



INDOOR ENVIRONMENTAL QUALITY: A HOW-TO GUIDE

Research evidence has confirmed strong links between indoor environmental quality (IEQ) and occupant wellbeing, satisfaction, comfort and productivity. With people spending approximately 90% of their time indoors, the importance of good IEQ should not be underestimated.

This guidance will help you understand the issues associated with IEQ, including how the factors affect humans, selected target limits, as well as measurement techniques and equipment. For your convenience, at the end of this note is a list of typical steps to take when conducting an IEQ Assessment.

ECONOMIC AND SOCIAL BENEFITS

There are significant economic and social benefits to be gained for building owners, facility managers and tenants by improving IEQ, including but not limited to:

- Increasing the revenue of tenants by increasing worker wellbeing and productivity;
- Reducing complaints and thus the need to conduct costly reactive maintenance; and
- Increasing the value of the asset through increased rental yield and reduced vacancy rate.

WHAT ARE THE FACTORS IN IEQ?

The following parameters are considered key contributing factors to the IEQ of a particular space:

- Thermal comfort - temperature, relative humidity, air speed;
- Ventilation - carbon dioxide (CO₂);
- Pollutants - carbon monoxide (CO), nitrogen dioxide and sulphur dioxide, particulates, volatile organic compounds (VOCs), microbes, formaldehyde;
- Acoustic comfort;
- Lighting comfort; and
- Occupant Satisfaction Survey.

To guide interpretation, each parameter measured is briefly discussed below. The references

quoted are generally the most well-established but it must be understood that, apart from standards, they refer to the published research conditions. Due to the variations in facilities, functions and occupants, each organisation and often, location, should optimise the guidance limits to best suit their own objectives but without compromising the minimum wellbeing standards set by authorities such as the World Health Organization (WHO), US Environmental Protection Agency (USEPA), and American Society for Heating, Refrigeration and Air-conditioning Engineers (ASHRAE). The guidelines for IEQ parameters and suitable equipment will be addressed within this document. Each region and country have guidelines and standards that can be applied appropriately. To simplify the discussion, examples from the major standard setting bodies will be used for general guidance.

The discussion of recommended limits is a large topic and draws on chronic, acute, short term and long term toxicological principles and wellbeing considerations that will not be discussed in this guidance note. To avoid confusion, common, authoritative or best practise limits are presented for initial analysis. Worldwide, there are a number of older and more recent schemes that essentially use the same data bases for their guidance levels. More detailed toxicological recommendations can be given after assessment of measurement reporting.

However, for this document, guidelines for all parameters discussed here, from the appropriate Green Building Council, should apply.

Thermal Comfort

Thermal comfort is a key component of IEQ and can be assessed initially by measuring:

- air temperature;
- radiant temperature;
- relative humidity; and,
- air speed

A number of personal factors also affect thermal comfort such as gender (Kingma & van Marken Lichtenbelt, 2015), an individual's clothing, level of physical activity, and acclimatisation of the local climate.

For example, ASHRAE has developed a standard to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions

(ANSI/ASHRAE Standard 55-2013 Thermal Environmental Conditions for Human Occupancy). This standard can be applied as the target for thermal comfort parameters.

Further to the thermal comfort ranges specified by ASHRAE 55 which give a general range which will be acceptable to the majority of occupants, studies conducted and summarised by Seppänen et al. (2006) have shown that human performance peaks with temperature in the range 21-23°C, and decreases above and below this range. Therefore, a performance-based temperature target of 21-23°C is recommended for increased productivity in office buildings. ASHRAE considers 40%-60% for relative humidity to be optimal, however psychrometric comfort bands and other factors such as activity, clothing and adaptation may increase the comfort bands.

However, as noted in the introduction, these ranges vary according to standards such as ASHRAE 55, ISO7730 and others and guidance from the chosen rating provider is required.

Ventilation (via Carbon Dioxide)

Ventilation rates do not directly affect occupant health or perception outcomes. They affect indoor environmental conditions including air pollutant concentrations that may modify the occupants' health or perceptions. Research has shown that exposure to an increased ventilation rate can lead to occupants reporting to having a clearer head, perceived fresher air and exerting less effort to complete tasks (Wang et al., 2011) and hence improved productivity and wellbeing. However, there are reports of feeling a "draft" when ventilation rates are too high, which has an impact on personal comfort (Thatcher & Milner, 2014).

