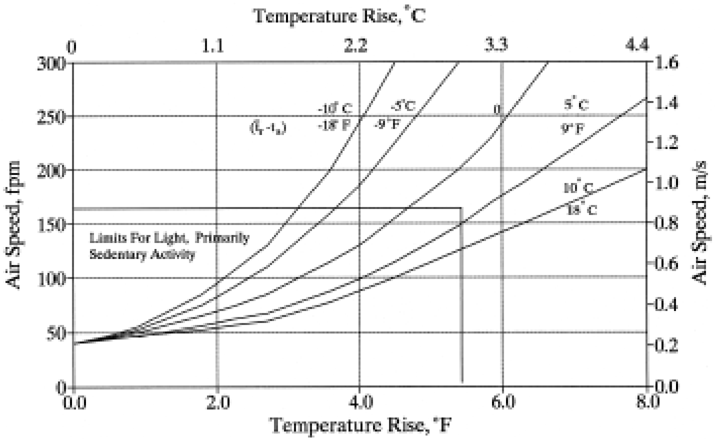


Figure 2.2 Air speed required to offset increased temperature

Figure 2.2 has a primary curve (marked '0') showing the relative increases for when air T and mean radiant T are equal, and other curves according to the difference: mean radiant T minus air T. These reflect the differing impacts of increased air speed: e.g. when mean radiant T is low and air T is high, elevated air speed is less effective at increasing heat loss. Also, note that ASHRAE allowed the offset using increased air speed, but not by more than 3 °C and with air speed no higher than 0.8 m/s.

Another aspect of air speed is draught. ASHRAE (2004) specified a requirement based on the sensitivity of the head to a draught from behind. The relationship for draught that is unacceptable to 20% of occupants is presented in Figure 2.3 for different levels of turbulence intensity. On average the turbulence intensity in occupied zones with mixing ventilation is 35% and with displacement ventilation or natural ventilation it is 20%. Note that for both of these conditions, air speeds range 0.15 to 0.3 m/s.

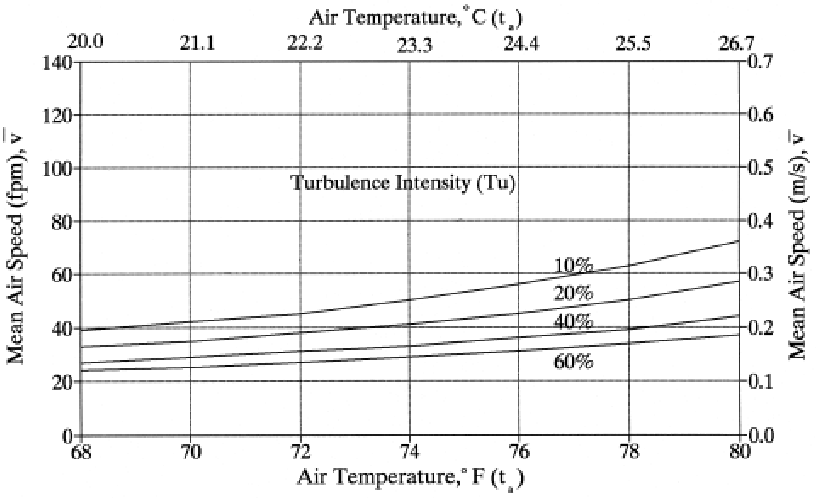


Figure 2.3 Allowable mean air speed to limit occupant dissatisfaction from draft to 20% (ASHRAE 2004)

2.2.3 Thermal Gradient

As the temperature at ceiling height is generally greater than the temperature at floor level, temperature as a function of height is considered as a factor that contributes to thermal comfort. ISO (1994) recommended that the vertical air temperature difference between 0.1 m and 1.1 m above the floor be less than 3 °C for both summer and winter conditions. The recommended surface temperature of the floor was 19 °C to 26 °C. ASHRAE (2004) recommended that the temperature gradient not exceed 3 °C between head and ankles (0.1 m and 1.7 m) levels, and also specified a floor surface temperature of 19 °C to 29 °C.

2.2.4 Radiant Temperature Asymmetry

Radiant temperature asymmetry is caused by radiation differences resulting from hot and cold surfaces (for example, heat gain or loss through a window, influence of ceiling or wall temperature on room temperature). Temperature asymmetry may cause local discomfort and reduce thermal acceptability of the space. Also, occupants are generally more sensitive to asymmetric radiation caused by a warm ceiling than by that caused by warm or cold vertical surfaces.

ISO (1994) recommended that the radiant temperature asymmetry from windows or other cold vertical surfaces to be less than 10 °C (0.6 m above the floor) and from a warm (heated) ceiling should be less than 5 °C. ASHRAE (1992) recommended radiant temperature asymmetry less than 5 °C in the vertical direction and less than 10 °C in the horizontal direction, these being the difference in radiant temperature at distances of 0.6 m and 1.1 m vertically and horizontally respectively. ASHRAE (2004) expanded the allowable radiant T asymmetry to be:

- warm ceiling < 5 °C
- cool wall < 10 °C
- cool ceiling < 14 °C
- warm wall < 23 °C.

2.2.5 Temperature Variation with Time

ASHRAE (2004) specified limits on operative T variations as follows:

- cyclic variation with frequency less than 0.25 h 1.1 °C
- drift or ramp changes for periods 0.25 – 4 h 1.1 – 3.3 °C.

2.2.6 Measuring the Thermal Environment

ASHRAE (2004) provided the following guidance for measuring thermal environments, whether in mechanically or naturally ventilated buildings. Measurements must be made in occupied zones where occupants spend their time at a representative number of locations, but at a minimum:

- in the centre of the room or zone
- 1.0 m inwards from the centre of each of the room's walls (for walls with windows, 1.0 m from

the centre of the largest window)

- locations where the most extreme thermal values may occur (near windows, diffusers, corners)
- humidity need be determined at only one location and any height within the occupied zone unless there is reason to expect large variation across the zone
- air T and speed shall be measured at 0.1, 0.6 and 1.1 m heights for seated occupants, and at 0.1, 1.1 and 1.7 m for standing occupants; operative T shall be measured or calculated at 0.6 m for seated occupants and 1.1 m for standing occupants
- radiant asymmetry shall be measured at 0.6 m high for seated and 1.1 m high for standing occupants.

ASHRAE Standard 55 and ISO 7730 both specify three levels of quality for acceptable thermal comfort, since in practice the levels attained will depend on a range of factors: technical, cost, environmental, energy and performance. Table 2.4 shows the recommended levels of acceptance for the three categories (General thermal comfort B corresponds to ASHRAE's 1992 recommendation). The different percentages express a balance struck between the aim of a few dissatisfied and what is practically obtainable using existing technology. Note that the PDs in Table 2.4 are not additive. In practice, a higher or lower number of dissatisfied persons may be found when using subjective questionnaires in field investigations.

Owing to the accuracy of instrumentation for measuring the input parameters, it can be difficult to verify that the PMV conforms to the Class A category (−0.2 < PMV < +0.2). Instead, the verification may be based on the equivalent operative temperature range, as specified in Table 2.5.

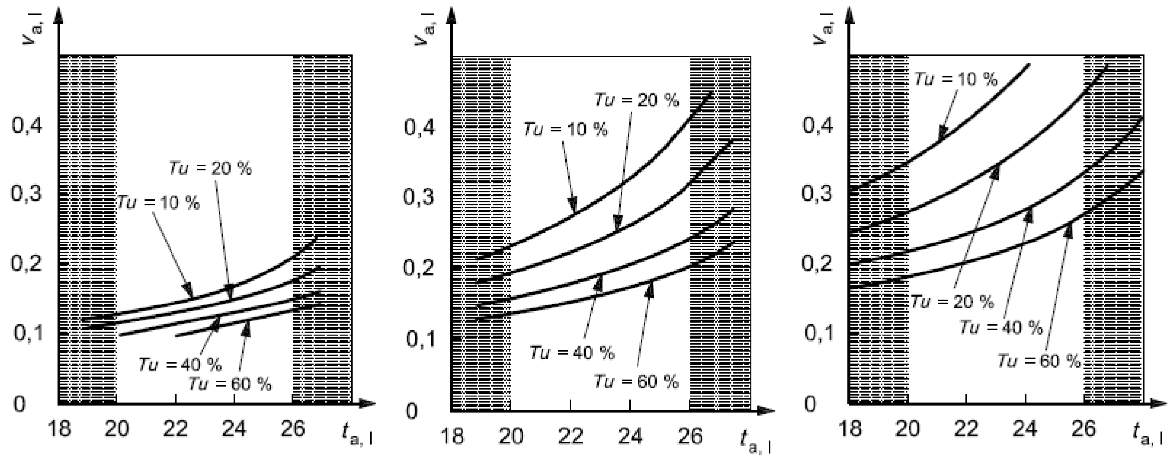
Table 2.4 Three quality categories of thermal environment (ISO 7730:2005)

Thermal state of the body as a whole (General thermal comfort)			**Local thermal discomfort**			
Category	**PPD %**	**Predicted mean vote**	**Draught rate, DR %**	**Percent dissatisfaction (%) caused by**		
				Vertical air temperature difference %	**Warm or cool floor %**	**Radiant temperature asymmetry %**
A	< 6	- 0.2 < PMV < + 0.2	< 10	< 3	< 10	< 5
B	< 10	- 0.5 < PMV < + 0.5	< 20	< 5	< 10	< 5
C	< 15	+ 0.7 < PMV < + 0.7	< 30	< 10	< 15	< 10

Figure 2.4 presents the Draft Rate dissatisfaction parameter for the three categories in Table 2.4. The maximum allowable mean air velocity is a function of local air temperature and turbulence intensity. The turbulence intensity may vary between 30 % and 60 % in spaces with mixed-flow air distribution. In spaces with displacement ventilation or without mechanical ventilation, the turbulence intensity is approximately 20%.

Table 2.5 Design criteria for operative temperature and air velocity for typical spaces (ISO 7730:2005)

Type of building / space	Clothing		Activity (met)	Categ -ory	Operative Temperature		Max. Mean Air Velocity (m/s)	
	Cooling Season: Summer (clo)	Heating Season: Winter (clo)			Summer (ºC)	Winter (ºC)	Summer	Winter
Office	0.5	1.0	1.2	A	24.5 ± 1.0	22.0 ± 1.0	0.12	0.10
				B	24.5 ± 1.5	22.0 ± 2.0	0.19	0.16
				C	24.5 ± 2.5	22.0 ± 3.0	0.24	0.21
Kindergarten	0.5	1.0	1.4	A	23.5 ± 1.0	20.0 ± 1.0	0.11	0.10
				B	23.5 ± 2.0	20.0 ± 2.5	0.18	0.15
				C	23.5 ± 2.5	20.0 ± 3.5	0.23	0.19
Department Store	0.5	1.0	1.6	A	23.0 ± 1.0	19.0 ± 1.5	0.16	0.13
				B	23.0 ± 2.0	19.0 ± 3.0	0.20	0.15
				C	23.0 ± 3.0	20.0 ± 4.0	0.23	0.18



Category A: DR = 10 % **Category B: DR = 20 %** **Category C: DR = 30 %**

Key

$t_{a,l}$ local air temperature, °C

$\overline{v}_{a,l}$ local mean air velocity, m/s

Tu turbulence intensity, %

Figure 2.4. Maximum allowable mean air velocity as a function of local air temperature and turnulence intensity.

Tables 2.6 to 2.8 give temperature values for the local thermal discomfort causes: vertical air temperature difference, warm/cold floor and radiant temperature asymmetry.

Table 2.6. Vertical air temperature difference between head and ankles

Category	Vertical air temperature difference [a] °C
A	< 2
B	< 3
C	< 4

[a] 1,1 and 0,1 m above floor.

Table 2.7. Range of floor temperatures

Category	Floor surface temperature range °C
A	19 to 29
B	19 to 29
C	17 to 31

Table 2.8. Radiant temperature asymmetry

Category	Radiant temperature asymmetry °C			
	Warm ceiling	Cool wall	Cool ceiling	Warm wall
A	< 5	< 10	< 14	< 23
B	< 5	< 10	< 14	< 23
C	< 7	< 13	< 18	< 35

2.3 Thermal Comfort Indicators for Office Workers in Naturally Conditioned Spaces

Naturally conditioned spaces must be equipped with operable windows that can be readily opened and adjusted by occupants. There must be no mechanical cooling and mechanical ventilation may be present but window adjustment must be the primary means of regulating thermal conditions. The space may have a heating system but this indicator cannot be used if the heater is operating. Allowable indoor operative T may be determined from Figure 2..5, which includes sets of limits for 80% and 90% acceptability, the latter being for higher standard of comfort. Note that this Figure is based on the adaptive model of thermal comfort that was derived from a global database of 21,000 measurements, mostly in office buildings (ASHRAE 2004).

Note that the allowable operative T limits in Figure 2.5 are limited to conditions where the mean monthly outdoor T ranges from 10 °C to 33.5 °C. No guidance is allowable outside this range. Also note that the limits account for local thermal discomfort effects and so these factors do not need separate evaluation.

