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<u>HIGH QUALITY INDOOR ENVIRONMENTS FOR OFFICE BUILDINGS</u>

Stephen K Brown
CSIRO Manufacturing & Infrastructure Technology
Steve.brown@csiro.au

ABSTRACT

The quality of office indoor environments is considered to consist of those factors that impact the occupants according to their health and well-being and (by consequence) their productivity. Indoor Environment Quality (IEQ) can be characterized by four indicators:

- Indoor air quality indicators
- Thermal comfort indicators
- Lighting indicators
- Noise indicators.

Within each indicator, there are specific metrics that can be utilized in determining an acceptable quality of an indoor environment based on existing knowledge and best practice. Examples of these metrics are: indoor air levels of pollutants or odorants; operative temperature and its control; radiant asymmetry; task lighting; glare; ambient noise. The way in which these metrics impact occupants is not fully understood, especially when multiple metrics may interact in their impacts. It can be estimated that the potential cost of lost productivity from poor IEQ may be much in excess of other operating costs of a building. However, the relative productivity impacts of each of the four indicators is largely unknown. The CRC Project 'Regenerating Construction to Enhance Sustainability' has a focus on IEQ impacts before and after building refurbishment. This paper provides an overview of IEQ impacts and criteria and the implementation of a CRC project that is currently researching these factors during the refurbishment of a Melbourne office building. IEQ measurements and their impacts will be reported in a future paper

Keywords: **office, air, thermal comfort, noise, lighting**

HIGH QUALITY INDOOR ENVIRONMENTS FOR OFFICE BUILDINGS

1.0 BACKGROUND

The CRC for Construction Innovation initiated the project "Regenerating Construction to Enhance Sustainability" in 2005, with overall objectives:

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

Specifically, the project outcome will be the delivery of superior refurbished **office** buildings according to a core set of four 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 before and after refurbishment and
- Waste minimisation.

This report presents the research to date on the core sustainability criterion of **high indoor environment quality**. The research plan is to develop IEQ design guidelines by:

- Identifying and defining **key indicators** for high quality indoor environments
- Specifying **sampling and measurement protocols** for performance measures of key IEQ indicators
- Specifying reliable, **scientific procedures** by which the indicators can be measured at any location
- Recommending **performance criteria** for each indicator
- Consideration of **design and specification implications** of performance targets
- Documenting the implementation of the guidelines in a **target building before and after refurbishment**.

Other CRC researchers will investigate occupant impacts for the same target building, allowing IEQ-occupant interactions to be evaluated.

2.0 SELECTION OF IEQ INDICATORS

IEQ indicators (Brown and Kivlighon 2005) were considered to be encompassed in the following factors:

- indoor air pollutant levels
- thermal comfort
- lighting and
- noise.

Building ventilation rate will significantly impact these factors if uncontrolled, but since it is currently tightly regulated in BCA via Australian Standard 1668, it was assumed that that ventilation performance had been optimised for BCA requirements. A key consideration in selecting the indicators was that they could be represented by performance metrics relevant to impacts on occupant satisfaction and acceptance of office environments.

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 in Australia are limited, especially in comparison to 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, and recommends health-based advisory IAQ goals
- the National Occupational Health and Safety Commission (NOHSC), which provides exposure guidelines for a large number of air contaminants in workplaces (only), which are generally called up in OHS regulation
- the World Health Organization (2000) which has recommended health-based environmental air quality guidelines for Europe, with application to both urban and indoor air exposures.

Table 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. These arise 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 (e.g. infants, the elderly, people with asthma).

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 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.

A large number of pollutants have been investigated in Australian buildings, some in great detail, but for others few observations are available and it is not possible to determine exposure levels for the Australian population or the most appropriate strategies to reduce exposure (Brown 1997). Based on this background, key indicators of IAQ are recommended as in Table 2. 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 an office building where members of the public and children may have access.

