International Performance Measurement & Verification Protocol

Concepts and Practices for Improved Indoor Environmental Quality

Volume II

Revised March 2002

www.ipmvp.org

International Performance Measurement & Verification Protocol

Concepts and Practices for Improved Indoor Environmental Quality

Volume II

International Performance Measurement
& Verification Protocol Committee

Revised March 2002
DOE/GO-102002-1517

www.ipmvp.org

Hard copies available, in limited quantities, from the Energy Efficiency
and Renewable Energy Clearinghouse at 1-800-363-3732.

Available electronically at http://www.doe.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Table of Contents

Acknowledgements

Participating Organizations

Brazil	• Institute Nacional De Eficiencia Energetica (INEE) • Ministry of Mines and Energy
Bulgaria	Bulgarian Foundation for Energy Efficiency (EnEffect)
Canada	• Canadian Association of Energy Service Companies (CAESCO) • Natural Resources Canada (NRC)
China	• State Economic and Trade Commission • Beijing Energy Efficiency Center (BECON)
Czech Republic	Stredisko pro Efektivni Vyuzivani Energie (SEVEn7)
India	Tata Energy Research Institute (TERI)
Japan	Ministry of International Trade and Industry (MITI)
Korea	Korea Energy Management Corporation (KEMCO)
Mexico	• Comision Nacional Para El Ahorro De Energia (CONAE) • Fideicomiso De Apoyo Al Programa De Ahorro De Energia Del Sector Electrico (FIDE)
Poland	The Polish Foundation for Energy Efficiency (FEWE)
Russia	Center for Energy Efficiency (CENEf)
Sweden	Swedish National Board for Technical and Urban Development
Ukraine	Agency for Rational Energy Use and Ecology (ARENA - ECO)
United Kingdom	Association for the Conservation of Energy
United States	• American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) • Association of Energy Engineers (AEE) • Association of Energy Services Professionals (AESP) • Building Owners and Managers Association (BOMA) • National Association of Energy Service Companies (NAESCO) • National Association of State Energy Officials (NASEO) • National Realty Association • U.S. Department of Energy (DOE) • U.S. Environmental Protection Agency (EPA)

IPMVP Committees

Executive Committee

1 Gregory Kats (Chair), Department of Energy, USA
2 Jim Halpern (Vice Chair), Measuring and Monitoring Services Inc., USA
3 John Armstrong, Hagler Bailly Services, USA
4 Flavio Conti, European Commission, Italy
5 Drury Crawley, US Department of Energy, USA
6 Dave Dayton, HEC Energy, USA
7 Adam Gula, Polish Foundation for Energy Efficiency, Poland
8 Shirley Hansen, Kiona International, USA
9 Leja Hattiangadi, TCE Consulting Engineers Limited, India
10 Maury Hepner, Enron Energy Services, USA
11 Chaan-min Lin, Hong Kong Productivity Council, Hong Kong
12 Arthur Rosenfeld, California Energy Commission, USA

Technical Committee

1 John Cowan (Co-chair), Cowan Quality Buildings, Canada
2 Steve Kromer (Co-chair), Enron Energy Services, USA
3 David E. Claridge, Texas A & M University, USA
4 Ellen Franconi, Schiller Associates, USA
5 Jeff S. Haberl, Texas A & M University, USA
6 Maury Hepner, Enron Energy Services, USA
7 Satish Kumar, Lawrence Berkeley National Laboratory, USA
8 Eng Lock Lee, Supersymmetry Services Pvt. Ltd., Singapore
9 Mark Martinez, Southern California Edison, USA
10 David McGeown, NewEnergy, Inc., USA
11 Steve Schiller, Schiller Associates, USA

Indoor Environmental Quality Committee

1 Bill Fisk (Chair), Lawrence Berkeley National Laboratory, USA
2 Jim Bailey, Building Dynamics, USA
3 Dave Birr, Synchronous Energy Solutions, USA
4 Steve Brown, CSIRO, Australia
5 Andrew Cripps, Building Research Establishment, UK
6 John Doggart, ECD Energy and Environment, UK
7 Dale Gilbert, Built Environment Research, Australia
8 Mike Jawer, Building Owners & Managers Association, USA