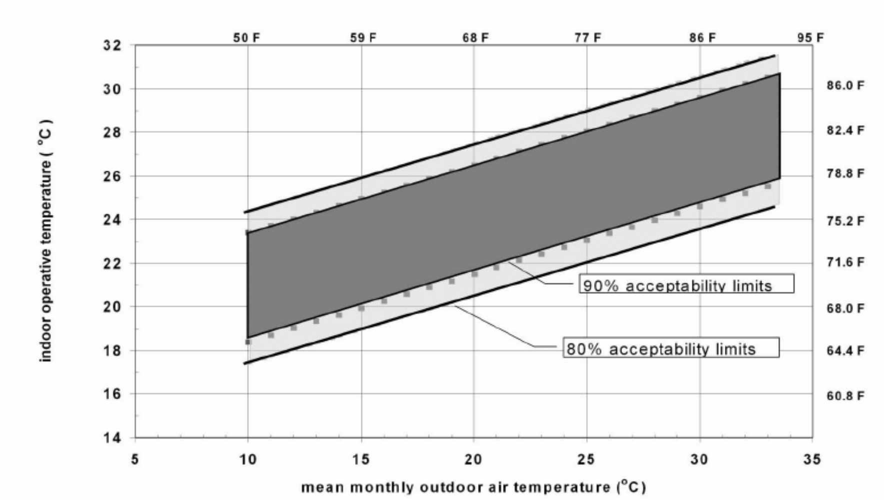


Figure 2.5 Acceptable operative temperature ranges for naturally conditioned spaces

2.4 Temporal Evaluation of General Comfort Conditions

ISO International Standard 7730-1994 provided the comfort criteria for evaluating moderate thermal environments. While it is understood that a revision is currently underway, we assume it will be similar to the ASHRAE (2004) standard already discussed. This discussion will present the 1994 standard as background information. ISO (1994) requires consideration of physical activity and clothing, as well as the environmental parameters: air temperature, mean radiant temperature, air velocity and air humidity. When these factors have been estimated or measured, the thermal sensation for the body as a whole can be predicted by calculating a predicted mean vote (PMV) index. PMV can be used to estimate the predicted percentage of dissatisfied (PPD) index, which provides information on thermal discomfort or thermal dissatisfaction by predicting the percentage of people likely to feel too hot or too cold in a given environment. PPD may be adjusted to account for other thermal effects such as draught, etc.

Boerstra *et al* (2003) described a new adaptive thermal comfort guideline which may be implemented in Holland by 2008. It was developed as an alternative to a ‘weighted exceeding hours method’ that is based on the PMV/PPD model. The guideline used:

- the momentary comfort performance
- the ‘over time’ comfort performance.

The momentary comfort performance was characterised using the steps:

1. measure the indoor operative T
2. calculate the running mean outdoor T (RMOT)
3. determine whether the space should be characterised as Alpha (no mechanical cooling or mechanical cooling with one T control per 2 occupants) or Beta (mechanical cooling with less than one T control per 2 occupants)
4. compare operative T and RMOT values to graphical comfort limits for 70 %, 80 % and 90 % acceptability.

The ‘over time’ comfort performance was derived by determining the momentary comfort performance during occupancy hours and then classifying buildings according to whether the indoor operative T was never outside the acceptability lines:

- Class A never outside the 90 % acceptability lines
- Class B never outside the 80 % acceptability lines
- Class C never outside the 70 % acceptability lines.

Figure 2.6 provides an example of this approach.

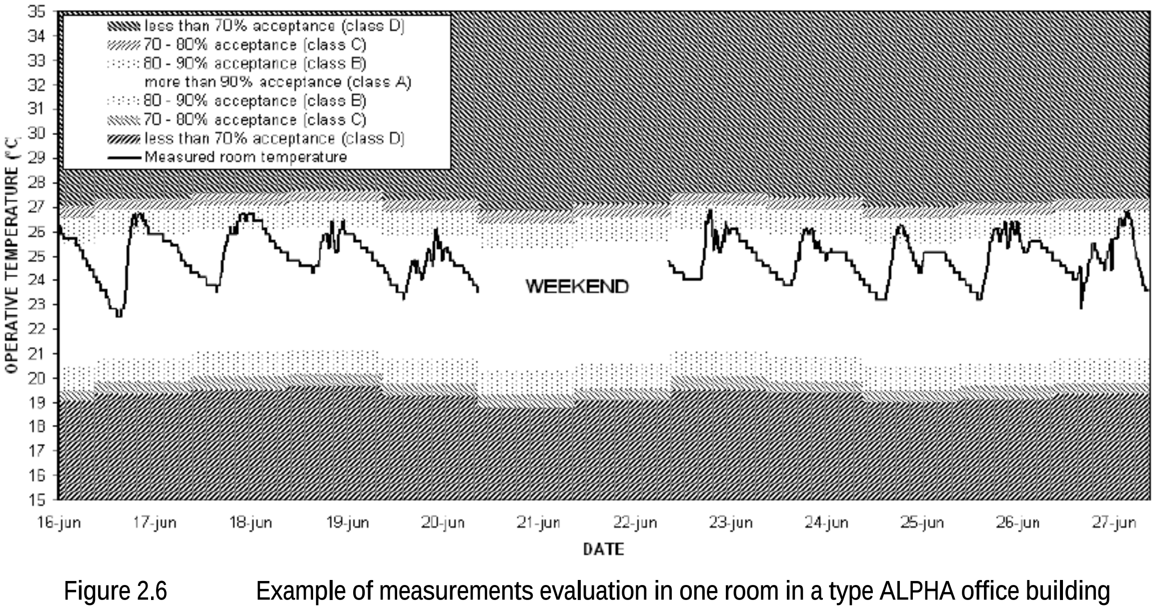


Figure 2.6 Example of measurements evaluation in one room in a type ALPHA office building

The top and bottom temperature limits differ per day, as they depend on the daily average outside temperature. In this example, the temperature as measured stays within the 80 % bandwidth. Therefore, this can be described as ‘class B thermal performance’.

Olsesen (2004) noted that ISO 7730 revision used several methods to sum the length of time the comfort range was exceeded, some with differential weighting of the time exceedance as a kind of degree-hour method. He showed the use of a weighting system based on PPD yielded higher weighting factors than one based on temperature differences. For example, Table 2.77 shows factors for a comfort range of 23 – 26 °C and sedentary work (1.2 met) and light summer clothing (0.5 clo). For temperatures above or below the comfort range, the number of hours should be multiplied by the weighting factor.

Table 2.7 Weighting factors for temporal assessment of thermal comfort levels

Temperature °C		**Weighting factors**	
		wf (°C)	**wt (PPD)**
Cool	20	3	4.7
	21	2	3.1
	22	1	1.9
Neutral	23	0	0
	24	0	0
	25	0	0
	26	0	0
Warm	27	1	1.9
	28	2	3.1
	29	3	4.7

3 LIGHTING QUALITY INDICATORS

Most of the tasks in CH1 will be office-based. Lighting levels need to be of a quality that provides an environment in which it is easy to see so that tasks can be safely performed without eye strain. During typical working hours, lighting inside offices tends to rely on a combination of both daylight from windows and electric lighting. *There is little doubt that people prefer to work by daylight* and enjoy the view. Also, this mixture of lighting methods enables a degree of flexibility which is a useful requirement referred to in some of the following sections. Windows can be a useful factor in avoiding or reducing eyestrain as they can allow an individual to focus on objects that are further away rather than having to focus within the near distance on objects such as computer screens for a prolonged time. However, the use of windows needs to be balanced with respect to any adverse thermal effects or lighting effects such as glare.

The standard international unit that is used to measure the amount of light per unit of surface area, also known as illuminance, is lux (symbolized lx). Australian Standards for interior lighting for office and screen based tasks (below) recommend a minimum of **160 lx *on the working plane*** *(below)* so that eyes are not strained due to a deficiency of light. However, the Standards note that ‘the greatest scope for increased productivity lies with improvement in lighting *quality* rather than in the provision of higher illuminances’, and so they recommend appropriate lighting and interior colour treatment to minimise visual fatigue and maintain efficiency during the whole work period. As an overview:

the lighting system should be so designed and installed as to effectively reveal the task(s) and to provide safe and comfortable visual environments

This discussion will ***not consider the selection of luminaires*** but will consider general aspects of interior lighting strategies, lighting colour, task-specific lighting that are important to provide high lighting quality in office buildings.

Several Australian and ISO Standards exist for interior lighting, as follows, and these have been used in this discussion:

- AS1680.1-1990 Interior Lighting Part 1: General Principles and Recommendations
- AS1680.2.1-1993 Interior Lighting Part 2.1: Circulation spaces and other general areas
- AS1680.2.2-1994 Interior Lighting Part 2.2: Office and screen-based tasks
- ISO 8995:2002 Lighting of Indoor Workspaces.

Definitions from these standards are:

- average illuminance (in a room): mean of illuminances either calculated (for uniform array of luminaires but excluding areas within 0.6 m of walls) or measured (through a regular grid of measurements at the working plane(s) at spacings of 1 m or greater, with 4 to 25 measurement points depending on the room index)
- room index (*K*) of a room is twice the plan area of the room divided by the area of its walls between the horizontal reference plane and the luminaire plane
- horizontal reference plane: the position of the horizontal reference plane over which the mean illuminance is to be calculated must be defined; unless otherwise stated it is normally assumed to be 0.7 m above the floor for tasks which are at desk height and 0.85 m above the floor for tasks which are at bench height
- luminaire plane: the horizontal plane containing the photometric centres of the luminaires
- average illuminance (over a task area): mean of illuminances within the task area
- initial illuminance: the average illuminance initially provided by the lighting system (with new lamps (< 100 h use), clean luminaries, clean room surfaces
- maintenance illuminance: average illuminance below which it is necessary to take remedial action
- luminance: the light level reflected from an illuminated surface
- cut-off angle of luminaire: the angle, measured from nadir in a given vertical half-plane, between the vertical axis and the line of sight at which all surfaces of high luminance (of lamps and of the luminaire) just cease to be visible
- task area: the area within which the task is located; this may be the whole of the room or a small part of it
- task illuminance: the value of maintenance illuminance which is recommended for a specific visual task
- task surroundings: surface visible within 45° of the line of sight when looking at details anywhere on the task; the surfaces may be in the same plane as the task or at some distance from it (note: 1. surfaces within 15° of the line of sight are referred to as the ‘immediate task surroundings’; 2. the actual size and shape of the task surroundings will depend on the size and shape of the task, the distance of the task from the eye of the observer and from the surface(s) against which the task is seen
- task detail: the minute portion of the task which is under examination at any given moment
- (visual) task: the whole object (large or small) which is to be examined, e.g. car body under assembly, document or drawing being read, watch being repaired
- uniformity of illuminance: the ratio of the minimum illuminance to the average illuminance on a given plane within the calculation or measurement area
- unwanted reflections: reflections in the task or its surroundings which interfere with visual efficiency and comfort in one or other of the following ways: 1. b*y reducing task contrast;* 2. b*y causing distraction and annoyance;* 3. *by causing glare*
- veiling reflections: a term sometimes applied to reflections which reduce task contrast
- working plane: the horizontal, vertical, or inclined plane in which the visual task lies.

3.1 Task Illuminance

The visibility of a task is generally determined by the visibility of the most difficult element that must be detected or recognised – this is generally referred to as the critical detail and this will be influenced by many factors (e.g. size, colour, observation time, contrast, position, experience etc).

The most important factor to achieving good task visibility is the luminance of the task and its surroundings, and the vision factors important to 'adaption luminance' are such that optimum levels exist for this luminance and for the ratio of luminances of the task: immediate surrounds: general surrounds (approx. 10:3:1).

Even though a task may be performed within three dimensions, it is generally carried out in more or less one plane and it is common to consider illuminance on that plane (called the ***'working plane'***). Note that achieving illuminances on working planes will facilitate the task visibility but does not necessarily achieve the desired visual appearance or comfort of a space. Also, in general there are three key factors to task illuminance:

1. increasing the illuminance on a task produces an increase in performance following a law of diminishing returns
2. the illuminance at which performance levels off is determined by the visual difficulty of the task (the smaller or the lower contrast in a task, the higher the illuminance level)
3. it is not possible to bring a difficult visual task to the same level of performance as an easy task simply by increasing the illuminance (e.g. consider the improvement from using a magnifier for tasks difficult to the unaided eye).

3.2 Interior Lighting

A large amount of office-based work involves using computers, although other tasks can include reading, writing or (detailed) drawing without the use of a computer, filing or other forms of communication. Some tasks require more intensive use of sight than other tasks and the visual requirements of individuals varies depending upon the tasks performed and a person's visual perception. Flexible lighting is generally recommended in order to accommodate for any possible diversity of visual requirements (Australian Standard® 1680.2.2—1994, 1994). More detail regarding the recommended illuminance with respect to the type of task is given in Table 3.1 (Australian Standard® 1680.2.0—1990, 1990).

The general areas of office buildings require an illuminance of 160 lx or more at working planes; lower lighting levels are acceptable in infrequently occupied areas such as locker rooms, storage rooms and corridors but these are not considered in this design specification for occupant lighting comfort. However, corridor lighting should be considered relative to occupied space lighting – AS1680.1 notes that the lighting differences of adjacent areas should not be pronounced (no more than 10:1) because of visual adaption factors. Also, the uniformity of illuminance within the room should not be less than 0.7 (i.e. the minimum illuminance on a given plane should not be less than 70% of the average illuminance).

The illuminance must be measured at the task areas of occupants. Illuminance will generally be lower close to walls (50% of average) and corners (25% of average) if luminaires are uniformly distributed in a space, and so as in the definition of average illuminance (above), no measurements should be made within 0.6 m of walls. Tasks should not be performed in these areas for this reason but if they are then the lighting must account for them.