Carbon dioxide (CO₂) measurements can be used to determine if the HVAC system is balanced and providing adequate ventilation to the building occupants. Hence, carbon dioxide is not only an indoor air pollutant but also a measure of ventilation effectiveness. As a guideline, a maximum 1000 ppm for CO₂ is generally accepted for indoor environments. Studies have shown that a higher risk of dissatisfaction with ventilation is associated with levels greater than 500 - 650 ppm (Newsham, 2008; Wargocki, 2016). In common practice, a wide range of office buildings has shown that CO₂ levels 200 ppm above outside levels are early indicators of inadequate ventilation.

In terms of personal productivity, research indicates that doubling the outdoor air supply rate can reduce illness and sick leave prevalence by roughly 10% and increase office work by roughly 1.5% (Wargocki et al., 2006).

Excessive CO₂, especially with emitted or exhaled bio-effluents from occupants, will affect occupant health, perception and performance. Naturally, directly entrained CO₂ and other pollutants such as carbon monoxide and volatile organic compounds (VOCs) from combustion sources such as fuel burners and loading docks must be eliminated.

More advanced studies include modelling and air exchange efficiency.

Air Pollutants

There are a number of air pollutants which are commonly found in indoor environments from construction, furnishing, personal and cleaning products which can have significant impacts on occupant wellbeing, satisfaction, comfort and productivity, including, but not limited, to the following:

- **Volatile Organic Compounds (VOCs)** play an important role because of their potential health relevance. The health effects of exposure to VOCs in the non-industrial indoor environment range from sensory irritation at low/medium levels of exposure to toxic effects at high exposure levels. As VOCs belong to different chemical classes, the severity of these effects at the same concentration level may differ by orders of magnitude. When many pollutants are present at low concentrations, their possible combined human health effects can be additive or multiplicative and their dose-response relationships difficult to predict based on present toxicological knowledge. However, they are known to have severe effects on chemically, allergenically or respiratory sensitive persons.

VOCs are part of a large group of chemicals that often exist as a complex mixture in indoor environments. As a result, it is more practical to initially test total VOC (TVOC) in the indoor environment rather than testing for specific chemicals. Past recommendations from the USEPA, Australian National Health and Medical Research Council (NHMRC), and the consensus of many researchers and indoor environment rating schemes is that a recommended limit of 500 ppb TVOC and less than 250 ppb of any one VOC is appropriate

in averaged office environments.

Chemical contaminants are of varying toxicity and discomfort. They mainly arise as emissions from construction materials, paints, furnishings, cleaning chemicals, combustion, cooking, personal products, industrial and even microbial sources. They are sometimes perceived by occupants as odours but most TVOC's are not directly detected or identified by occupants but their effects on wellbeing are present as irritations, allergies and long term toxic, mutagenic and teratogenic effects.

Detailed study of specific VOCs can be made by collection on specific adsorbents and detected by GCMS.

Formaldehyde can also be considered to be a VOC but it requires its own method of detection.

- [Formaldehyde](#) is a volatile chemical used widely by industry to manufacture building and fit-out materials, fabrics, cleaning fluids and numerous other office products. Formaldehyde can also be a by-product of combustion and certain natural processes. It is generally considered independently due to its particular toxicology, sources such as insulation, adhesive and composite timber products and specific detection methods.

Exposure to formaldehyde produces irritation of eyes, nose and throat, headaches and dizziness. Since 2004, formaldehyde has been classed as a human carcinogen. The recommended limit given by the WHO is $0.1\text{mg}/\text{m}^3$ (30min average), LEED V4 recommend 0.04 milligrams per cubic metre ($40\mu\text{g}/\text{m}^3$). A threshold limit of $0.009\text{mg}/\text{m}^3$, or $9\mu\text{g}/\text{m}^3$, is being proposed by the French Centre Scientifique et Technique du Bâtiment (CSTB) and some companies.

- [Carbon monoxide \(CO\)](#), [nitrogen dioxide \(NO₂\)](#) and [sulfur dioxide \(SO₂\)](#) are toxic air contaminants that are produced by various industrial processes, or when fuels are burned such as vehicular, heating or bioburning exhaust externally or as unvented gas cooking in the indoor environment.

Carbon monoxide is a highly toxic, colourless and odourless air contaminant that is produced when fossil fuels such as petrol, diesel or gas are burned. The vehicular activities or gas heating emissions in the immediate vicinity of the building or within, may lead to the ingress of exhaust into the building. The no-action threshold limit, defined as the limit to

which it is believed a worker can be exposed day after day for a working lifetime without adverse effects, for CO as the recommended limit given by the WHO, National Australian Built Environment Rating System (NABERS) and Leadership in Energy and Environmental Design (LEED) version 4 is 10 mg/m³ (or 9 ppm).