9 Gregory Kats, Department of Energy, USA
10 Ken-ichi Kimura, Waseda University, Japan
11 Satish Kumar, Lawrence Berkeley National Laboratory, USA
12 Hal Levin, Hal Levin & Associates, USA
13 Richard Little, National Academy of Sciences, USA
14 David Mudarri, Environmental Protection Agency, USA
15 Tedd Nathanson, Public Works and Government Services, Canada
16 Andy Persily, National Institute of Standards and Technology, USA
17 Arthur Rosenfeld, California Energy Commission, USA
18 Sumeet Saksena, Tata Energy Research Institute, India
19 Olli Seppanen, Helsinki University of Technology, Finland
20 Jan Sundell, Int l Center for Indoor Environment and Energy, Denmark
21 Steve Turner, Chelsea Group, USA
22 Ole Valbjoern, Danish Building Research Institute, Denmark

Indoor Environmental Quality Reviewers

1 Ed Arens, University of California, Berkeley, USA
2 Jan W Bakke, Norway
3 Carl-Gustaf Bornehag, Hibbitt, Karlsson & Sorensen, Inc., Sweden
4 Terry Brennan, Camroden Associates, USA
5 Graham Charlton, Australian Institute of Refrigeration, Air-Conditioning & Heating, Australia
6 Susan Clampitt, General Services Administration, USA
7 Geo Clausen, Technical University, Denmark
8 Jim Coggins, Energy Applications, Inc., USA
9 Catherine Coombs, Steven Winter Associates, Inc., USA
10 Joan Daisey, Lawrence Berkeley National Laboratory, USA
11 Richard deDear, Macquarian University, Australia
12 Angelo Delsante, CSIRO, Australia
13 David Grimsrud, University of Minnesota, USA
14 Shirley Hansen, Kiona International, USA
15 Sten Olaf Hansen, Norwegian University of Science and Technology, Norway
16 Jim Harven, Custom Energy, USA
17 Matti J. Jantunen, National Public Health Institute, Finland
18 Erkki Kahkonen, Finnish Institute of Occupational Health, Finland
19 Pentti Kalliokoski, University of Kuopio, Finland
20 Greg Kurpiel, Johnson Controls, USA
21 Marianna Luoma, VTT Building Technology, Finland
22 Mark Mendell, NIOSH, USA
23 Jack McCarthy, Environmental Health and Engineering Inc., USA

24 Aino Nevalainen, National Public Health Institute, Finland
25 Rob Obenreder, General Services Administration, USA
26 Bud Offermann, Indoor Environment Engineering, San Francisco, USA
27 Deo Prasad, University of New South Wales, Australia
28 Dan Prezembel, The RREEF Funds, USA
29 John Reese, Department of Energy, USA
30 Ed Reid, American Gas Cooling Center, USA
31 James Rogers, Energy Consultant, USA
32 Jorma Sateri, Finnish Society of Indoor Air Quality and Climate, Finland
33 Christine Schweizer, Environment Australia, Australia
34 Jaikrishna Shankavaram, Carnegie Mellon University, USA
35 Staffan Skerfving, Lund University, Sweden
36 John Talbott, Department of Energy, USA
37 Steve Taylor, Taylor Engineering, USA
38 John Tiffany, Tiffany Bader Environmental, USA
39 Gene Tucker, Environmental Protection Agency, USA
40 Dave Warden, DWT Engineering, Canada
41 Davidge Warfield, Tri-Dim Filter Corporation, USA
42 Jim Woods, HP Woods Research Institute, USA

Technical Coordinator

Satish Kumar, Lawrence Berkeley National Laboratory, USA
Email: SKumar@lbl.gov, Phone: 202-646-7953

We would like to gratefully acknowledge the many organizations that made the IPMVP possible. In particular we would like to thank the Office of Building Technology, State and Community Programs in the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, which has provided essential funding support to the IPMVP, including publication of this document.

The reprinting of Volume I and II of the IPMVP has been made possible through a generous grant from the U.S. Department of Energy's Federal Energy Management Program (FEMP). FEMP's gesture is greatly appreciated by the IPMVP.