For general lighting systems, the recommended illuminances should be provided throughout the space on these horizontal planes (unless determined otherwise by a specific appraisal of a task):

- for tasks which are at desk height – 0.7 m above the floor
- for tasks at bench height – 0.85 m above the floor
- for tasks with surfaces that are not predominantly horizontal (e.g. filing, screen-based equipment), the recommended illuminances should be provided on these surfaces.

The average *initial* illuminances for office-based tasks that should be provided by the lighting system will need to be significantly higher than the ***recommended maintenance illuminance*** in order to allow for the progressive loss of light from: lamp ageing/dust accumulation; dust accumulation on room surfaces; dirt build-up on windows. AS1680.2.2 specifies only the recommended values for maintenance illuminance, noting that a maintenance cycle should be adopted to ensure average illuminance remains above these specifications, and providing general guidance (Appendix 12, AS1680.1) on appropriate maintenance regimes. Recommended average maintenance illuminances are presented in Table 3.1.

Table 3.1 Recommended interior illuminance for office and screen-based tasks

Task/room type	Recommended illuminance (lx)
General tasks: typing, reading, writing	
- task	320
- background	160
Screen-based task	
- keyboards	160
- reference material	
• good, simple	240
• average detail	320
• poor, fine detail	600
- background	160
- microform reading	20 – 40
Drawing offices	
- drawing board	600
- reference material	
• good, simple	320
• poor, fine detail	600
- background	240
Meeting rooms	320
Training/seminar rooms	240
Conference rooms/board rooms	240
Reception areas	
- enquiry desk	320
- entrance hall, lobby, foyer	160
Photocopying and printing room	
- intermittent	160
- sustained	240
- colour	240
Filing area	
- clear detail	240
- fine detail	320

General considerations for the application of these illuminances (AS1680.2.2) are:

Screen-based equipment: since the information displayed on the screen is self-luminous, the illuminance provided by general lighting can be lower than needed for paper-based office tasks if the operator has to attend to information only on the screen; if the operator has to refer to paper-based inputs or take notes, these tasks require illuminance (general or local) over the task as specified above.

Workstations: since these are likely to require multiple tasks and working planes, lighting will need to be appropriate to the characteristics and duration of each task – hence careful task analysis is required for designing the lighting of workstations. Key factors to consider are:

- medium-height (1.5 to 1.8 m) partitions around workstations create shadows and reduce the illuminance on desk and bench areas
- countering this effect by increasing general lighting may have a high energy demand
- workstations are most suited to use of local lighting in conjunction with a relatively low level of general (environmental) lighting for circulation spaces.

Screen-based tasks: for adequate screen task visibility (which will be dependent on screen type and nature of images), visual comfort will depend mainly on:

- freedom from distracting reflections
- correct relationship between the illuminance of task surroundings and the task itself
- control of glare from luminaires and windows
- freedom from distractions in task surroundings (e.g. movement of people or objects).

3.3 Directional Effects of Lighting (including glare)

Glare is caused by an excess of light. Glare can cause eye fatigue/discomfort (also known as discomfort glare) and increasing amounts of glare can cause temporary vision impairment (also known as disability glare). Windows tend to be a more common source of glare than electric lighting. Techniques which can be used in order to avoid or minimise glare from windows include:

- Reducing window size;
- Tinting windows;
- Using curtains or other window coverings.

Electric lighting needs to be sufficiently flexible as previously discussed in order to allow for glare to be avoided or minimised. Where screen-based equipment is used, tasks require a direction of view closer to horizontal than for conventional desk work and so glare from lighting is of greater significance. AS1680.1 provides two alternative systems for control of discomfort glare:

- a luminaire selection system
- a glare evaluation system.

The latter is within the realm of indoor environment assessment, and provides a ***Unified Glare Rating*** that should be no greater than 19 for general offices:

$$\mathrm{UGR} = 8.\log\left(\frac{0.25}{L_\mathrm{b}}.\sum\frac{L^2.\omega}{p^2}\right)$$

where L_b is the background luminance (cd/m^2), L is the luminance of the luminous parts of each luminaire in the direction of the observer's eye (cd/m^2), ω is the solid angle of the luminous parts of each luminaire at the observer's eye (steradian), p is the Guth position index for each individual luminaire which relates to its displacement from the line of sight.

AS1680.1 notes that glare can be more significant where one or more of the following exist:

- the room is large (room index of 2 or more);
- visual tasks are difficult and require sustained attention;
- the direction of task view is at or above horizontal for significant periods;
- room surfaces/equipment are abnormally dark or poorly lit.

Note that this index was **not** used in this study when applied to building assessment. The MABEL team carrying out the assessment rejected the UGR as impracticable (Mark Luther, pers. Comm.), instead using a CCD camera based luminance mapping technology. This records the luminance distribution within the field of view. Weinold and Christoffersen (2006) noted that the UGR and similar ratings were inadequate since they were developed for small glare sources such as artificial lighting. They carried out experiments with occupants in offices with daylight glare from windows and confirmed that such ratings were poorly predictive of occupant assessments. Instead, they used CCD camera luminance mapping and a 'Daylight Glare Probability' rating (DGP) they developed from an existing discomfort glare algorithm and an empirical approach, as follows:

$$\mathrm{DGP} = 5.87 \times 10^{-5}E_\mathrm{v} + 9.18 \times 10^{-2}\log\left(1+\sum_i \frac{L_{\mathrm{s},i}^2\,\omega_{\mathrm{s},i}}{E_\mathrm{v}^{1.87}P_i^2}\right) + 0.16$$

where E_v is the vertical eye illuminance [lux]; L_s the luminance of source [cd/m^2]; v_s the solid angle of source; P is a position index. When applied to the comfort responses of 75 occupants and 349 different scenarios, they found a high level of correlation (R^2 = 0.94) between DGP and occupant dissatisfaction (Figure 3.1). Note however that this approach has not been applied to MABEL data, which has essentially been presented as a series of CCD images.

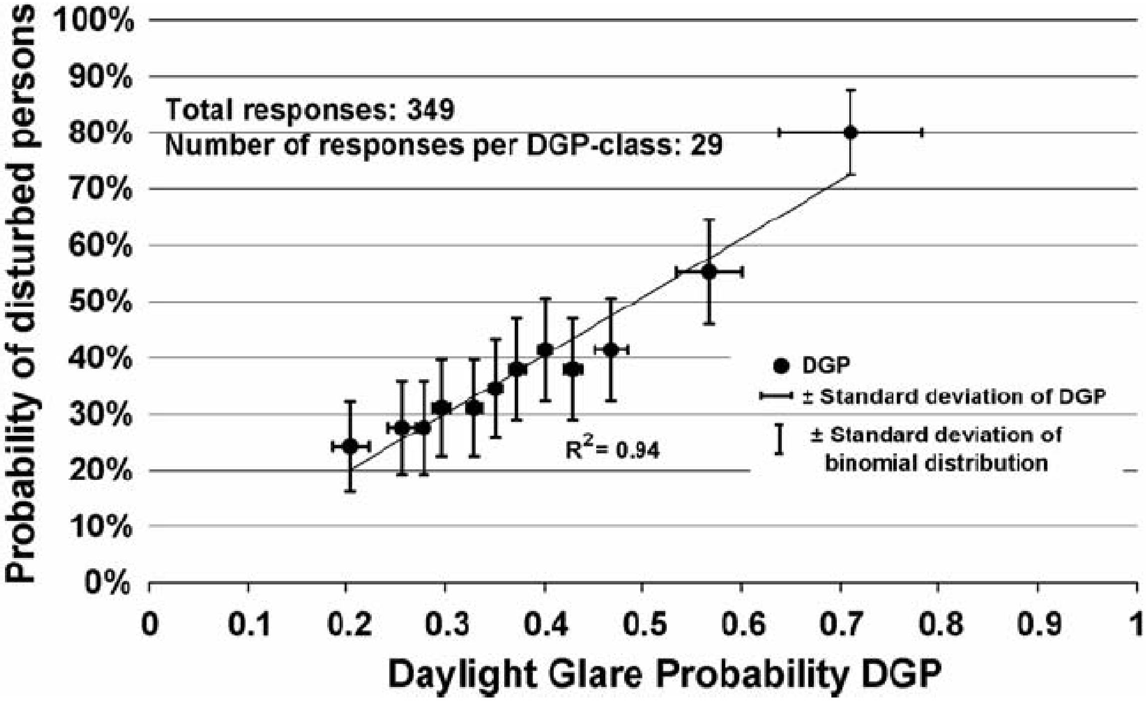


Figure 3.1 Correlation between Daylight Glare Probability and occupant dissatisfaction (Weinold and Christoffersen 2006).

3.4 Colour Temperature

The colour of light from a source is another point of consideration for the quality of the indoor environment. Colour temperature utilises the concept of a theoretical black body radiator. A black body radiator converts heat energy into electromagnetic radiation (light) and is 100% efficient. The colour temperature of a black body radiator is the temperature to which it must be heated in order to emit a certain colour of light. Many metals which are used to produce light in electric lights closely approximate the behaviour of a black body radiator. If a black body radiator is heated to approximately 3000 K, it emits light of a yellow-white colour, at 5000 K, it emits light of a blue-white colour. In general, rooms that are lit to less than or equal to 240 lx are best lit using an electric light that emits a warm colour temperature as listed in Table 3.2 (Australian Standard® 2659.1—1988, 1988).

Table 3.2 Colour appearance and colour temperature of electric lights

Colour Appearance	Correlated Colour Temperature (K)
Warm	< 3300
Intermediate	3300 ≤ 5300
Cold	> 5300

3.5 Ballast Flicker

Flicker from electric lights can cause eye fatigue and is distracting. The effectiveness of conversion of electrical energy to light energy depends upon the method used to produce electric light. The two methods used to produce light from electricity are incandescence and electrical discharge. Incandescence is produced by running electricity through a metal filament which creates enough heat to produce light. Electrical discharge lamps work by using a ballast to create and maintain an electrical arc through a gas which produces light (lightning is a natural source of this type of lighting). Figure shows which lamps depend upon which lighting method (Rusk, 2004).

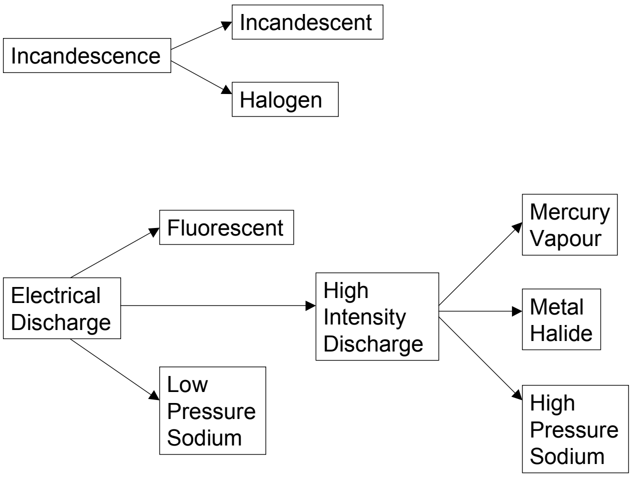


Figure 3.2 Classes of lamps

All electric lamps that depend upon the mains power supply are subject to flicker caused by alternating current. Flicker is most noticeable from electrical discharge lamps, most notably from fluorescent lamps. Electrical discharge lights use either an electronic or a magnetic ballast to supply enough voltage to allow current to flow. Magnetic ballasts do not change the input frequency of the power supply. Electronic ballasts can change the input frequency, which allows them to have the capability of changing the amount of flicker. It is recommended that fluorescent lighting have a high frequency (20 kHz – 60 kHz) electronic ballast. In addition to removing flicker, they are less likely to produce a high-pitched sound (Canadian Centre for Occupational Health and Safety, 2003). Standards Australia has recommended that lights that rely on electronic ballasts have ballast frequencies of between 20 kHz – 50 kHz, lower than this recommendation can cause a buzzing noise and higher than the recommendation can lead to interference with radio waves (Australian/New Zealand Standard™ 60929: 2000, 2001).

3.6 Lighting Measurement Protocol

Lighting measurements need to be made at one or more heights that are typical of viewing distance. Instruments used to measure light must receive only direct light. Recommended instruments used to measure light are a goniophotometer and a photometric integrator. Goniophotometers are used to measure light intensity in selected directions. Photometric integrators are used to measure light output ratios (Australian Standard® 1680.3 — 1991, 1991).

Illuminance measurements are required to be made at floor level on a horizontal plane along a uniformly distributed gridlines at points less than or equal to 1 m The first row of measurements are required to be taken at greater than or equal to 0.5 m. Exceptions are:

- Along a corridor which is less than or equal to 1.5 m width, measurements can be taken along one row in the centre;
- Rooms in which the floor area is less than 4 m^2, the measurement can be taken as close to the centre as possible; and
- Large areas in which the design is such that the lighting is sufficiently consistent so that representative measurements can be made by measuring a minimum of 20% of the floorspace (Australian/New Zealand Standard™ 1680.0: 1998, 1998).

Illuminance measurements must be adjusted and rounded with respect to any corrections required as a result of calibration (Australian/New Zealand Standard™ 1680.0: 1998, 1998).