Table 1 IAQ, environmental and occupational exposure goals for air contaminants

Pollutant	NHMRC IAQ goals		NOHSC Occupational Exposure Stds	NEPM Ambient Air Standards	WHO Air Quality Guidelines
	Goal	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)

Table 2. Key indicators for indoor air quality

Indoor air pollutant	Possible sources	IAQ criterion (averaging period)	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	"	4100 μg/m^3 (24 h)	High
VOC: xylenes	"	1200 μg/m^3 (24 h)	Low
PM2.5	Auto exhausts	25 μg/m^3 (24 h)	High
Carbon monoxide	Auto exhausts	9 ppm (8 h)	High
Carbon dioxide	Exhaled breath	800ppm (1h)	High
Ozone: at equipment 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

Thermal comfort is commonly defined as that 'condition of mind which expresses satisfaction with the thermal environment' (International Organization for Standardization (ISO), 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 at typical levels for office environments.

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.

2.2.1 Mechanically conditioned offices

For given values of humidity and air speed, the thermal comfort zone can be defined in terms of operative temperature or in terms of combinations of air temperature and mean radiant temperature (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2004), 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 nonuniform environment. In most practical cases, this 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, 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 nonuniform 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 ASHRAE (2004) Standard 55 specifies operative air temperature according to two equivalent procedures: a simplified graphical method or a computer program based on a heat balance model; only the former will be presented. 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 1 are for 80% occupant acceptability (based on 10% dissatisfaction for whole body and 10% for partial body comfort). Note that the thermal comfort zone extends across operative T from 19°C to 28°C, the specific operative temperature depending on clothing and humidity levels.

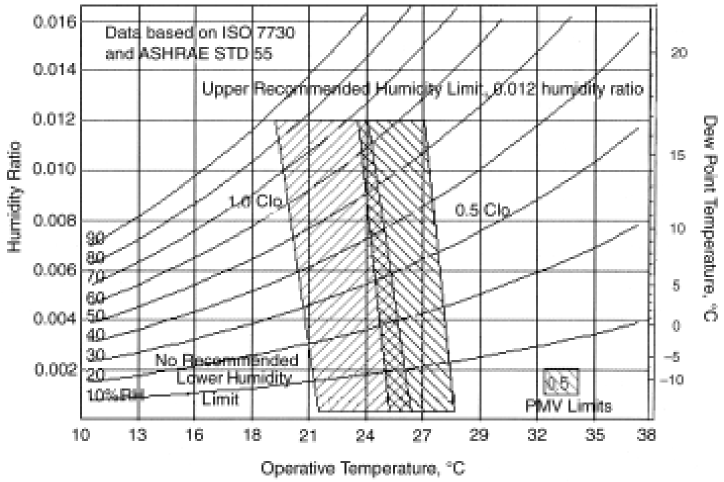

Figure 1. Acceptable ranges for operative temperature and humidity in 'typical' office spaces (ASHRAE 2004)

Relative humidity (RH) that is too high or too low can lead to skin, eye and respiratory irritation (ASHRAE 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 which corresponds to upper RHs of 55 – 85%RH. 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 et al 1997). Hence it is considered that relative humidity in buildings should not exceed 70% RH.

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 (Christiansson 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, it is considered that the air velocity should be within the range

0.05 – 0.2 m/s. Note that ASHRAE (2004) has specified that air speed may be increased above 0.2 m/s so as to increase the maximum temperature for acceptability **if occupants are able to control the air speed**. The amount of increase is limited to 3°C with air speed to not exceed 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 unacceptable to 20% of occupants was provided for different levels of turbulence intensity. For the turbulence levels normally found in mechanically ventilated building, acceptable air speeds ranged from 0.15 to 0.3 m/s.

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.

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 reduced thermal acceptability of a 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.

ASHRAE Standard 55 and ISO 7730 both suggest the specification of three levels of acceptance for thermal comfort, since in practice the levels attained will depend on a range of factors: technical, cost, environmental, energy and performance. Table 3 shows the recommended levels of acceptance for three categories (B corresponds to ASHRAE's 1992 recommendation).

Table 4 lists criteria for general thermal comfort for the three levels of acceptance for several types of spaces (Olesen, 2004).