Disclaimer

This Protocol serves as a framework to determine energy and water savings resulting from the implementation of an energy efficiency program. It is also intended to help monitor the performance of renewable energy systems and to enhance indoor environmental quality in buildings. The IPMVP does not create any legal rights or impose any legal obligations on any person or other legal entity. IPMVP has no legal authority or legal obligation to oversee, monitor or ensure compliance with provisions negotiated and included in contractual arrangements between third persons or third parties. It is the responsibility of the parties to a particular contract to reach agreement as to what, if any, of this Protocol is included in the contract and to ensure compliance.

1 Introduction

This year 2000 edition of International Performance Measurement and Verification Protocol (IPMVP) has been expanded to address indoor environmental quality (IEQ) issues. It provides information that will help energy efficiency professionals and building owners and managers maintain or improve IEQ and occupant health and comfort during the implementation of building energy conservation measures in retrofits or new construction of commercial and public buildings.

Volume II focuses exclusively on indoor environmental quality issues (See Preface of Volume I for overview of IPMVP). This volume starts with a general introduction to IEQ. Best practices for maintaining a high level of IEQ are then reviewed. The potential positive and negative influences of specific energy conservation measures on IEQ are summarized in a tabular format in *Section 5*. The remainder of the document addresses IEQ measurement and verification procedures that may be used to address the following goals: 1) ensure that the energy conservation measures have no adverse influence on IEQ, 2) quantify the improvements in IEQ resulting from implementation of energy conservation measures, and 3) verify that selected IEQ parameters satisfy the applicable IEQ guidelines or standards. A multi-step procedure for IEQ measurement and verification is presented, followed by a discussion of general approaches for measurement and verification and then by a table of measurement and verification alternatives linked to specific IEQ parameters.

This document has been prepared by an international team of IEQ and building energy efficiency experts and reflects the current state of knowledge. The IPMVP, including the IEQ volume will be updated every two years.

2 Purpose

The International Performance Measurement and Verification Protocol (IPMVP) provides a framework and guidance for the measurement and verification of building energy performance, emphasizing the changes in energy performance that result from implementation of energy conservation measures in buildings. Many building energy conservation measures have the potential to positively or negatively affect indoor pollutant concentrations, thermal comfort conditions, and lighting quality. These and other indoor environmental characteristics are collectively referred to as indoor environmental quality[1].

IEQ can influence the health and productivity of building occupants. Small changes in occupant health and productivity may be very significant financially, potentially exceeding the financial benefits of energy conservation (Fisk and Rosenfeld, 1998). It is important that these IEQ considerations be explicitly recognized prior to selection and implementation of energy conservation measures[2]. Consequently, the primary purpose of this document is to provide information that will help energy conservation professionals and building owners and managers maintain or improve IEQ when they implement building energy conservation measures in non-industrial commercial and public

1. The term indoor air quality (IAQ) is sometimes used for the same purpose, although IAQ is also used more narrowly in reference to the levels of pollutants in indoor air.

2. Conversely, when selecting measures to improve IEQ, the potential impacts of these measures on building energy use should be considered. This document does not directly address this situation but it includes some relevant information.

buildings[1]. This document also describes some practical IEQ and ventilation measurements that, in certain circumstances, can also help energy conservation professionals maintain or improve IEQ.

3 How to Use

Section 4 and *5* of this document introduce IEQ through discussions of IEQ parameters, indoor pollutant sources, IEQ standards, and methods of maintaining a high level of IEQ. These sections are designed to educate building energy professionals about IEQ and to provide a foundation for subsequent sections of the document. Professionals with a strong working knowledge of IEQ issues can skip *Section 4* and *5*. *Section 6* describes the linkage between specific energy conservation measures and IEQ, highlighting measures that are particularly attractive because they often improve IEQ while saving energy. This information is provided in a table so readers can quickly identify the information relevant to their situation. Some users of this document may not need to read beyond *Section 6* because their energy conservation efforts are not likely to significantly influence IEQ. *Section 7* provides a discussion of the application of *Section 6* to specific buildings. *Section 8* addresses IEQ measurement and verification (M&V). An overall IEQ M&V procedure is provided along with a description of basic M&V approaches and a table of M&V alternatives for specific IEQ parameters. The most practical and useful M&V alternatives are highlighted. *Section 9* discusses how to implement the concepts laid out in this document. Concluding remarks and references are in *Sections 10* and *11*, respectively.