4 SOUND COMFORT INDICATORS

The World Health Organisation (WHO) consider sound pressure level and sound level to be useful terms for assessing sound (Concha-Barrientos *et al.*, 2004). Sound pressure level is defined in terms of decibels (dB). A decibel is a measure of sound with respect to the root-mean-square pressure (P) created by the sound's air vibrations, compared to a reference pressure (P_0) and can be written as:

$$dB = 10 \log_{10}\left(\frac{P}{P_0}\right)^2$$

(r.m.s sound pressure levels are used as the average sound pressure level is 0 (Australian Standard® 2659.1—1988, 1988)). The reference pressure, P_0, is set at 20 µPa which is considered to be the threshold of human hearing (Australian Standard® 1259.2—1990, 1990) and causes a practically negligible pressure change which is enough to move the membrane in the human ear by a distance of less than the diameter of an atom (Australian Standard® 2659.1—1988, 1988).

Table 4.1 provides the numerical values of sound pressure that are associated with different sources of sound (Henderson, 2004).

Table 4.1 Sound pressure levels of different sources

Source	Sound Pressure Level (dB)
Threshold of Hearing	0
Whisper	20
Normal Conversation	60
Walkman at Maximum Level	100
Threshold of Pain	130
Instant Eardrum Perforation	160

Sound level is defined in terms of the frequency over which humans are generally capable of hearing, which ranges from 20 Hz to 20 kHz and the greatest sensitivity is to frequencies in the approximate range of 1 kHz to 5 kHz (Australian Standard® 2659.1—1988, 1988). An 'A-filter' or 'A-weighting' is used to label sound over the frequencies of 20 Hz to 20 kHz and the units used to describe sound level are dB(A). Populations which are exposed to 37 dB(A) for one year experience annoyance which deteriorates to severe annoyance at 42 dB(A) after one year of exposure.

Equivalent continuous A-weighted sound pressure levels ($L_{Aeq,T}$) is a term that is used to indicate the sound level over a defined number of hours. For sound that is encountered during working hours, usually an 8 hour day, the continuous A-weighted sound pressure level is denoted by $L_{Aeq,\,8h}$. Equivalent continuous A-weighted sound pressure levels can be calculated using the following equation:

$$L_{Aeq,T} = 10 \log_{10}\left\{\left(\frac{1}{T}\int_{t_1}^{t_2} p_A^2(t)dt\right)/p_0^2\right\} dB(A)$$

$L_{Aeq,\,T}$ is the equivalent continuous A-weighted sound pressure level over a specified time (T), such that $T = t_2 - t_1$

p_A (t) is the instantaneous A-weighted sound pressure of the sound signal

p_0 is the reference sound pressure of 20 µPa (Australian Standard® 1259.2—1990, 1990).

4.1 Sources of Sound in an Office Environment

4.1.1 Background Sound

Background sound tends to be of a low intensity and is present for most of the time. Sources of background sound in an office include: computers, lights and ventilation systems. Excessive amounts of background sound can cause stress which can impede upon an individual's ability to work well. The UK's Sustainable Development Unit recommend that separate rooms/offices should have an $L_{Aeq,T}$ value of less than 40 dB(A) and an open plan office should have an $L_{Aeq,T}$ value of less than 45 dB(A) (UK Government, 1999).

Apart from $L_{Aeq,}$ measurements, other measurements used to evaluate background sound are L_{10} and L_{90}. L_{10} is the A-weighted sound level that occurred for equal to or greater than 10% of the time that the measurement was made (≥ 90% for L_{90}).

4.1.2 Impact Sound

Impact sound is of a high intensity but lasts for only a short amount of time. Impact noise within in an office can come from sources such as electric staplers or doors slamming. It's highly unlikely that sounds that occur within an office environment can cause damage to hearing.

The Victorian Workcover Authority and version No. 001 of the Victorian Occupational Health and Safety (Noise) Regulations 2004 state that the sound exposure standard should not exceed 85 dB(A) referenced to 20 µPa at an employees ear position over eight hours (WorkSafe Victoria Victorian Workcover Authority, 2004; Victorian Government, 2004).

4.2 Control of Office Noise

Sound from sources that are used in an office, such as printers and photocopiers, can be minimised by keeping them in a separate room. The WHO recommend that excessive sound should be controlled in order: (a) reducing the sound source, (b) reducing the sound propagation and finally (c) reducing the sound amongst workers (Concha-Barrientos *et al.*, 2004). Table 4.2 lists recommended A-weighted equivalent design sound levels (Australian Standard® 2822—1985, 1985). The satisfactory design sound level is the amount of sound which is satisfactory for most people, the maximum design sound level is that which causes most people to be dissatisfied.

Table 4.2 Recommended A-weighted equivalent design sound levels and reverberation times for different uses within buildings

Occupancy type	**Recommended design sound level $L_{Aeq,T}$, dB(A), (Satisfactory – Maximum)**	**Recommended reverberation time(s)**
Board and conference rooms	30 – 40	0.6 to 0.8
Cafeterias	45 – 50	*
Call centres	40 – 45	0.1 to 0.4
Computer rooms	45 – 50	*
Corridors and lobbies	45 – 50	0.4 to 0.6
Design offices	40 – 45	0.4 to 0.6
Draughting offices	40 – 50	0.4 to 0.6
General office areas	40 – 45	0.4 to 0.6
Private offices	35 – 40	0.6 to 0.8
Public spaces	40 – 50	0.5 to 1.0
Reception areas	40 – 45	*
Rest rooms and tea rooms	40 – 45	0.4 to 0.6
Toilets	50 – 55	—
Undercover carparks	55 – 65	—

* It is recommended that reverberation time be minimised as much as possible.

Table 4.2 also presents recommended reverberation times for spaces. Reverberation time is the amount of time required for reverberant sound pressure to decay within an enclosure by 60 dB and is symbolised by RT(60) (Australian Standard® 2822—1985, 1985). A **lowe**r reverberation time indicates a quieter environment and such environments tend to house materials which are relatively effective at absorbing sound. The recommended reverberation times given in Table 4.2 (Australian Standard® 2822—1985, 1985) refer to medium sound frequencies (for example, 500 Hz) and for a room of relatively standard volume.

Note that the sound levels recommended in Table 4.2 are for a non-occupied office with building service equipment in operation, i.e. it is directed at estimating the background noise from the latter. In practice there will be additional sources of background noise in an office, such as city traffic, office equipment and occupants themselves. For such a scenario, the effect of background noise on the ability to carry out a conversation could be considered. This factor is well understood (USEPA 1974), as presented in Figure ... This shows that the highest noise level that permits relaxed conversation with 100% sentence intelligibility throughout a room is 45 dBA, but that 99% intelligibility occurs at ~55 dBA.

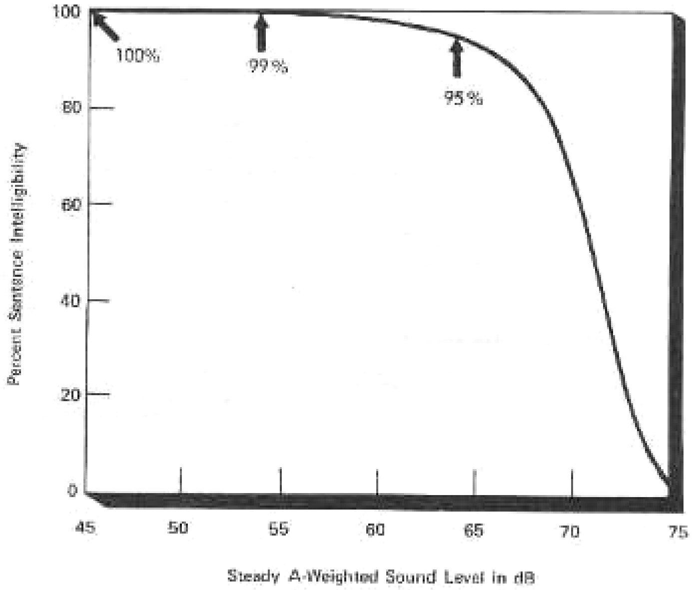


Figure 4.1 Speech intelligibility indoors at different levels of background noise (USEPA 1974)

4.3 Sound Measurement Protocol

Measurements need to be taken the during the same times and in the same spaces which are representative of when and where people will be located and by ensuring that there is no bias resulting from an excess or deficiency of reflective surfaces such as furniture. Recommended measurement positions are a minimum of 1 m from walls, 1.2 m to 1.5 m above the floor and about 1.5 m from windows (Australian Standard® 2659.1—1988, 1988). The microphone and instrument case need to be placed on an angle specified by the manufacturer which allows the sound level meter to be optimally responsive regardless of the sound's angle of incidence (Australian Standard® 1259.1—1990, 1990).

In order to check the ambient sound level of a completed, fitted building, L_{Aeq} measurements should be taken while the space is not occupied and for enough time to ensure that sources of sounds have been located. Operating conditions (for example, air conditioning, occupied neighbouring spaces of the building, windows open or closed as normal) of the building should be representative of normal use. Measurements should be taken in the spaces which are considered to be representative of where occupants will spend the majority of time and during the same times in which the building will be used- this is done so that outside traffic noise- which can vary noticeably with time is correctly taken into consideration (Australian Standard® 2822—1985, 1985).

5 OCCUPANT FEEDBACK ON ENVIRONMENTAL COMFORT

An environmental tool that has been used with some success in IAQ comfort studies is the occupant questionnaire. Applied to a statistically significant sample of occupants (approx. 30), it provides a direct measure of the comfort levels experienced by the occupants. CSIRO derived a questionnaire from the 'office environment survey' developed by Raw (1995) for the UK Health & Safety Executive. Elements of this questionnaire are shown below (

Table 5.1 and Table 5.2

Table 5.1 Workplace environmental comfort survey part one

WORKING CONDITIONS
Is your work space cramped?
Are you within sight of an external window?
In your work space can you change - temperature?
- ventilation?
- lighting?
Is your work space regularly cleaned?
Is your work station comfortable?
Are you satisfied with your overall work conditions?
On average, how many hours per day do you operate a VDU? ______ hours

INDOOR CLIMATE During *the past two months* have you had *any discomfort at your place of work* from any of the following conditions?

Temperature too high	**Most days**	**Weekly**	**Less often**	**Never**
Temperature too low				
Temperature variable during day				
Draughts				
Humid air				
Dry air				
Stuffy air				
Unpleasant smell				
Tobacco smoke				
Dust & dirt				
Poor lighting (dim, glare, flickering)				
Noise (from traffic or from building)				
Static electricity, electric shock				
Other (specify) …………………………………				

Table 5.2 Workplace environmental comfort survey part two

SYMPTOMS OR COMPLAINTS During the past two months have you experienced episodes of the following symptoms or complaints at work? (Please cross one box per symptom and then indicate if symptom is reduced when away from the office; answer NO if you are undecided).

	Most days	**Weekly**	**Less Often**	**Never**	**If experienced, was symptom reduced away from office?**	
					Yes	**No**
Irritation/watering of eyes						
Dry eyes						
Irritation/running of nose						
Blocked or stuffy nose						
Hoarse, dry or sore throat						
Chest tightness/breathing difficulty						
Flu-like symptoms (including aches in limbs and/or fever)						
Rash or irritated skin						
Dry skin						
Headache						
Feeling lethargic or very tired						

Note that this is NOT a productivity survey – it is an instrument to determine the levels of comfort (or dissatisfaction) that occupants express for their working environment.

6 FEATURES OF CH1 AND CH2 INFLUENCING IEQ ASSESSMENT

6.1 Sub-floor Ventilation

Leite and Tribess (2003) showed that occupants of an environmental chamber were thermally comfortable to ISO 7730-1994 *when sub-floor air supply was used* for the climate of Sao Paulo, Brazil. Thermal gradients were small (< 3 °C), air velocities were low (< 0.1 m/s) and floor temperatures were not perceived as cold. They recommended the thermal comfort parameters of Table 6.1 for such office buildings.

Table 6.1 Thermal comfort parameters for office buildings with sub-floor air supply

Variable	**Winter**	**Summer**
Clothing, I_{cl} (clo)	$0.7 \leq I_{cl} \leq 1.1$ clo	$0.5 \leq I_{cl} \leq 0.7$ clo
Operative temperature, t_0 (ºC)	22 – 24	23 – 26
Air velocity, V_a (m/s) (at 1.10 m level)	$V_a \leq 0.1$	$V_a \leq 0.1$
Relative humidity, (RH) (%)	40 – 60	40 – 60

Note that these operative temperatures vary little from the Category B thermal comfort level of typical offices (Table 2.5) of 20-24ºC (winter) and 23-26ºC (summer). It is assumed here that equivalent levels of thermal comfort will result at the same operative temperatures whether ventilation is sub-floor or (the more typically used) dilution.

As discussed with Figure 2.4, sub-floor ventilation will lead to a lower turbulence factor than mixed, dilution ventilation systems, and for the former a higher air velocity can be tolerated before draft discomfort is worsened. Local air velocities of 0.1-0.2 m/sec can still provide Category A or B performance with sub-floor ventilation systems.

6.2 Interactive Effects of IEQ Factors

The IEQ factors discussed here have been considered in isolation for their impacts on occupants. While interactive effects may occur (and are known to occur) they are beyond the scope of this study.

An interactive effect of indoor air pollutants and indoor air temperature has been shown with exposure to a VOC mixture and different air temperatures, these influencing nasal volumes, sensory irritation and comfort (Jorgensen *et al*. 1993). More recently, Fang *et al*. (2004) investigated the rating of 'perceived air quality' by female office workers exposed for 6 hour periods to a range of T/RH conditions and different ventilation rates (10 or 3.5 L/s/person). They confirmed the previously found correlation between acceptable perceived air quality and enthalpy (Figure 6.1). They also observed that the decrease in perceived air quality when ventilation rate was decreased could be counteracted by decreasing T/RH from 23°C/50% RH to 20°C/40% RH.