The no-action threshold limit for NO₂ as the recommended upper limit given by the WHO is 0.12 ppm. The Australian NEPM recommends an SO₂ limit of 0.08 ppm (averaged over 1 day).

- **Ozone** is a reactive gas which exists in both the outdoor and indoor environment. Although there are sources of ozone in the indoor environment such as fluorescent lights (via UV), brushed motors and some photocopiers these tend to be insignificant and indoor ozone concentrations tend to track outdoor concentrations with a slight time lag that depends on the air exchange rate. Ozone is removed by indoor surfaces as well as by gas-phase reactions, and hence, indoor concentrations tend to be smaller than co-occurring outdoor levels.

The no-action threshold limit is set by National Environmental Protection Measures (NEPM) (0.08ppm) and USEPA (0.07ppm).

- **Particulates** are ubiquitous and highly variable contaminants in relation to source, composition and size. For the purpose of most studies, airborne particulates in two size fractions are measured: PM₁₀ and PM_{2.5} as particulate matter or dust with a mean effective diameter of 10 and 2.5 micrometres or less, respectively. Particulates are commonly present in air and may be deposited in the lung, mouth, throat or nose and be ingested. All people are continuously exposed to particulates from vehicular, combustion, construction, and industrial sources. Building filtration systems are only partially effective in reducing the exposure to particulates.

Recent epidemiological research suggests that there is no threshold at which health effects do not occur but the health effects vary widely depending on the composition of the particles, the size of the particles and the sensitivity of individuals. Generally, in non-industrial indoor environments, such as offices, symptoms may include minor irritation of mucous membranes, increased respiratory symptoms and aggravation of asthma.

The recommended limit given by NEPM and NABERS for Australia and LEED V4 is 0.05 milligrams per cubic metre ($0.05\text{mg}/\text{m}^3$) for PM_{10} and 0.015 milligrams per cubic metre ($0.015\text{mg}/\text{m}^3$) for $\text{PM}_{2.5}$.

Due to the varying composition of the particulates, in addition to size ranges, it may be advisable to collect particulates on filter membranes and subject them to elemental analysis by inductively coupled plasma mass spectrometry.

- **Microbiological contaminants** commonly found in buildings are bacteria and fungi (moulds and yeasts and their spores) as well as viruses. Micro-organisms are generally found on surfaces (such as carpet, ceiling, tiles, etc.), within the building's water systems, as well as in the air on dust and aerosol particles. Spores are more likely to be airborne. The building characteristics, conditions, use and maintenance leading to increased moisture or humidity indoors could change the number of aerosols containing micro-organisms that can be inhaled, increase or diminish the viability of the inhaled micro-organisms, or modify the susceptibility of occupants to infection. The obvious costs of respiratory illness include health care expenses and the costs of absence from work. Additionally, respiratory illness may cause a performance reduction at work. Previous studies have shown that viral respiratory illnesses can adversely affect performance on several computerised and paper-based tests that simulate work activities (Fisk, 2000).

It is generally accepted that levels of both total viable mould and total viable bacteria should be below 500 colony forming units per cubic metre of air ($500\text{cfu}/\text{m}^3$) and / or less than outside levels to indicate the indoor environment is not amplifying microbial growth. However, due to the complex biological, chemical and morphological nature of microbial matter, there has been no consensus on recommended levels. Some more recent bio-genomics work (Healthy Buildings 2015 Europe and Americas) have indicated both harmful and beneficial presence of microbial species but it is generally considered unsatisfactory if they are generated by the building or its occupants.

There is an increased awareness of the possibility of legionella aerosols, not just from cooling towers but also from potable water systems within buildings. This is particularly important for facilities housing vulnerable occupants such as hospitals, aged and child care.

Specific bacterial or fungal identification can be made on suitably collected microbiological

contaminants by specialists to determine specific risk profiles.

Noise or Acoustic Comfort

Acoustic comfort is the preferred term for noise as this potentially complex subject is more than just the loudness of noise. Auditory information can be a stimulus, distraction or annoyance.

Acoustic satisfaction for occupants requires speech privacy and comfortable sound levels. Distracting noise has a detrimental effect on complex task performance. Memory and problem solving decline with realistic office noise. For offices, 35 dBA is the most commonly accepted sound pressure limit.

Following the initial sound pressure survey, problem areas can be examined for source elimination or design management by use of reverberation, frequency, duration and other specialist studies.

Lighting

Lighting and lighting comfort is a large and rapidly evolving subject with the advent of controllable intensity and colour from LED type technologies.