4 General Introduction to Indoor Environmental Quality

4.1 Important Energy-Related IEQ Parameters

Many characteristics of the indoor environment may influence comfort, health, satisfaction, and productivity of building occupants. The following indoor-environmental characteristics are most likely to be influenced by building energy conservation measures:

- indoor thermal conditions such as air temperature and its vertical gradient, mean radiant temperature, air velocity, and humidity;
- concentrations of pollutants and odors in indoor air and amount of pollutants on surfaces;
- lighting intensity and quality;

This document provides more detailed information on indoor air pollution than on thermal comfort and lighting because the users of the IPMVP are less likely to be knowledgeable about indoor air pollution.

4.2 Indoor Thermal Conditions

The influence of the indoor thermal environment on thermal comfort is widely recognized. Thermal comfort has been studied for decades resulting in thermal comfort standards and models for predicting the level of satisfaction with the thermal environment as a function of the occupants clothing and activity level

1. This document is not intended as substitute for local codes or as a guide to diagnosis and solving specific IAQ and health problems. Hospitals and other health care facilities have special indoor air quality requirements that are not addressed in this document.

(ASHRAE 1997). Despite the significant attention placed on thermal comfort by building professionals, dissatisfaction with indoor thermal conditions is the most common source of occupant complaints in office buildings (Federspiel 1998). In a large field study (Schiller et al. 1988), less than 25% of the subjects were moderately satisfied or very satisfied with air temperature. Also, 22% of the measured thermal conditions in the winter, and almost 50% of measured thermal conditions in the summer, were outside of the boundaries of the 1988 version of the ASHRAE thermal comfort zone. These findings indicate that greater effort should be placed on maintaining thermal conditions within the prescribed comfort zones. Even in laboratory settings with uniform clothing and activity levels, it is not possible to satisfy more than 95% of occupants by providing a single uniform thermal environment (Fanger 1970) because thermal preferences vary among people. Task conditioning systems that provide occupants limited control of the air temperature and velocity in their workstation are being explored as a means to maximize thermal comfort (e.g., Arens et al. 1991, Bauman et al. 1993).

Extremes in humidity will adversely influence thermal comfort (ASHRAE 1997, Chapter 8). ASHRAE s thermal comfort zones for summer and winter have a lower absolute humidity boundary of 0.045 g H2O per kg dry air corresponding approximately to a 30% RH at 20.5°C and a 20% RH at 27°C. Relative humidities below approximately 25% have been associated with complaints of dry skin, nose, throat, and eyes. At high humidities, discomfort will increase due substantially to an increase of skin moisture. The upper humidity limits of ASHRAE s thermal comfort zone vary with temperature from approximately 60% RH at 26°C to 80% RH at 20°C.

Air temperature and humidity also influence perceptions of the quality of indoor air and the level of complaints about non-specific building-related health symptoms (often called sick building syndrome symptoms). Higher air temperature has been associated with increased health symptom prevalences in several studies (Skov et al. 1989, Jaakkola et al. 1991, Wyon 1992, Menzies et al. 1993). Occupants perceived acceptability of air quality has been shown to decrease as temperature and humidity increase in the range between 18°C, 30% RH and 28°C, 70% RH (Fang et al. 1997, Molhave et al. 1993).

4.3 Indoor Lighting

The quality of the indoor environment depends significantly on several aspects of lighting (IES 1993, Veitch and Newsham 1998) including the illuminance (intensity of light that impinges upon a surface), the amount of glare, and the spectrum of the light[1]. There is evidence that a decrease in the amount of flicker in light, i.e., the magnitude of the rapid cyclic change in illuminance over time, may be associated with a decrease in headache and eyestrain (Wilkens et al. 1988) and with an increase in worker performance (Veitch and Newsham 1997). In many indoor spaces, the indoor environment is influenced by both daylight and by artificial lighting. Characteristics of windows and skylights and their shading affect the daylighting of indoors. The quality of electric indoor lighting is a function of the types, locations, and number of luminaires, and the optical characteristics of indoor surfaces such as their spectral reflectivity and color.

1. The evidence for effects of spectrum of light on satisfaction and performance is mixed (e.g., Veitch 1994, Berman 1992)

The method of lighting control, such as no control, automatic dimming of artificial light, and manual control of overhead or task lighting may also influence lighting quality.