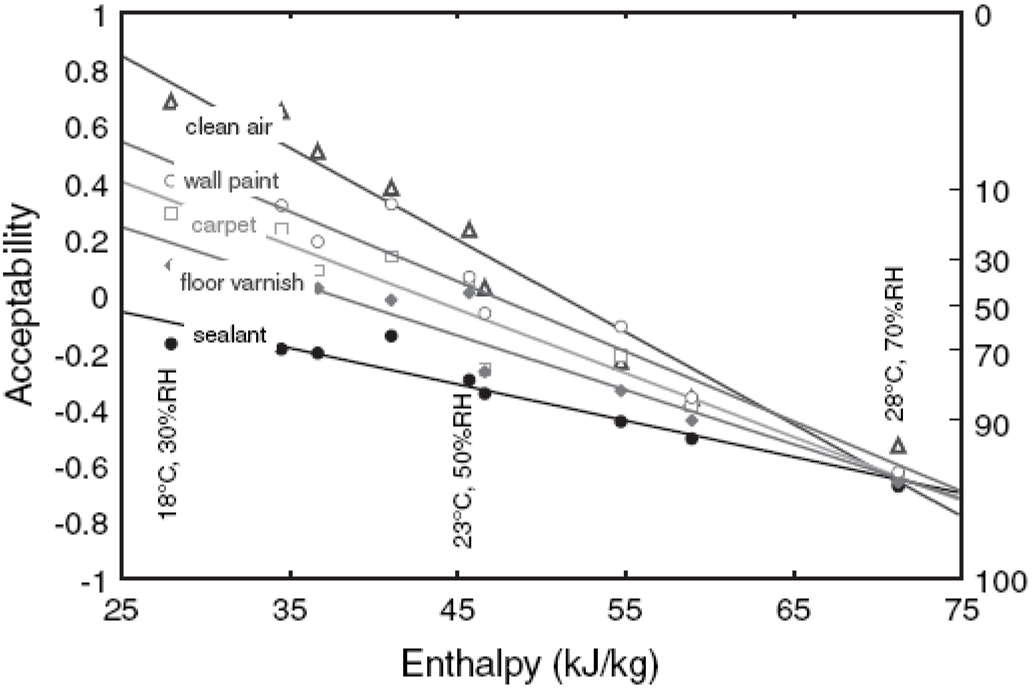


Figure 6.1 Linear correlation between acceptability and enthalpy of five air samples – clean outdoor air and air polluted by wall paint, carpet, floor varnish and sealant

6.3 Plan for Measurement of CH1 and CH2

Melbourne City Council has an existing office building in Melbourne city centre, referred to as Council House 1 (CH1), which was constructed in 1970 (Figure 6.2). The building has three floors of car park, each partially enclosed, for 230 cars, a retail area of $400m^2$, offices on seven floors each of $1070m^2$ per floor totalling $7490m^2$, and a roof level plant room. The structure is a concrete sway frame with horizontal bracing required at gable ends or between columns in one southern bay. The core walls are not structural. Floor to floor height is 3150mm with a slab thickness of 235mm, with a down-stand beam in the core area of 465mm which gives a clearance of 2450mm. There is an up-stand beam around the perimeter of 560mm.

Windows are formed within pre-cast façade units of size 3150mm H X 1565mm W and have a glass area of 2110mm H X 1380mm W. This gives a glass area of 69% of the total façade area. The west side glass is treated with a reflective film which is de-laminating. The roof covering needs replacing and the lower basements leak badly. All service installations were considered in need of replacement. A NABERS assessment of the building had been carried out separately for MCC and showed poor performance on energy/greenhouse, stormwater run-off and pollution, landscape diversity and toxic materials (no indoor air assessment provided). While not formally assessed, it is considered unlikely the building would achieve a “B Grade” office standard. It **was** planned that CH1 would be upgraded and refurbished to an “A grade” standard in 2006. An IEQ assessment plan was developed for Levels 1, 4 and 6 of CH1 based on the above discussion, and these were carried out in July 2005 and February 2006.

Figure 6.2 Exterior of CH1 building

However the Council decided not to implement the CH1 refurbishment and so a replacement MCC building, Council House 2 (CH2), was used as a surrogate for CH1. The CH2 building was designed and built with a specific focus on sustainability and provision of a high quality indoor environment for occupants, similar to planning for CH1. CH2 consists of shops at ground level (with own ventilation systems) and nine office levels housing approximately 540 staff, including approximately one-half of the staff relocated from CH1. CH2 was designed as a benchmark sustainable building and was the first building in Australia to receive a 6-star design rating from the Australian Green Building Council. Key features of CH2 included:

- a sewer mining plant to deliver up to100,000 litres of recycled water per day (note this had not yet started operating at the time of IEQ assessments)
- a low energy cooling system based on phase-change material
- vaulted concrete ceilings to improve air circulation, cooling and natural light, with ceiling mounted chillers
- automatic windows that open at night to cool the building in summer (these operated when the concrete slab ceilings exceeded 21°C and the outside temperature was ≥2 °C below that of the concrete ceiling)
- 100% fresh-air supply, nominally at 2 air changes per hour, from floor vents in a suspended floor plenum (operated on a timer with 1 h in front of occupant arrival and 1 h after departure)
- a CO2 monitoring system to control ventilation rate to keep it below 800 ppm
- a facade of louvres to track the sun and shade the Western side
- roof-mounted wind turbines to draw hot air out of the building
- use of low-emission fit-out materials (the major interior surface was uncoated concrete, with some areas of paper gypsumboard painted with low-emission paint; mechanically fixed carpet tiles were used throughout; most office furniture was powder-coated low emission MDF and low-emission plywood sealed with a water-based lacquer)
- an open-plan office lay-out, common for both staff and managers.

CH2 (Figure 6.3) was occupied by MCC staff in October 2006 and 'tuning' of the operation of the building was considered to be a requirement by the building designers over its first few months of occupancy. Hence CSIRO could not assess IEQ until March 2007 (summer) and August 2007 (winter), 5 and 10 months after occupancy. These IEQ assessments were performed identically to those of CH1 but were carried out for CH2 on Levels 2, 6 and 8. Note that the first assessment would ideally have been carried out within 1 month of occupancy when VOC and formaldehyde pollution are expected to be greatest (Brown 2002). Also of special significance was the upgrading of the lighting system the month before the August 2007 assessment, by adding extra strip lighting and adjusting light levels to suit workstations.

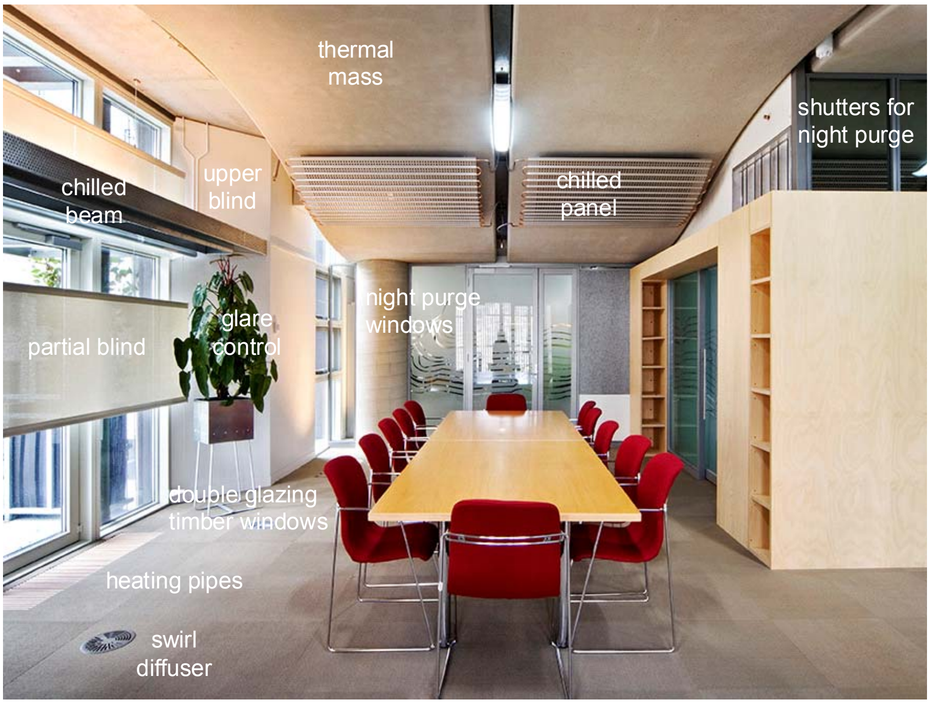


Figure 6.3 Interior view of CH2 building (source: MCC report)

The focus of measurements in CH1 and CH2 were the indoor environments of the 7 and 9 storeys, respectively, of offices, though the impacts from surrounding environments (e.g. car exhausts from enclosed car parks on lower levels; noise from outside traffic or other external operations) were considered in design of the measurement protocol.

It was considered that IEQ assessment of offices should be carried out with the following over-arching guidelines:

- Assessment only during working hours with the building occupied
- Assessment both before and after refurbishment
- Each assessment to be duplicated for two seasons (summer and winter), the first being as close as possible to the building refurbishment,
- Provided that all levels of offices had a common air supply system and occupants had similar tasks/activities, measurements to be made on 3 levels (approximately bottom, mid- and top levels) over 5-8 consecutive work days,

Measurements should be made at two distant locations on each level, with duplicate measurement of these locations on separate days.Assuming that the 6 or 9 storeys of offices have the same air supply system (whether mechanically conditioned or by mixed mode) and have similar tasks/activities, the following measurements and criteria are recommended (Table 6.2) for characterisation of the indoor environment quality:

Table 6.2 Recommended measurements for CH1 and CH2

IEQ Factor	**Measurement location(s)* CH1/CH2**			**Sampling Period in Working Shift (h)**	**Criteria for high performance rating (levels not to be exceeded for time averages specified)**
	Office Levels	**Loc-ations /Level**	**Out-door**		
Indoor Air Quality					
TVOC	1,4,6/2,6,8	2	1	1	500 µg/m^3 (1 h)
Benzene	1,4,6/2,6,8	2	1	1	10 µg/m^3 (1 h)
Toluene	1,4,6/2,6,8	2	1	1	4100 µg/m^3 (1 h)
Formaldehyde	1,4,6/2,6,8	2	1	0.5	100 µg/m^3 (0.5 h)
PM2.5	1,4,6/2,6,8	2	1	8	25 µg/m^3 (8 h)
CO	1,4,6/2,6,8	2	1	8	9 ppm (8 h), 25ppm (1 h)
CO_2	1,4,6/2,6,8	2	1	8	800 ppm (1 h)
Microbial	1,4,6/2,6,8	20	-	-	none visible/no moisture
Thermal Comfort**					
Operative T	1,4,6/2,6,8	5+	1	8 (total per level)	Figure 2.1 or Figure 2. (90%)
Air velocity	1,4,6/2,6,8	6+	-	2 min	0.05 – 0.2 m/s
RH	1,4,6/2,6,8	2	1	8	40-70% (1 h)
Thermal gradient (0.1 – 1.7 m)	1,4,6/2,6,8	6+	-	2 min	3 °C
Floor T	1,4,6/2,6,8	6	-	2 min	19 – 29 °C
Radiant T asymmetry (0.1 – 0.6 m)	1,4,6/2,6,8	5	-	2 min	warm ceiling < 5 °C cool wall < 10 °C cool ceiling < 14 °C warm wall < 23 °C
Lighting					
Illuminance (min)	1,4,6/2,6,8	6+	-	2 min	160 lx
Task illuminance	1,4,6/2,6,8	8	-	2 min	160 – 600 lx (Table 3.1)
Glare	1,4,6/2,6,8	4	-	2 min	UGR < 19
Noise					
Amb. office noise	1,4,6/2,6,8	5+	-	1 h	40 – 45 dB(A)
Reception area	1,4,6/2,6,8	1	-	1 h	40 – 45 dB(A)
Public spaces	1,4,6/2,6,8	1	-	1 h	40 – 50 dB(A)
Occupant Comfort Survey					
	1,4,6/2,6,8	30	-	4 h	20% complaint rate

* Measurements aimed to be carried out in low-, mid- and upper-Levels of each building

** Thermal Comfort measurements to be at a minimum:

- in the centre of the room or zone
- 1.0 m inwards from the centre of each of the room's walls (for walls with windows, 1.0 m from the centre of the largest window)
- locations where the most extreme thermal values may occur (near windows, diffusers, corners)
- humidity need be determined at only one location and any height within the occupied zone unless there is reason to expect large variation across the zone
- air T and speed shall be measured at 0.1, 0.6 and 1.1 m heights for seated occupants, and at 0.1, 1.1 and 1.7 m for standing occupants; operative T shall be measured or calculated at 0.6 m for seated occupants and 1.1 m for standing occupants
- radiant asymmetry shall be measured at 0.6 m high for seated and 1.1 m high for standing occupants.