Table 3 Three categories of thermal environment

Thermal state of the body as a whole				**Local thermal discomfort**		
Category	**PPD %**	**Predicted mean vote**	**Draught rate, DR %**	**Vertical air temperature difference %**	**Warm or cool floor %**	**Radiant temperature asymmetry %**
A	< 6	- 0.2 < PMV < + 0.2	< 15	< 3	< 10	< 5
B	< 10	- 0.5 < PMV < + 0.5	< 20	< 5	< 10	< 5
C	< 15	+ 0.7 < PMV < + 0.7	< 25	< 10	< 15	< 10

Table 4. Criteria for operative temperature for typical buildings

Type of building	Clothing (clo)		Activity (met)	Category	Operative Temperature (ºC)	
	Summer	Winter			Summer	Winter
Office	0.5	1.0	1.2	A	24.5 ± 0.5	22.0 ± 1.0
				B	24.5 ± 1.5	22.0 ± 2.0
				C	24.5 ± 2.5	22.0 ± 3.0
Cafeteria / Restaurant	0.5	1.0	1.4	A	23.5 ± 1.0	20.0 ± 1.0
				B	23.5 ± 2.0	20.0 ± 2.5
				C	23.5 ± 2.5	20.0 ± 3.5
Department Store	0.5	1.0	1.6	A	23.0 ± 1.0	19.0 ± 1.5
				B	23.0 ± 2.0	19.0 ± 3.0
				C	23.0 ± 3.0	20.0 ± 4.0

Note that while the mean operative temperatures are the same for the different categories, the allowable spread of operative temperatures changes markedly across categories.

2.2.2 Naturally ventilated offices
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 temperature may be determined from Figure 2, which includes limits for 80% and 90% acceptability. 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). Also, this guidance applies only to conditions where the mean monthly outdoor temperature ranges from 10°C to 33.5°C. No guidance is allowable outside this range.

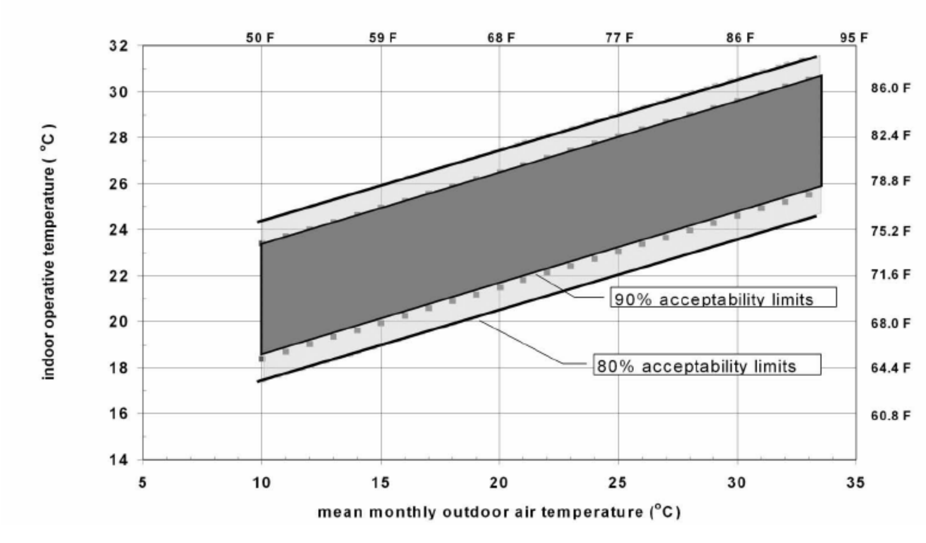

Figure 2. Acceptable operative temperature ranges for naturally conditioned spaces

2.3 Lighting Quality Indicators
Lighting levels need to be of a quality that provides an environment in which it is easy to see so that office 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

outcome. Windows can assist in avoiding or reducing eyestrain by allowing an individual to focus on distant objects rather than prolonged viewing of close objects such as computer screens. However, the use of windows needs to be balanced with respect to any adverse thermal effects or unwanted lighting effects such as glare.