Lighting characteristics influence the quality of vision and can have psychological influences on mood and on perceptions about the pleasantness of a space. Because extremes in lighting have a clear impact on performance, indoor lighting in commercial buildings is usually maintained within the limits specified in guidelines or standards. The recommended range of illuminance is a function of the type of visual activity and the age of the occupants. Guidelines also provide recommendations for the maximum luminance ratio, i.e., range of luminance in the visual field. Occupants satisfaction with lighting may vary with illuminance and with the characteristics of the lighting system (Katzev 1992).

4.4 Indoor Pollutants, Their Sources, and Health Effects

There are a large number of indoor air pollutants that can influence occupant health and the perceived acceptability of indoor air. The following paragraphs introduce these pollutants.

Gaseous human bioeffluents: Humans release a variety of odorous gaseous bioeffluents, e.g., body odors, which influence the perceived acceptability of indoor air. Historically, most standards and guidelines for minimum ventilation rates in buildings have been based primarily on the ventilation needed to maintain indoor air acceptable to a large proportion (e.g., 80%) of visitors when they initially enter a space with occupants as the only indoor pollutant source. In the last decade, concerns about other sources of odors and adverse health effects from air pollutants have increasingly influenced building ventilation standards.

Carbon dioxide (CO_2) is one of the gaseous human bioeffluents in exhaled air. Humans are normally the main indoor source of carbon dioxide. Unvented or imperfectly vented combustion appliances can also increase indoor CO_2 concentrations. The outdoor CO_2 concentration is often approximately 350 ppm[1], whereas indoor concentrations are usually in the range of 500 ppm to a few thousand ppm. At these concentrations, CO_2 is not thought to be a direct cause of adverse health effects; however, CO_2 is an easily-measured surrogate for other occupant-generated pollutants, such as body odors.

The indoor CO_2 concentration is often used, sometimes inappropriately, as an indicator of the rate of outside air supply per occupant. If the number of occupants and the rate of outside air supply are constant and the CO_2 generation rate of occupants is known, the rate of outside air supply per occupant is related to the equilibrium indoor CO_2 concentration in a straightforward manner as predicted by a steady-state mass balance calculation (Persily and Dols 1990). However, in many buildings, CO_2 concentrations never stabilize during a workday because occupancy and ventilation rates are not stable for a sufficient time period. If the CO_2 concentration has not stabilized at its equilibrium value and the steady-state relationship between CO_2 and ventilation rate is used to estimate the rate of outside air supply, the estimated outside air ventilation rate may be substantially in error.

1. In urban areas, outdoor CO2 concentrations may substantially exceed 350 ppm and vary considerably with time.

Carbon monoxide (CO) and nitrogen oxides (NOx): Indoor concentrations of CO and NOx may be higher than outdoor concentrations due to indoor unvented combustion (e.g., unvented space heaters), failures in the combustion exhaust vent systems of vented appliances, and leakage of air from attached parking garages into the building. Tobacco smoking can cause a small increase in indoor CO concentrations. Short-term exposures to highly elevated concentrations of CO can cause brain damage or death (NRC 1981). Lower concentrations can cause chest pain among people with heart disease (NRC 1981). NO_2 is usually considered to be the most important of the indoor nitrogen oxides. High concentrations (e.g., 0.5 ppm) of NO_2 can cause respiratory distress in individuals with asthma and concentrations of approximately 1 ppm cause increased airway resistance in health individuals (NRC 1981). Long term exposure to much lower concentrations of NO2 may be associated with increased respiratory illness among children (Vedal 1985).

Volatile organic compounds (VOCs): VOCs are a class of gaseous pollutants containing carbon. The indoor air typically contains dozens of VOCs at concentrations that are measurable. VOCs are emitted indoors by building materials (e.g., paints, pressed wood products, adhesives, etc.), furniture, equipment (photocopying machines, printers, etc.), cleaning products, pest control products, and combustion activities (cooking, unvented space heating, tobacco smoking, indoor vehicle use). Humans also release VOCs as a consequence of their metabolism and use of personal products such as perfumes. The outdoor air entering buildings also contains VOCs. VOCs in contaminated soil adjacent to the building can also be drawn into buildings.