7 INDOOR ENVIRONMENT QUALITY MEASUREMENTS IN CH1, PRE-REFURBISHMENT, WINTER 2005/SUMMER 2006

IAQ measurements in CH1 were reported to MCC in two reports, both provided in Appendix A to this document. These reports should be referred to for sampling and analysis methodologies which were consistent across all assessments of CH1 and CH2. General findings for IAQ in CH1 were:

1. There was a high level of consistency found according to season for both indoor air pollutant concentrations and occupant perceptions of indoor environments.
2. CO2 levels ranged from 560-710 ppm, much below the criterion 800 ppm, indicating that ventilation was adequate to remove occupant odours.
3. **Most IAQ measures were within the recommended criteria, except for formaldehyde concentration and the occupant comfort survey, in particular on Level 6**.
4. **Formaldehyde concentrations on Level 6 exceeded the IAQ criterion,** especially in summer, but no specific source for the formaldehyde could be identified and it was concluded that there were dispersed formaldehyde sources (e.g. office furniture, wall partitions) on this Level.
5. VOCs, formaldehyde, fungi/bacteria and fine particles ($PM_{2.5}$) were present in CH1, while ozone from office equipment and carbon monoxide were not detected. Indoor air concentrations of VOCs and formaldehyde exceeded those outdoors, showing there were indoor sources for these pollutants. Fungi and $PM_{2.5}$ were much lower indoors than outdoors, by a factor of 10- to 20-fold, showing there to be no indoor sources and significant cleaning of intake air due to filtration by the mechanical ventilation system.
6. Similar indoor air VOCs were observed in both seasons and there was no specific and consistent trend in the VOC concentrations according to the location or Level sampled. This was considered to indicate that VOC sources within CH1 were uniformly dispersed through the building. Sources for the VOCs were not known, though several were considered to originate with outdoor air used to ventilate the building (e.g. benzene, hexanal, benzaldehyde and 1,2,4-trimethylbenzene), others (ethanol, acetone, and limonene) were clearly indoor source related (probably from consumer products used by occupants), and some (toluene and xylene) were contributed to by indoor sources and outdoor air.
7. Indoor formaldehyde concentrations showed a trend in both seasons for increased formaldehyde concentrations at higher building Levels (Table 7.1), but this was not found to be significant ($p \leq 0.05$). However a seasonal effect was significant for Level 4 and near-significant for Level 6, for higher formaldehyde levels in summer. This effect could be related to the higher indoor temperature/humidity in summer c.f. winter since this factor is known to increase formaldehyde emissions from wood-based panels.

Table 7.1. Averaged formaldehyde concentrations in CH1 with testing of statistical significance.

Level	Winter Average (μg/m³)	Summer Average (μg/m³)	t-test Significance for		
			season	Comparison to level 6	
				winter	summer
1	27±7	42±15	0.22	0.11	0.08
4	42±10	63±9	0.04	0.34	0.12
6	63±29	110±35	0.06	-	-
roof	<10	17±1	-	-	

8. **The occupant survey found that there were climate problems in CH1 from (in decreasing prevalence): air stuffiness, poor temperature control, dry air, lighting and noise.** Lighting and noise were considered poor at approximately one-half the prevalence reported for the other problems.
9. **Higher frequencies of occupant reported symptoms were observed on Level 6 than other Levels, more so in summer, consistent with the higher formaldehyde**

concentration observed on this Level. The most prevalent daily/weekly symptoms on Level 6 in summer were dry eyes (39%), lethargy/tiredness (36%), dry skin (20%), blocked nose/sore throat (16-19%), headache (12%) and chest tightness (8%).

In summary, while most of the air pollutants in CH1 occurred at concentrations much below the IAQ criteria, indoor air quality in CH1 was compromised by elevated formaldehyde concentrations, especially on Level 6. Occupant feedback on comfort and reported symptoms were consistent with the latter, indicating that the formaldehyde pollution exerted an effect on the occupants.

MABEL reports on thermal comfort, lighting and noise for CH1 are presented in Appendix B. Note that MABEL assessments typically use default values of clothing (0.7 clo) and metabolic rate (1.0 met) to estimate whole body predicted percentage dissatisfied (PPD) in both winter and summer. This approach differs from that recommended by ISO (2005) which recommended default values of 0.5clo/1.2met (summer) and 1.0clo/1.2met (winter). This difference can exert a significant effect on PPD estimates and so CH1 data was assessed using both approaches. Table 7.2 compares the PPD estimates based on MABEL and ISO defaults. It is seen that while the ISO defaults showed CH1 had high quality thermal comfort in winter (all Levels) and summer (Level 1), the MABEL defaults indicated reduced thermal comfort. Both defaults predicted dissatisfaction for Levels 4 and 6 in summer, though the MABEL defaults tended to underestimate the dissatisfaction. It is concluded that the MABEL default values can exert a large influence on the thermal comfort assessment c.f. the ISO defaults, and that the latter must be used in design specifications, unless site-specific clo and met values are estimated. The data and findings presented here will be based on the ISO defaults.

Table 7.2. Comparison of thermal comfort assessment of CH1 using MABEL defaults and ISO defaults for clo and met

			MABEL Defaults	**ISO Defaults**			
Building Level	Year	Meast Location	**PPD (avg of 3 hts)**	PPD high	PPD mid	PPD low	**PPD (avg of 3 hts)**
CH1-1	**Win 2005**	**Core**	**0.12**	**0.06**	**0.05**	**0.05**	**0.05**
		1A	**0.09**	**0.07**	**0.06**	**0.05**	**0.06**
		1B	**0.10**	**0.07**	**0.06**	**0.05**	**0.06**
		1C	**0.11**	**0.06**	**0.05**	**0.05**	**0.05**
		1D	**0.09**	**0.06**	**0.05**	**0.05**	**0.06**
		1E	**0.10**	**0.07**	**0.05**	**0.05**	**0.06**
		1F	**0.13**	**0.05**	**0.05**	**0.05**	**0.05**
CH1-4	**Win 2005**	**Core**	**0.05**	**0.10**	**0.09**	**0.08**	**0.09**
		4A	**0.07**	**0.06**	**0.05**	**0.05**	**0.05**
		4B	**0.07**	**0.05**	**0.06**	**0.05**	**0.05**
		4C	**0.07**	**0.07**	**0.07**	**0.06**	**0.07**
		4D	**0.07**	**0.07**	**0.07**	**0.07**	**0.07**
		4E	**0.07**	**0.08**	**0.07**	**0.06**	**0.07**
CH1-6	**Win 2005**	**Core**	**0.14**	**0.05**	**0.05**	**0.05**	**0.05**
		6A	**0.07**	**0.08**	**0.07**	**0.06**	**0.07**
		6B	**0.13**	**0.05**	**0.05**	**0.06**	**0.05**
		6C	**0.13**	**0.05**	**0.05**	**0.05**	**0.05**
		6D	**0.09**	**0.06**	**0.05**	**0.05**	**0.05**
		6E	**0.09**	**0.06**	**0.06**	**0.05**	**0.06**
CH1-1	**Sum 2006**	**Core**	**0.06**	**0.07**	**0.06**	**0.06**	**0.06**
		1A	**0.15**	**0.07**	**0.06**	**0.05**	**0.06**
		1B	**0.12**	**0.05**	**0.05**	**0.05**	**0.05**
		1C	**0.16**	**0.06**	**0.06**	**0.06**	**0.06**
		1D	**0.09**	**0.05**	**0.05**	**0.05**	**0.05**
		1E	**0.12**	**0.06**	**0.05**	**0.06**	**0.06**
		1F	**0.11**	**0.05**	**0.05**	**0.05**	**0.05**
CH1-4	**Sum 2006**	**Core**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
		4A	**0.15**	**0.12**	**0.10**	**0.09**	**0.10**
		4B	**0.08**	**0.25**	**0.22**	**0.27**	**0.25**
		4C	**0.12**	**0.17**	**0.15**	**0.17**	**0.16**
		4D	**0.11**	**0.11**	**0.10**	**0.10**	**0.10**
		4E	**0.12**	**0.14**	**0.11**	**0.10**	**0.12**
CH1-6	**Sum 2006**	**Core**	**na**	**0.05**	**0.06**	**0.05**	**0.05**
		6A	**0.10**	**0.10**	**0.11**	**0.15**	**0.12**
		6B	**0.15**	**0.14**	**0.17**	**0.24**	**0.18**
		6C	**0.17**	**0.22**	**0.19**	**0.22**	**0.21**
		6D	**0.06**	**0.09**	**0.07**	**0.07**	**0.08**
		6E	**0.13**	**0.13**	**0.16**	**0.19**	**0.16**

General MABEL findings for CH1 were:

1. While measurements did not include floor temperature measurements, but it is considered likely the Category A criterion was achieved because internal temperatures were well within the range given in Table 2.7. The air velocities in both buildings were generally in the range 0.05-0.10m/sec and horizontal radiant temperature asymmetry was <14°C. Similarly, the vertical temperature difference was always below 2°C, a Category A classification (Table 2.6). Hence, thermal comforts from Draft Rating, Radiant Asymmetry and Vertical Temperature Difference were within Category A for both seasons. The key metric for thermal comfort assessment of CH1 was the whole body PPD as presented in Table 7.2.
2. Whole body thermal comfort in Winter exhibited low dissatisfaction values (PPD ~5%) for all Levels, i.e. CH1 had a high quality thermal comfort environment. In comparison, Summer thermal comfort was high quality on Level 1 but not Levels 4 and 6 where PPDs of 10-20%

were found for sites around the building perimeter, generally because operative temperatures were low . Occupant questionnaire responses showed high levels of complaint of **daily** temperature variability in both winter (38% complaint) and summer (27% complaint).

3. Task illuminance exceeded 160 lux in all cases, showing that background illuminance met the criterion (Table 6.2), but the reading/writing/typing target of 320 lux was not achieved at many locations in Winter, with a bias to lower illuminances at lower Levels, probably due to lower daylight penetration in this season (Table 7.3). By comparison, task illuminance in Summer generally achieved the 320 lux target. However, the occupant questionnaire found a low level of dissatisfaction (daily/weekly incidence) with lighting for each Level and each season (12-17% in Winter; 0-17% in Summer).
4. The background **office activity** noise was low for the open office areas, probably due to the highly sound absorbing environment which contributed to a 'dead' acoustic quality. Reverberation times showed that there was little to no reverberation within the large open office environments. Work area measurements in the occupied office, an 'active environment' with people conversing, ranged from 42-55 dBA (ave±SD = 50.0±3.2 dBA) with no trend according to building Level or season. Generally, the criterion level of 40-45 dBA was exceeded, but this is for buildings that are operating but **unoccupied**. It is estimated from Figure 4.1 that speech intelligibility of 99% would be achieved in CH1, and this is considered a more realistic criterion for noise assessment of this occupied space.

In overview, CH1 was considered to exhibit poor indoor air quality due to formaldehyde (especially on Level 6), though **all** other air quality metrics were acceptable. Thermal comfort, noise and lighting exhibited a range of qualities, from moderate to good, and the occupants exhibited continuous, frequent complaints of stuffy air and temperature variability (both too hot and too cold). In both seasons, occupants reported high (20-30%) symptom prevalence related to their occupancy of the building for dry eyes, lethargy/tiredness and headache, with greatest prevalence on Level 6. Notably, this Level had the highest formaldehyde levels, exceeding recommended criteria in summer.

Table 7.3. Task illuminace performances in CH1 and CH2

Building	Level	% Measurements > 320 lx	
		Winter	Summer
CH1	1	42	86
	4	67	86
	6	87	100
CH2	2	5	33
	6	33	33
	8	17	11

8 INDOOR ENVIRONMENT QUALITY MEASUREMENTS IN CH2, SUMMER & WINTER 2007

It was originally planned that CH1 would have IEQ re-assessed after refurbishment. However, Melbourne City Council decided not to implement the refurbishment and so a replacement MCC building, Council House 2 (CH2), was used as a surrogate for CH1. The CH2 building was designed and built with a specific focus on sustainability and provision of a high quality indoor environment for occupants, similar to planning for CH1. CH2 consisted of shops at ground level (with own ventilation systems) and nine office levels housing approximately 540 staff, including approximately one-half of the staff from CH1. An IEQ assessment identical to that of CH1 was carried out for CH2 on Levels 2, 6 and 8. CH2 was designed as a benchmark sustainable building and was the first building in Australia to receive a 6-star design rating from the Australian Green Building Council. Key features of CH2 included:

- a sewer mining plant to deliver up to100,000 litres of recycled water per day (note this had not yet started operating at the time of IEQ assessments)
- a low energy cooling system based on phase-change material
- vaulted concrete ceilings to improve air circulation, cooling and natural light, with ceiling mounted chillers
- automatic windows that open at night to cool the building in summer (these operated when the concrete slab ceilings exceeded 21°C and the outside temperature was ≥2 °C below that of the concrete ceiling)
- 100% fresh-air supply, nominally at 2 air changes per hour, from floor vents in a suspended floor plenum (operated on a timer with 1 h in front of occupant arrival and 1 h after departure)
- a CO2 monitoring system to control ventilation rate to keep it below 800 ppm
- a facade of louvres to track the sun and shade the Western side
- roof-mounted wind turbines to draw hot air out of the building (believed to not be operating at the time of IEQ assessment)
- use of low-emission fit-out materials (the major interior surface was uncoated concrete, with some areas of paper gypsumboard painted with low-emission paint; mechanically fixed carpet tiles were used throughout; most office furniture was powder-coated low emission MDF and low-emission plywood sealed with a water-based lacquer)
- an open-plan office lay-out, common for both staff and managers.