Different areas of the building such as offices, meeting rooms and corridors have different lighting requirements. However as a primary measurement, tools such as NABERS adopt at desk vertical and horizontal lux measurements and a uniformity ratio of 3:1 to prevent over illumination of screen based work. For most cases, standards require desk illumination of about 350 lux and screen illumination of 100-150 lux. Further studies in problem areas can focus on glare, spectrum/ colour/ temperature, distribution and other parameters judged important by lighting specialists. The issue of energy conservation is also considered by some Green Building Council tools.

Occupant Satisfaction Survey

It is critical to obtain an occupant satisfaction response as well as the above mentioned measurements and these should be done within a closely specified time limit, for example as

described in the NABERS protocol. The NABERS protocol advises well established and professionally designed occupant surveys such as those developed by the Centre for the Built Environment (CBE) at Berkley University USA, Building Use Study (BUS) supplied by ARUP UK, or Building Occupants Survey System Australia (BOSSA) offered by Sydney University.

It should be emphasised that development of a comparable and effective building occupant survey requires specialist skills to provide that meaningful and comparable results that are able to be correlated to physical measurements.

Presentation and processing of occupant surveys and correlation is another aspect to consider. Care should be taken to consider personal, cultural and regulatory considerations.

EQUIPMENT SUITABLE FOR MEASUREMENT

All equipment used to measure the able parameters must have a current and valid calibration certificate to an accredited standard. Non-calibrated equipment is unlikely to give reliable, comparable data. Measurements are preferably taken by a person with suitable scientific and technical skills to be able to work the equipment, evaluate the suitability of the equipment to deliver the required detection limits, accuracy and reproducibility, design the sampling strategy to represent occupant exposure and to interpret the results. Different rating tools give guidance on the number of samples, locations and times for sampling.

The equipment must be suitable for use in occupied offices without unduly disturbing the occupants. Due to the wide variety of makes and models, it is not possible to provide specific recommendations or illustrations in this document but it is important to use equipment that has been certified and currently calibrated to ISO 17025 or a similar International Laboratory Accreditation Council (ILAC) acceptable standard. Most low cost surface solid state devices are not yet at this stage but there is intensive development, competition and claims in this market sector. In most cases, wearables are not suitable for the IEQ measurements discussed here. Suitable handheld and calibrated equipment can be found from manufacturers such as TSI, SKC and GrayWolf.

The effect of data from measurements on their own need to be verified by expertly constructed questionnaires to the occupants, since different communities and populations react in different ways to the possible combinations to the above parameters however there

are exposure limits, based on toxicological assessment, to minimise occupant dissatisfaction, sickness or loss of productivity.

- **Thermal Comfort:** Temperature is measured using thermocouple based digital thermometers whilst air speed is measured with a platinum wire anemometer.
- **Carbon Dioxide:** Carbon dioxide is measured using infra-red based equipment.
- **Carbon Monoxide:** Carbon monoxide is measured in the office space using infra-red based equipment.
- **Particulates:** On-site office measurements of particulates is conducted optically using a conventional or laser light source with either a mini-cyclone or size selective inlet to screen out larger particles. Alternatively, gravimetric assessment can be made using membrane filtration, after a mini-cyclone pre-treatment and weighing on a microbalance at an accredited laboratory.
- **Volatile Organic Compounds:** TVOC is measured by collecting the compounds by adsorption onto either a micro capillary or macro charcoal tube for thermal or solvent desorption into a gas chromatograph or mass spectrometer. Field instruments are not reliable as yet for IEQ assessment but, since they give instantaneous response, they are useful for tracing VOC sources in buildings.
- **Microbial Matter:** The traditional methods of measurement use collection onto agar plates with validated sampling heads. New enzyme, PCR or molecular methods are now available for identification of samples filtered or impinged in the office space.
- **Formaldehyde:** Formaldehyde is measured either with a fuel cell based field meter or, more reliably by adsorption onto chemically treated silica or resin and analysed by liquid or gas chromatography.
- **Acoustic Comfort:** Acoustic sound pressure is measured within the office space with a good quality sound pressure meter, able to discriminate sound pressure in the A spectrum and average results over various time ranges to discriminate short term incidental and sustained noise sources.

Again, it is important to stress that whilst equipment is available that can be operated relatively simply, IEQ assessment is based on appropriate sampling location, calibration, assessment, communication and wellbeing/health responsibilities. This requires training and

appropriate qualifications to provide defensible and accreditable reports. This also applies to the choice of analytical laboratories.