New building materials and furnishings generally emit VOCs at a much higher rate than older materials. Emission rates for many VOCs may decline by an order of magnitude during the first few weeks after the materials are installed in the building. However, the emission rates of some VOCs, such as formaldehyde emissions from pressed wood products, decline much more slowly. Because of concerns about the health effects of VOCs, many manufacturers have worked to reduce the VOC emissions of their products, and some will provide emission information to their customers.

Some VOCs are suspected or known carcinogens or causes of adverse reproductive effects. Some VOCs also have unpleasant odors or are irritants. VOCs are thought to be a cause of non-specific health symptoms that are discussed subsequently.

The total volatile organic compound (TVOC) concentration, often used as a simple, integrated measure of VOCs, is defined as the total mass of measured VOCs per unit volume of air, exclusive of very volatile (e.g., formaldehyde) organic compounds. Laboratory studies in which humans have been exposed to mixtures of VOCs under controlled conditions (Molhave et al. 1986 and 1993) have documented increased health symptoms at TVOC concentrations of the order of milligrams per cubic meter of air. A panel of 12 Nordic researchers reviewed the literature on VOCs/TVOCs and health and concluded that indoor pollution including VOC is most likely a cause of health effects and comfort problems and that the scientific literature is inconclusive with respect to TVOC as a risk index for health and comfort (Andersson et al. 1997). As an indicator of health effects, the TVOC concentration is inherently flawed because the potency of individual VOCs to elicit irritancy symptoms varies by orders of magnitude (Tenbrinke 1995). The potency for other potential health effects such as cancer or reproductive effects is also highly variable among compounds.

Despite these limitations, unusually high TVOC concentrations in commercial buildings, above one or two mg m-3 (Daisey et al. 1994), do indicate the presence of strong VOC sources. Further investigations to determine the composition of the VOCs and/or to identify the sources may be warranted. The probability of adverse heath or comfort effects caused by the high TVOC exposures will depend on the composition of the VOC mixture and on the concentrations of odorous or harmful compounds.

Radon is a naturally-occurring radioactive gas. The primary source of radon in most buildings is the surrounding soil and rock. Radon enters buildings from soil as soil gas is drawn into buildings and also enters by diffusion through the portions of buildings that contact soil. Earth-based building materials and water from wells can also be a source of radon. Radon exposure increases the risk of lung cancer (BEIR VI 1998).

Ozone is brought into buildings with outdoor air. Certain types of office equipment, such as photocopy machines and laser printers, can also be a source of indoor ozone. Ozone causes pulmonary inflammation and other pulmonary health effects. Ozone is removed from indoor air by reaction with indoor surfaces; thus indoor ozone concentrations are usually lower than outdoor concentrations. If indoor sources of ozone are limited, increasing the ventilation rate, while decreasing concentrations of indoor-generated pollutants, will usually increase the indoor ozone concentration.

In addition to the direct effects of ozone on health, ozone can react chemically with VOCs in the indoor air or with surface materials. These reactions may produce VOCs that may be a source of chemical irritation (Weschler and Schields 1997).

Moisture is not a pollutant but it has a strong influence on indoor environmental quality. Water vapor is generated indoors due to human metabolism and human activities involving water use, as well as due to unvented combustion activities and by humidifiers. Moist soil may be a source of moisture in indoor air and in the flooring materials that contact the soil. The implications of high humidity for human health are complex and still a subject of debate (Baughman and Arens 1996, Arens and Baughman 1996). In some situations, high relative humidities may contribute to growth of fungi and bacteria that can adversely affect health.

Condensation of water on cool indoor surfaces (e.g., windows) may damage materials and promote the growth of microorganisms. Water leaks, such as roof and plumbing leaks, and exposure of building materials to rain or snow during building construction are a frequent source of material damage and growth of microorganisms. There is quite strong evidence that moisture problems in buildings lead to adverse respiratory health effects such as a higher prevalence of asthma or lower-respiratory-tract symptoms (e.g., Brunekreef 1992, Dales et al. 1991, Spengler et al. 1993; Smedje et al. 1996, Division of Respiratory Disease Studies 1984). There are many case studies of moisture-related microbiological problems in commercial buildings. The presence of humidifiers in commercial building HVAC systems has been associated with an increase in various respiratory health symptoms.