Even though a task may be three dimensional, it is generally carried out in more or less one plane and it is common to provide 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).

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 recommend a minimum of 160 lx on the working plane so that eyes are not strained due to a deficiency of light. Also, the uniformity of illuminance within a 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). 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 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). Good task visibility depends on both the luminance of the task and its surroundings and optimum levels exist for the ratio of the luminances of task: immediate surrounds: general surrounds at approximately 10:3:1. Lighting levels lower than 160 lx are acceptable in infrequently occupied areas such as locker rooms, storage rooms and corridors, though the lighting differences of adjacent areas should not be pronounced (no more than 10:1) because of visual adaption factors.

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 due to:

- lamp ageing/dust accumulation
- dust accumulation on room surfaces
- dirt build-up on windows.

AS1680.2.2 specifies recommended values for maintenance illuminance as presented in Table 5.

Table 5. Recommended interior illuminance for office and screen-based tasks (note: lamp colour and glare factors also specified)

Task/room type	**Recommended illuminance (lx)**
General tasks: typing, reading, writing	

- task - background	320 160
Screen-based task - keyboards - reference material • good, simple • average detail • poor, fine detail - background - microform reading	 160 240 320 600 160 20 – 40
Drawing offices - drawing board - reference material • good, simple • poor, fine detail - background	 600 320 600 240
Meeting rooms Training/seminar rooms Conference rooms/board rooms	320 240 240
Reception areas - enquiry desk - entrance hall, lobby, foyer	 320 160
Photocopying and printing room - Intermittent - Sustained - Colour	 160 240 240
Filing area - clear detail - fine detail	 240 320

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. 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*** (UGR, which is also specified in ISO 8995:2002 Lighting of Indoor Workplaces) 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
- 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.

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. 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.

Flicker from electric lights can cause eye fatigue and is distracting. 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). Frequencies 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).

2.4 Sound Comfort Indicators

Sound level is defined in terms of the unit decibel (A) which is measured at the frequencies over which humans generally hear, 20 to 20 kHz, using an 'A' filter (Australian Standard® 2659.1—1988, 1988). 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 $L_{Aeq,8h}$. Background sound tends to be of a low intensity and is present for most of the time in any environment. 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 $L_{Aeq,8h}$ value of less than 40 dB(A) and an open plan office less than 45 dB(A) (UK Government, 1999).

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. High intensity impact noise can damage hearing, but it is considered highly unlikely to occur within an office environment, and so the averaged 8 hour noise level is an appropriate metric. Also, sound from short-term sources, such as printers and photocopiers, can be minimised by keeping them in a separate room. The WHO recommend that excessive sound should be controlled by first reducing the sound source, then reducing the sound propagation, and finally, protecting workers (Concha-Barrientos *et al.*, 2004).

Table 6 lists recommended A-weighted equivalent design sound levels in Australia (Australian Standard® 2822—1985, 1985), with a range given from satisfactory to maximum levels. The satisfactory design level is the amount of sound which is satisfactory for most people, while the maximum level is that which causes most people to be dissatisfied.

2.5 Occupant Questionnaire on Environmental Comfort

While the above air and physical metrics aim to focus on the key indicators of IEQ, it is considered that the complexity of IEQ and the environment-occupant interaction is such that a direct feedback of occupant experience is also required in the assessment of IEQ. Applied to a statistically significant but random sample of occupants (approx. 30), this can provides a direct measure of the comfort levels experienced by occupants. Occupant experience was assessed with a two page questionnaire developed from the 'office environment survey' of Raw (1995) for the UK Health & Safety Executive. This is a self-administered questionnaire, applied by the occupants at the time of IEQ assessment, and has no questions related to measurement or assessment of productivity. Key questions relate to:

- Working conditions
- Discomfort from indoor climate in preceding two months
- Symptoms or health complaints in preceding two months linked to presence in office.