CH2 was occupied by MCC staff in October 2006 and ‘tuning’ of the operation of the building was considered to be a requirement by the building designers over its first few months of occupancy. Hence it was not possible to assess IEQ until March 2007 (summer) and August 2007 (winter), 5 and 10 months after occupancy. Note that the first assessment would ideally have been carried out within 1 month of occupancy when VOC and formaldehyde pollution are expected to be greatest (Brown 2002). Also of special significance was the upgrading of the lighting system the month before the August 2007 assessment, by adding extra strip lighting and adjusting light levels to suit workstations.

General IAQ findings for CH2 were:

1. There was a high level of consistency found according to season for both indoor air pollutant concentrations and occupant perceptions of indoor environments (i.e. there was little seasonal effect on the measurements)
2. **All IAQ measures were within the recommended criteria, with the formaldehyde concentration being much lower than levels normally seen in office buildings (such as found in CH1) probably due to the low-emitting office furniture used**
3. CO2 levels ranged from 500-690 ppm, below the criterion 800 ppm, indicating that ventilation (based on 100% fresh air) was adequate to remove occupant odours
4. VOCs, formaldehyde, fungi/bacteria and fine particles ($PM_{2.5}$) were generally uniformly distributed in CH2, while ozone from office equipment and carbon monoxide were generally below detection. Indoor air concentrations of some VOCs exceeded those outdoors by

approximately 3-fold, showing there were indoor sources for these pollutants, though indoor TVOC levels were ~one-third the criteria level. VOCs measured by GC/MS were similar in both seasons, varying from a TVOC concentration of <50 $\mu g/m^3$ outdoors to 50-180 $\mu g/m^3$ within CH2, this level of elevation normally being found in typical *established* buildings (Brown 2001), whereas *new* buildings (1-3 months old) can exhibit TVOC concentrations in thousands $\mu g/m^3$. TVOC concentrations above 500 $\mu g/m^3$ are considered to indicate the need to remove strong VOC sources from buildings. CH2 was assessed at 5 and 10 months after construction and would not be classified as 'new'.

5. Fungi and $PM_{2.5}$ were much lower indoors than outdoors, by a factor of 10-fold or more, showing there were no indoor sources and significant cleaning of intake air due to filtration by the mechanical ventilation system.
6. Similar indoor air VOC species were observed in both seasons and there was no specific and consistent trend in the VOC concentrations according to the location sampled or the season. Also, there was little difference between the dominant VOC species found in CH2 or CH1. This is considered to indicate that **VOC sources within CH2 were uniformly dispersed through the building and were from similar sources as in CH1**
7. **The occupant survey found that there were indoor environment problems in CH2 from (in decreasing prevalence): poor lighting, noise, poor temperature control and air stuffiness, with the poor lighting complaint persisting in winter after the lighting system had been modified**
8. **High incidences of occupant reported symptoms were observed for irritation/watering of eyes (approx. one-half of all occupants) in both seasons, possibly associated with poor lighting.** In winter, there were also high incidences of lethargy (34-44%) and headache (24-60%) which are not consistent with the IAQ measurements which show CH2 to be a high quality environment.

MABEL measurements in CH2 showed that:

1. As for CH1, dissatisfaction from draft, vertical thermal difference and radiant asymmetry were low and were within a Category A classification (Table 2.4) for both Summer and Winter
2. Whole body thermal comfort for CH2 is presented in Table 8.1, which shows that generally the building performed to Category A classification, with a reduction to Category B at a few locations in both seasons.
3. While not quantified, glare problems from ceiling lighting were observed since the ceilings throughout the building (bare concrete) were non-reflective, creating very high contrast levels.
4. While a general illuminance of 160 lx was achieved, task illuminance was below 320 lx for a high proportion of locations on all Levels and for both seasons (Table 7.3). While MCC changed the artificial lighting between the Winter and Summer assessments, improvement appeared limited to a few specific locations. Despite this, a specific focus on the use of task lights during the Summer assessment showed that the 320 lx illuminance was achievable by users if they chose to use task lights where available (these were mostly available at workstations but not general areas).
5. Reverberation times on Levels 2 and 6 (Level 8 not assessed) were within the 0.4-0.6 sec. criterion range; in fact an ideal frequency-time decay behaviour was observed, where longer decay occurred for lower sound frequency, which provided a balance between speech intelligibility and speech privacy in the open-plan spaces. Also, noise measurements in CH2 when occupied ranged from 43-57 dBA (ave±SD = 50.5±3.4 dBA). It is concluded that the noise environmental quality was of a high standard with a speech intelligibility of ~99% predicted.

Overall, CH2 was concluded to provide a high quality indoor environment from indoor air, thermal comfort and noise, but lesser quality from lighting. Consistent with the latter, occupants reported symptoms of eye irritation, lethargy and headache.

Table 8.1. Whole body PPD for CH1 and CH2

			CH1 (PPD% at 3 heights)				CH2 (PPD% at 3 heights)			
Building Level	**Season**	**Meast Location**	**PPD high**	**PPD mid**	**PPD low**	**PPD (avg)**	**PPD high**	**PPD mid**	**PPD low**	**PPD (avg)**
Lower	Winter	Core	6	5	5	5	7	6	6	6
		A	7	6	5	6	7	7	6	7
		B	7	6	5	6	7	6	6	6
		C	6	5	5	5	6	5	5	5
		D	6	5	5	6	6	5	5	5
		E	7	5	5	6	7	6	6	6
		F	5	5	5	5	7	7	6	6
Middle	Winter	Core	10	9	8	9	6	7	5	6
		A	6	5	5	5	11	11	10	11
		B	5	6	5	5	11	10	10	11
		C	7	7	6	7	10	10	9	9
		D	7	7	7	7	9	8	8	8
		E	8	7	6	7	10	9	9	9
		F	-	-	-	-	10	10	9	10
Upper	Winter	Core	5	5	5	5	11	5	9	9
		A	8	7	6	7	6	5	5	5
		B	5	5	6	5	6	6	6	6
		C	5	5	5	5	7	7	7	7
		D	6	5	5	5	7	7	6	6
		E	6	6	5	6	6	6	6	6
		F	-	-	-	-	6	6	6	6
Lower	Summer	Core	7	6	6	6	5	6*	15*	9
		A	7	6	5	6	5	5	5	5
		B	5	5	5	5	5	6	5	5
		C	6	6	6	6	5	6	7	6
		D	5	5	5	5	5	5	6	5
		E	6	5	6	6	5	5	5	5
		F	5	5	5	5	5	5	5	5
Middle	Summer	Core	5	5	5	5	5	6*	17*	9
		A	12	10	9	10	5	7	6	6
		B	25	22	27	25	5	6	6	6
		C	17	15	17	16	5	8	6	6
		D	11	10	10	10	6	6	6	6
		E	14	11	10	12	6	6	6	6
		F	-	-	-	-	6	6	6	6
Upper	Summer	Core	5	6	5	5	9	10*	28*	16
		A	10	11	15	12	8	11	10	10
		B	14	17	24	18	9	9	9	9
		C	22	19	22	21	7	8	8	8
		D	9	7	7	8	8	9	8	8
		E	13	16	19	16	9	10	8	9
		F	-	-	-	-	8	8	8	8

* PPD values at mid- and low-heights as provided by MABEL report have been swapped since an instrument error was suspected

9 OVERVIEW & DISCUSSION

In overview, CH1 exhibited poor indoor air quality due to formaldehyde (esp. on Level 6), variable thermal comfort, but good quality for lighting and noise. The occupant questionnaire observed continuous, high incidence complaints of stuffy air and temperature variability (both too hot and too cold). Occupants also reported high (20-30%) symptom prevalence related to building occupancy and for both seasons for dry eyes, lethargy/tiredness, and headache, with greatest prevalence on Level 6, consistent with the formaldehyde pollution observed on that Level. CH2 was considered to exhibit high quality indoor air, though this was 5 months after construction and air quality conditions at initial occupancy are unknown. Thermal comfort and noise were rated as high quality, but lighting was not. Occupants perceived the building to be poorly lit, noisy, variable in temperature and with stuffy air, showing some consistency with physical measurements.

The main purpose of this Task is not to assess these buildings, but to use this assessment to evaluate the field application of design guidelines for indoor environment quality. This discussion will consider lessons learnt from such application and design guidelines that are appropriate and implementable.

9.1 Indoor air quality

A range of indoor air pollution metrics have been selected for measuring IEQ in office buildings relevant to their impacts on occupant well-being and comfort. These have been assessed in a target ‘traditional’ building and a new sustainable design building, both without significant problems or inconsistencies in applying the methodologies. Generally, it is considered that these metrics present an acceptable specification for high IEQ, based on their methodologies for measurement, their acceptance criteria and the strategy for their sampling in buildings. The following outcomes arise from this research:

- **Building sampling strategy – outcome 1:** it was previously recommended (Brown 1997) that IAQ problems in buildings should be investigated in a systematic, step-wise process, tailored to suit the individual nature of the building and the IAQ problems encountered (Figure 9.1). The key first steps were to review the building plans, conduct a walk-through inspection and ensure the ventilation system was functioning, these then being followed by the Office Environment Survey of occupants (as used in this study). These initial steps then acted to inform an air sampling strategy for the building. In ‘Regenerating Construction ….’ these steps do not fit within a design specification, but are part of any subsequent IEQ assessment to ensure delivery of high IEQ. This project showed that where IAQ metrics failed to meet criteria (Level 6 of the traditional building CH1), the occupant experience was worse for poor comfort and high symptom incidence.
  Recommendation 1: a key building sampling strategy will be the application of the Office Environment Survey to building occupants on selected Levels; this should be applied prior to adopting an IEQ building sampling strategy and should act to inform such a strategy.
- **Building sampling strategy – outcome 2:** since the IAQ metrics varied little from Level to Level, from location to location within Levels or from season to season, the building sampling strategy could be reduced somewhat (e.g. to a minimum of one location on each of three Levels, without duplication, irrespective of season). However, such reduction should not occur unless similar factors exist to those in the current target buildings, i.e.
    - similar operations and tasks occur on all building Levels
    - the same HVAC system services all building Levels
    - a walk-through inspection of the building has been completed which shows there are no poor practices at specific locations
    - an office environment questionnaire is completed by occupants on three selected Levels and shows similar experience of comfort and symptoms.

Recommendation 2: the IAQ sampling strategy may be reduced where pre-assessment inspection shows building Levels are similar

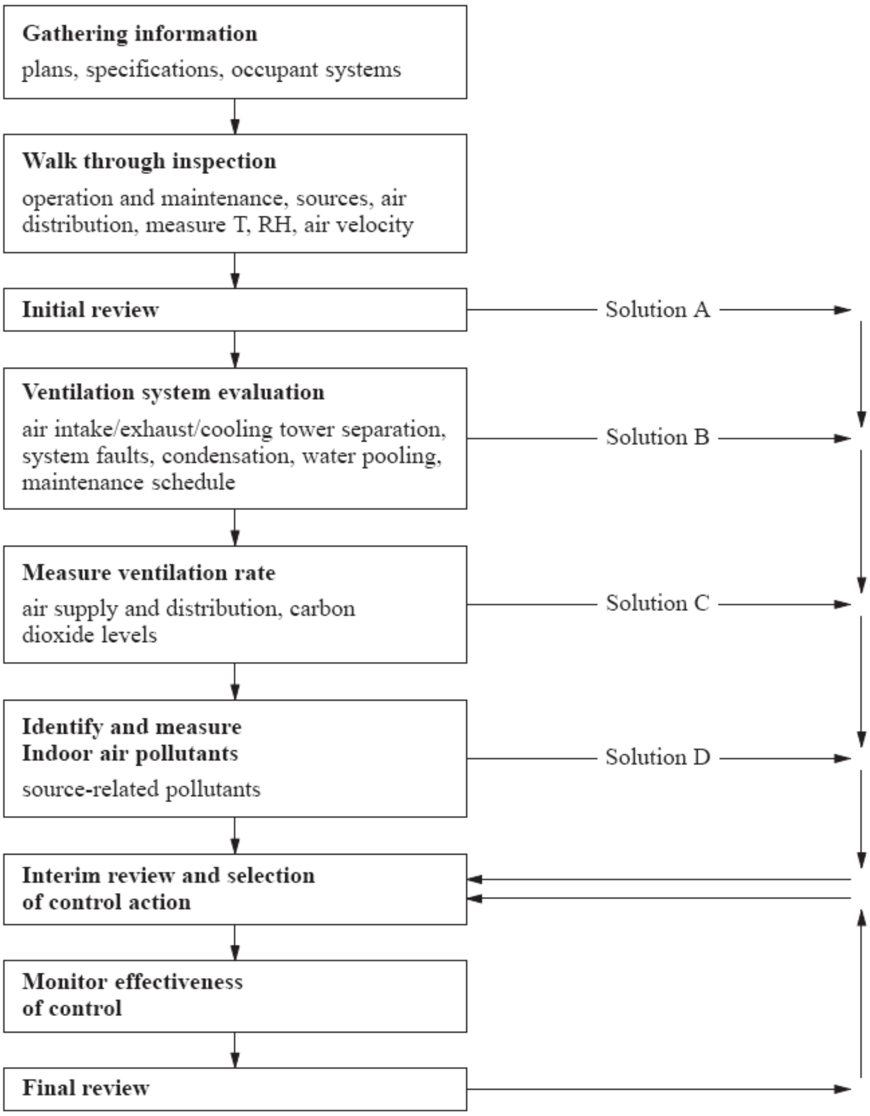


Figure 9.1. Systematic strategy for assessment of IAQ in buildings (Brown 1997)

- **IAQ criteria:** nearly all IAQ metrics were within the recommended criteria, the one exception being formaldehyde on Level 6 of the traditional building, and consistent with this observation occupant comfort and health symptoms were worst for this Level; thus the formaldehyde criteria appears to be at a level that discriminated poor IAQ. This should be the case since all IAQ criteria were selected on the basis of health significance.