Particles are present in outdoor air and are also generated indoors from a large number of sources (Owen et al. 1992) including tobacco smoking and other combustion processes. Some particles and fibers may be generated by indoor equipment (e.g. copy machines and printers). Mechanical abrasion and air motion may cause particle release from indoor materials. Particles are also produced by people, e.g., skin flakes are shed and droplet nuclei are generated from sneezing and coughing. Some particles may contain toxic chemicals. Some particles, biologic in origin, may cause allergic or inflammatory reactions or be a source of infectious disease. Increased morbidity and mortality is associated with increases in outdoor particle concentrations (EPA 1996), even when concentrations are in the vicinity of the U.S. national ambient air quality standard (50 µgÆm^3 for particles smaller than 10 micrometer). Of particular concern are the particles smaller than 2.5 micrometers in diameter, which are more likely to deposit deep inside the lungs (EPA 1996). A national ambient air quality standard for particles (http://www.epa.gov/airs/criteria.html) smaller than 2.5 micrometers was established by the US Environmental Protection Agency (EPA) in 1997 (15 µgÆm^3 for the three-year average of the annual arithmetic mean concentration; 65 µgÆm^3 24-hour average).

Particle size is important because it influences the location where particles deposit in the respiratory system (EPA 1996), the efficiency of particle removal by air filters, and the rate of particle removal from indoor air by deposition on surfaces. The large majority of indoor particles are smaller than 1 µm. Particles smaller than approximately 2.5 µm are more likely to deposit deep inside the lungs. Many of the **bioaerosols** are approximately 1 µm and larger, with pollens often larger than 10 µm. These larger particles deposit preferentially in the nose.

Non-infectious bioaerosols include pollens, molds, bacteria, dust mite allergens, insect fragments, and animal dander. The sources are outdoor air, indoor mold and bacteria growth, insects, and pets. These bioaerosols may be brought into buildings as air enters or may enter buildings attached to shoes and clothing and subsequently be resuspended in the indoor air. The health effects of non-infectious bioaerosols include allergy symptoms, asthma symptoms, and hypersensitivity pneumonitis which is characterized by inflamation of the airway and lung (Gammage and Berven 1997).

Infectious non-communicable bioaerosols are airborne bacteria or fungi that can infect humans but that have a non-human source (Gammage and Berven 1997). The best known example is Legionella, a bacterium that causes Legionnaires Disease and Pontiac Fever. Cooling towers and other sources of standing water (e.g., humidifiers) are thought to be a source of aerosolized Legionella in buildings. Legionella may also be present in potable water systems and aspiration of potable water is also thought to be a potential source of infection with Legionella. Some fungi, from sources within a building, can also infect individuals who are immune compromised.

Infectious communicable bioaerosols generated by one person may cause disease in others. These bioaerosols contain bacteria or virus within small droplet nuclei produced from the drying of larger liquid droplets, often expelled during coughing or sneezing. Examples of respiratory diseases transmitted, at least in part, by bioaerosols include tuberculosis, influenza, measles, and some types of common colds. Several studies, as reviewed in Fisk and Rosenfeld (1997), have indicated that building characteristics may significantly influence the incidence of respiratory disease among building occupants.

Fibers in indoor air include those of asbestos, and man-made mineral fibers such as fiberglass, and glass wool. The primary indoor sources are building materials, especially insulation products. Exposures to asbestos in industrial settings have been shown to cause lung cancer and other lung disease. Fiberglass and glass wool fibers are a source of skin irritation. The link between fiberglass and glass wool fibers and lung cancer remains uncertain.

Environmental tobacco smoke (ETS) is the diluted mixture of pollutants caused by smoking of tobacco and emitted into the indoor air by a smoker (as opposed to the mainstream smoke inhaled by a smoker). Constituents of ETS include submicron-size particles composed of a large number of chemicals, plus a large number of gaseous pollutants. ETS is a source of odor and irritation complaints. Panels of experts have reviewed the scientific evidence pertaining to the health effects of ETS and concluded that ETS is causally associated with lung cancer and heart disease in adults and asthma induction, asthma exacerbation, acute lower respiratory tract infections, and middle ear infection in children (EPA 1992, California EPA 1997).