GUIDELINE LIMITS

Practical peer established guideline limits, based on research and applied experience, have been used by a number of major rating systems. For example, the Australian Government's National Australian Built Environment Rating System (NABERS) has pioneered the use of standardised methodologies for assessing and rating indoor environment quality and the related occupant satisfaction of the measured spaces in occupied buildings. This has been used since 2008 to validate un-rated and green buildings accredited by design rating systems from WGBBC members such as LEED, Building Research Establishment Environmental Assessment Method (BREEAM), GBCA and IGBC throughout Australia and New Zealand and less intensively in The UK. LEED, BREEAM, German, French and Japanese systems and more recently Delos Inc. also publish limits that are used for rating.

The key guidelines used by widely accepted and established standard or rating setting agencies are presented below. Some commercial products, some purporting even to be standards, have set aspirational limits that have not yet been evaluated or have insufficient data with respect to operational IEQ.

Table 1 below summarises a selection of target limits and recommended investigation limits:

Table 1: Selected Air Quality Target Limits

IAQ Parameter	Cited Threshold	Cited Reference
Temperature	21-24°C	ASHRAE 55
Relative humidity	40-60%	ASHRAE 55
Carbon dioxide	1000ppm 500 ppm	ASHRAE 62 Wargocki 2016
Carbon monoxide	9ppm	LEED V4 / NABERS
Particulates - PM ₁₀	0.05mg/m ³	LEED V4 / NABERS
Particulates - PM _{2.5}	0.015mg/m ³	LEED V4
Total Volatile Organic Compounds	500µg/m ³	LEED V4 /NABERS
Formaldehyde	40µg/m ³ (27ppb) 100µg/m ³ (80ppb)	LEED V4 / NABERS
Sulphur dioxide	0.01ppm (24hr TWA) 0.2ppm (10min TWA)	WHO
Nitrogen dioxide	0.12ppm	WHO
Ozone	0.08ppm 0.05ppm	LEED V4 WELL
Total viable mould count	500cfu/m ³	SS 554 Code of practice for indoor air quality
Total viable bacteria count	500cfu/m ³	SS 554 Code of practice for indoor air quality
Acoustic comfort	35-45db	NABERS
Lighting	320 lux (horizontal) 160 lux (vertical)	NABERS
Occupant satisfaction survey	CBE/BUS	NABERS

A TYPICAL SEQUENCE OF ACTIONS TO CONDUCT AN IEQ STUDY IS AS FOLLOWS:

For rating a building:

Assuming that the Facility Manager is not a rating professional,

1. Read the appropriate rating document for requirements and procedures. Visit the rating authority website (not always the Green Building Council for your country).
2. Contact an accredited rating professional and obtain advice for options, needed information, and procedures.
3. Check any aspect of the advice with the rating authority either on website or directly.
4. Supply the basic information needed by the rating professional eg NLA, occupants, floor plans, HVAC details, past problems and existing IEQ data – including BMS data.
5. Request a budgeted proposal from the rating professional for both physical measurements and occupant survey.
6. Conduct a presentation to stakeholders eg with CEO, CFO, HRM, FMM with the rating professional to finalise an agreed scope.
7. Obtain a final costed and detailed proposal from the rating professional.
8. Conduct a presentation to office floor stakeholders eg with Section managers, unions, HRE delegates, with the rating professional and FMM to schedule the study for maximum participation, if an occupant satisfaction survey is required and to ensure minimum disruption of a normal working day. Do not schedule studies during holiday periods or abnormal absences or activities.
9. Conduct the site measurements and occupant survey as required by the accredited professional – specialist monitoring organisations and laboratories may have to be subcontracted.
10. The accredited professional assesses the data and supplies the report to the senior stakeholders.
11. The accredited professional to conduct a presentation to the required stakeholders. Since this data is of significance to occupant health and wellbeing, the HRM must be

involved and the presentation to be balanced and sensitive to occupants and organizational needs.

12. The stakeholders and accredited professional decide if the data warrants formal accreditation.
13. USE the data as KPI's for continuous improvement, occupant communication or maintenance of excellence.
14. Submission of report for accreditation
15. Share the accreditation decision with stakeholders and customers and PRM.
16. Use the data for HRM and CFO wellness and productivity assessments.
17. Start preparations for the next assessment.

Whilst the above appears to be involved and possibly complex, by liaison with a suitably qualified professional the process can be considerably simplified, and become an effective and efficient indoor environment quality study. An additional benefit is the positive effects on staff perception of management's concern of their wellbeing. In all situations the data should be used for ongoing management as a key performance indicator and a guide for remediation of unsatisfactory conditions.

WorldGBC thanks CETEC for their work on this Guidance Note.

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