Table 6. Recommended A-weighted equivalent design sound levels and reverberation times for different uses within buildings

Activity/Occupancy type	**Recommended design sound level $L_{Aeq,8h}$, 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.

3.0 APPLICATION TO AN OFFICE REFURBISHMENT

Melbourne City Council owns an office building in Melbourne city centre that has three lower levels of carparking, six levels of offices occupied by its staff, and a plant room on the 10th level. This building was constructed approx. 1970 and is planned to be upgraded and refurbished in 2006. Refurbishment will result in the same six levels remaining as offices (though with substantial changes to layout, ventilation, windows etc) and the CRC project focus is only on these offices, though the impacts from surrounding environments (e.g. car exhausts from enclosed car parks on levels 1-3; noise from outside traffic or proposed roof-top occupancies) were considered in design of the measurement protocol. Overall, it was considered that IEQ assessment must be carried out both before and after refurbishment, in each case for two seasons (summer and winter), and as close as possible to the building refurbishment. Assuming that the six levels of offices had a common air supply system and occupants had similar tasks/activities before and after refurbishment, measurements and criteria were recommended as in Table 7. All factors are to be measured over 5-8 consecutive work days, with the building fully occupied and within business hours. These measurements will be presented in future reports.

Table 7. IEQ assessment plan for Melbourne City Council CH1

	Measurement location(s)	Sample time	

	levels	locations	out-door	sample	sample days	performance
IAQ						
TVOC	1,4,6	2	1	1h	2	500 μg/m^3 (1h)
Benzene	1,4,6	2	1	1h	2	10 μg/m^3 (1h)
Toluene	1,4,6	2	1	1h	2	4100 μg/m^3 (1h)
Formaldehyde	1,4,6	2	1	0.5h	2	100 μg/m^3 (0.5h)
PM2.5	1,6	2	1	8h	5	25 μg/m^3 (8h)
CO	1,6	2	1	8h	5	9 ppm(8h), 25ppm(1h)
CO2	1,6	2	1	8h	5	800 ppm (1h)
Microbial	1,6	20	-	-	-	none visible
Ventilation						
Effective air changes/h (ACH)	1,4,6	1	-	1h	2	< 1 ACH infiltration > 2 < 6 ACH w/mech.
Thermal Comfort						
Operative T	1,4,6	5+	1	8h (total)	5	Fig1 or Fig 2 (90% satisfaction achieved)
Air velocity	1,4,6	5	-	2 min	5	0.05-0.2 m/s (2 min)
RH	1,4,6	2	1	8h	5	30-70% (1h)
Thermal gradient	1,4,6	5	-	2 min	2	<3°C (2 min)
Floor T	1,4,6	5	-	2 min	2	19-29°C (2 min)
Radiant T assym (0.1-0.6m)	1,4,6	5	-	2 min	2	warm ceiling < 5°C cool wall < 10°C cool ceiling < 14°C warm wall < 23°C
Lighting						
Illuminance (min)	1,4,6	6+	-	2 min	3	>160 lx
Task illuminance	1,4,6	8+	-	2 min	3	160-600lx (Table 5)
Glare	1,4,6	4+	-	2 min	3	UGR < 19
Noise						
Sound level $L_{Aeq,T}$,	1,4,6	5+	-	1h	3	Table 6
Reverberation time	1,4,6	2	-	1h	1	Table 6
Occupant Comfort Survey	1,4,6	30	-	4h	1	<20% complaint rate

4.0 CONCLUDING REMARKS

A range of physical and air pollutant factors have been selected for measuring IEQ in office buildings relevant to their impacts on occupant satisfaction and acceptance of office environments. These have been measured in a target building in the winter of 2005 without significant problems or inconsistencies. The second season measurements will be carried out in summer 2005, just prior to the refurbishment commencing. After refurbishment, it is expected that measurements will be repeated approximately 1-2 months (summer) and 6-7 months (winter) after occupancy of the building. The impact of refurbishment on occupants' productivities is being assessed within another part of the CRC project and the linkage between the IEQ metrics and occupant experience will be explored in the final phase of the project.

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