Recommendation 3: the IAQ criteria should be accepted in 'Regenerating Construction …' as protective for occupant health and well-being

- Many of the IAQ metrics were much below the criteria. For example, $PM_{2.5}$ was generally 2-5 µg/m^3, well below the criterion of 25 µg/m^3, even when the latter was exceeded outdoors. Where measured concurrently, it was found that the outdoor air $PM_{2.5}$ level was reduced by an average of 90% for CH1 and 79% for CH2. The winter 2007 measurements in CH2 included the number concentration of particles <1 µm, and showed indoor levels were reduced by an average of 62% of outdoor levels. Generally, ventilation system filters have low efficiency for capturing such particles, as shown by the following data for Ultrafine Particles (UFP) and $PM_{2.5}$ (L. Morawska, QUT, personal comm.):

Filter Type	Filter Efficiency(E) at 100% air flow	
	UFP	**PM2.5**
Bag (95%)	0.65	0.65
Bag (85%)	0.55	0.58
Bag (65%)	0.23	0.28
Pleated	0.035	0.092

The types of filters used in CH1 and CH2 are not known, though Bag(65%) is considered likely for CH1. It is well known that filter efficiencies will improve as the filter becomes loaded with particulates, and this may explain the high removal efficiencies observed in these buildings.

- Another IAQ metric that was much below the criterion was viable fungi concentration; generally indoor levels are expected to be much lower than those outdoors unless indoor contamination has occurred due to persistent moisture; this study has shown very similar levels of fungi for both buildings, across all locations and for both seasons. Note that Parat et al (1997) reported such behaviour for a mechanically ventilated office building that was intensively monitored for one year, but found much higher and variable levels in a naturally ventilated building.
- IAQ sampling for TVOC used two procedures:
    - sampling onto a sorbent followed by desorption and GC analysis, a detailed and expensive procedure, but that recommended by CEC (1999)
    - an average of a direct-reading photo-ionization detector (PID), the instrument ppbRAE, being promoted by distributors as a more economical alternative than the sorbent GC procedure.

  At present, no correlation has been established between these procedures. In fact, a correlation is considered unlikely because the PID sensor responds differently for different VOCs. The present study aimed to determine a ‘trigger’ level for the PID measurement, above which it was considered that GC sampling should be used (i.e. the PID would be used to identify when elevated levels of TVOC were present and GC analysis should be used). However, the TVOC criteria of 500 μg/m^3 was never exceeded in the study buildings, most measurements being 100-150 μg/m^3. Combining all building measurements (Appendix A), an approximate relationship between the measures was:

  $$\text{GC } (\mu g/m^3) = 40 + 2.0 \text{ PID(ppb)}$$

  which shows that a PID measurement of approx. 200 ppb was approximately equivalent to a GC measurement of 500 μg/m^3, though this correlation must be considered uncertain for other buildings.

  Recommendation 4: the ppbRAE should be used for assessing IAQ with caution, and only as a device for determining the absence of VOC pollution rather than for determining the level of pollution and its health significance, the latter requiring GC/MS sampling and analysis.
- It is significant to note that the pollutant loads in CH1 and CH2 were very similar except for the formaldehyde pollution observed in CH1. It might be considered that CH1 should have exhibited higher pollutant loads because it recirculated ~80% of the indoor air in a dilution ventilation mode, whereas CH2 was supplied with 100% outdoor air in a displacement ventilation mode. Conversely, CH2 was a new building and many studies have shown new buildings have much higher VOC levels than established buildings. However, new building emissions usually decay to background levels in approx. 6 months. Since CH2 was both designed with low emission materials/contents and not accessed until 5 months after occupancy (an MCC restriction while the building was ‘tuned’), the assessment may have missed assessing the temporarily high pollutant loads at first occupancy. In fact, MCC contracted CSIRO to assess IAQ at 2 weeks after occupancy, with the following median pollutant levels (Table 9.1).

Table 9.1. Indoor pollutant loads with age of CH2

Pollutant	Median concentration (μg/m^3) after occupancy for		
	2 weeks[a]	5 months	11 months
Formaldehyde	7	4	11
Total VOC	Not meas'd	110	130
Benzene	<3	4.1	1.5
Toluene	9	19	5.9

[a] Single measurements made on Levels 2, 5, 8

Though less detailed than IAQ measurements for the current project, the 2 week measurements show that pollutant levels were low in CH2 even early after occupancy, demonstrating that the design decisions on low emission materials/contents prevented high pollutant loads at first occupancy.
Recommendation 5: a sustainable building refurbishment or construction may be expected to meet IAQ criteria for formaldehyde and VOCs soon after construction if low emission materials/contents are utilised.

9.2 Thermal comfort, lighting and noise

- **Thermal comfort metrics:** While several metrics for thermal comfort were employed in this research, all but one were found to demonstrate that high thermal comfort was achieved. Thus thermal comfort was high (Category A in Table 2.4) for the metrics of draft, vertical temperature difference and radiant asymmetry, but varied from high to low for whole body thermal comfort. Thus, the latter is the key metric for assessing thermal comfort impacts in the present buildings, though the other metrics could be significant for other cases.
- **Thermal comfort sampling strategy:** sampling employed two 'comfort carts' which measured thermal metrics at three heights (0.1m, 0.6m, 1.1m) by continuous logging. One cart was placed central to a building Level and remained there for the whole work day. The second was placed at each of six locations sited near perimeter workstations, each being monitored for 15 minutes at three time across the work day. Three Levels were assessed, each for one work day, by this strategy. The strategy is considered to provide a 'snapshot' of thermal comfort since measurement at several locations over several days on each Level would be needed to determine any impact from climatic variations (especially radiant effects from sunlight through windows). However, the latter strategy was considered too work-intensive and expensive to implement, and might be considered for further assessment should the 'snapshot' strategy show poor thermal comfort. ***Recommendation 6: the thermal comfort sampling strategy was considered to provide a 'snapshot' measurement, appropriate for identifying the need for more extensive assessment.***
- **Assessment of whole body thermal comfort:** Whole body thermal comfort was estimated by the MABEL team using single default values for clothing (clo 0.8) and activity (met 1.0), whether for summer or winter, which differed from those recommended by ISO of 0.5 clo/1.2 met for summer and 1.0 clo/1.2 met for winter. This project required that the ISO defaults be used, and comparison with the MABEL default showed that different estimates of dissatisfaction resulted.

  Recommendation 7: estimation of whole body thermal comfort in offices should use the ISO default values of 0.5 clo/1.2 met for summer and 1.0 clo/1.2 met in winter, unless actual estimates of occupant clo values are available.
- **Lighting metrics - Glare:** the lighting metric of Glare has been shown in recent research to require a new approach, based on CCD camera mapping and a 'daylight glare probability index'. This technology was new and not fully available in this study.
- **Lighting metrics – Task illuminance:** Task illuminance was found to be poor in CH2 and occupants appeared to be impacted by this performance, but this factor was complicated by the availability of task lights. Generally, task lights were provided at workstations and when

used, the task illuminance achieved the criterion level. However, many other office areas (work benches etc) lacked task lights and could not achieve the criterion. Of course, this factor may be considered within the occupant's capability for control by placement of task lights as appropriate.
Recommendation 8: Task illuminance in offices can be achieved by occupants when specific and appropriate task lights are provided. Task illuminance should be assessed with task lights operating if present.

- **Noise metrics:** noise level and reverberation time are appropriate metrics, as specified in Australian Standards, though noise levels in the occupied office should also be considered.
Recommendation 9: The noise level in an occupied office is an additional metric and a criterion of 55 dBA (averaged from several locations and times) should provide approximately 99% speech intelligibility.

10 CONCLUSIONS

This study has reviewed current literature and practices and recommended a comprehensive list of 'Metrics' for four 'Indicators' of Indoor Environment Quality (IEQ) in offices – Indoor Air Quality, Thermal Comfort, Lighting and Noise. These application of these Metrics was carried out in an established building due for refurbishment and a new, sustainable-design building. Generally, the Metrics were found to be:

- appropriate for IEQ assessment
- implementable under field conditions.

Some adjustments to the metrics have been recommended, such as reduced sampling and additional metrics.

Overall, it is considered that the assessment and specification of high quality indoor environments can be achieved by:

- the IAQ criteria of Table 2.3
- thermal comfort to Category A in Table 2.4
- lighting that achieves a general illuminance of 160 lux, task lighting of 320 lux (or higher for detailed tasks), and a Daylight Glare Probability Index of 0.3 (predicted dissatisfaction <30%)
- noise levels in an unoccupied but operating office of 40-45 dBA, in an occupied and operating office of <55 dBA (average), and reverberation time of 0.4-0.6 sec. (as in Australian Standard).

Note that these are targets for a design team to aim for at the planning stage of a building. After construction, specific measurement and sampling strategies are required to determine if the targets have been met, as presented in this study.

11 OTHER INFORMATION

Council house 2 (CH2) website:
http://www.melbourne.vic.gov.au/info.cfm?top=171&pg=1223

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13 GLOSSARY

Acronym	
ACH	air changes per hour
ACGIH	American Conference of Governmental Industrial Hygenists
AS	Australian Standard
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BCA	Building Code of Australia
Bq	Bequerel
CH1	Council House 1
CH2	Council House 2
CO2	Carbon dioxide
dBA	A-weighted decibels
f/mL	fibres per millilitre
IAQ	indoor air quality
IEQ	indoor environment quality
ISO	International Standards Organization
Lx	Lux (measure of illuminance)
MABEL	Mobile Australian Built Environment Laboratory
MCC	Melbourne City Council
NABERS	National Australian Built Environment Rating Scheme
NEPM	National Environmental Protection Measure
NHMRC	National Health & Medical Research Council
NOHSC	National Occupational Health & Safety Commission
OHS	occupational health & safety
PD	percent dissatisfied
PM2.5	particle mass concentration (diameter<2.5 μm)
ppb	parts per billion (1000 million)
ppbRAE	a detector from RAE Systems (USA) to measure ppb levels of VOCs
PPD	predicted percent dissatisfied
ppm	parts per million
SBS	sick building syndrome
T	temperature
TBL	triple bottom line
TVOC	total volatile organic compounds
$\mu g/m^3$	microgram of pollutant per cubic metre of air
VOC	volatile organic compound
WHO	World Health Organization

APPENDIX A – INDOOR AIR QUALITY REPORTS FOR CH1 AND CH2 (CD-ROM ATTACHED)

A CD ROM attached to this report contains the following COMMERCIAL-IN-CONFIDENCE reports which were funded by Melbourne City Council and were provided to MCC as the attached documents. These are not to be distributed.

A.1

INDOOR AIR QUALITY MEASUREMENTS AT MELBOURNE CITY COUNCIL CH1, 200 LT. COLLINS ST, PRE-REFURBISHMENT, WINTER 2005
SK Brown, KJ Mahoney, M Cheng & B Tiganis, CMIT Doc. 2005/xxx

A.2

INDOOR AIR QUALITY MEASUREMENTS AT MELBOURNE CITY COUNCIL CH1, 200 LT. COLLINS ST, PRE-REFURBISHMENT, WINTER 2005/SUMMER 2006
SK Brown, M Cheng and KJ Mahoney, CMIT (C)-2006-200

A.3

INDOOR AIR QUALITY MEASUREMENTS AT MELBOURNE CITY COUNCIL CH2 - FIRST (SUMMER 2007) ASSESSMENT AFTER OCCUPANCY
CSE Doc. USP2007/009
Stephen Brown, May 2007

A.4
INDOOR AIR QUALITY MEASUREMENTS AT MELBOURNE CITY COUNCIL CH2 - FIRST (SUMMER 2007) & SECOND (WINTER 2007) ASSESSMENTS AFTER OCCUPANCY
CSE Doc. USP2007/013
Stephen Brown, October 2007

APPENDIX B – MABEL REPORTS FOR CH1 AND CH2

A CD ROM attached to this report contains the following COMMERCIAL-IN-CONFIDENCE reports which were funded by Melbourne City Council and were provided to MCC as the attached documents. These are not to be distributed.

B.1

MABEL Monitoring of the Melbourne Council House -1 Offices
November 2005
Dr. Mark B. Luther, School of Architecture and Building, Deakin University, Geelong Victoria 3217

B.2
MABEL Monitoring of the Melbourne Council House -1 Offices
(November 2005 original), June 2006 update
Dr. Mark B. Luther, School of Architecture and Building, Deakin University
Geelong Victoria 3217

B.3
MABEL Measurement of CH2
May 2007
Dr. Mark B. Luther, School of Architecture and Building, Deakin University
Geelong Victoria 3217

B.4
MABEL Measurement of CH2 Summer & Winter
November 2007
Dr. Mark B. Luther, School of Architecture and Building, Deakin University
Geelong Victoria 3217

**Cooperative Research Centre
for Construction Innovation**
9th Floor, L Block
QUT Gardens Point
2 George Street
BRISBANE QLD 4001
AUSTRALIA
Tel: +61 7 3138 9291
Fax: +61 7 3138 9151
Email:
enquiries@construction-innovation.info
Web:
www.construction-innovation.info

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