4.5 Controlling Indoor Pollutant Concentrations

The indoor concentration of a particular air pollutant depends on the outdoor concentration, the indoor pollutant generation rate, and on the total rate of pollutant removal by ventilation, air cleaning, and other removal processes. A simple mass balance equation can be used to illustrate the relationship among these variables at steady state in a space with well-mixed air:

$$\text{Indoor Conc.} = \text{Outdoor Conc.} + \frac{\text{Indoor Pollutant Generation Rate}}{\text{Ventilation rate} + \text{Air Cleaning Rate} + \text{Rate of Other Removal Processes}} \qquad \textbf{Eq. 1}$$

4.5.1 Pollutant Sources

The indoor pollutant generation rate is a function of the type and quantity of indoor pollutant sources. For pollutants that have primarily indoor sources, excluding human bioeffluents, the indoor pollutant source strength tends to vary over a wider range than the other parameters that affect indoor pollutant concentrations. The indoor pollutant generation rate is often considered to be most important determinant of the indoor pollutant concentration. Eliminating or minimizing the emissions of pollutants from indoor sources is a highly effective and energy efficient means of reducing indoor pollutant concentrations.

4.5.2 Ventilation

In addition to minimizing the emissions of pollutants from indoor sources, to maintain acceptable IEQ, ventilation with outside air must be provided at an adequate rate. The ventilation rate, i.e., the rate of outside air supply, is usually normalized by the floor area (LÆs^{-1}Æm^{2}), number of occupants (LÆs^{-1} per person), or indoor air volume (h^{-1} or air changes per hour). The outside air supplied to a building must be distributed properly to the various rooms to maintain acceptable IEQ throughout the building. The required rate of outside air supply often changes with time because of changes in occupancy and indoor pollutant emission rates.

Often, local exhaust ventilation is used in rooms with high pollutant or odor sources. Exhaust ventilation is more efficient in controlling indoor pollutant concentrations than general ventilation of the entire space (general ventilation is often called dilution ventilation). Exhaust ventilation is a means of controlling pressure differentials, as described below.

4.5.3 Pressure Control

HVAC systems are often used in commercial buildings to maintain pressure differences between indoors and outdoors or between different indoor spaces. Maintaining buildings under positive pressure relative to outdoors can help to maintain IEQ by limiting the infiltration of outdoor air that may adversely affect thermal comfort and that may contain moisture and pollutants. Maintaining pressure differences between different indoor spaces can limit the rate of pollutant transport between these spaces. For example, smoking rooms, bathrooms, and laboratories are often depressurized so that pollutants generated within these rooms do not leak into the surrounding rooms.

4.5.4 Air Cleaning

Gaseous or particulate air cleaning (ASHRAE 1996, Chapters 24 and 25) may be used to remove air pollutants from recirculated indoor air or from incoming outdoor air. Most commercial buildings use particle filters in the HVAC system. Commonly, these filters have a low particle removal efficiency for particles smaller than approximately one micrometer in diameter (Hanley et al. 1994). However, particle filters with a wide range of efficiencies for submicron-size particles are readily available for use in commercial buildings and indoor particle concentrations may be lowered substantially by the use of higher efficiency air filters. To maintain the efficiency of filter systems, the filter installation method must prevent significant air leakage between or around the filters. In contrast to particle filters, gaseous air cleaners, such as beds of activated carbon, are used in only a small minority of buildings because of their higher costs and uncertain performance; however, considerable effort is being devoted to the development of new technologies for gaseous air cleaning.

Air cleaning systems require regular maintenance. For example, air filters must be periodically replaced to prevent reductions in air flow and to limit odor emissions and microbiological growth from soiled filters.

4.5.5 Natural Pollutant Removal Processes

For some pollutants there are other natural removal processes. Examples are loss of ozone due to its reaction with indoor surfaces and the deposition of particles on surfaces. These removal processes can substantially influence the indoor concentrations of these pollutants.

4.5.6 Air Recirculation and Air Flow Patterns

The indoor air flow pattern also influences IEQ. Mechanical recirculation of air spreads pollutants emitted from localized sources throughout a building so that a larger population is exposed; however, recirculation may decrease the pollutant concentration near the source. Also, recirculation of air through air cleaning systems can reduce indoor pollutant concentrations.

The pattern of airflow within rooms also influences indoor pollutant exposures. A floor-to ceiling indoor airflow pattern, called displacement ventilation, can reduce pollutant concentrations in the breathing zone. A short-circuiting air flow pattern between supply and return air grills at ceiling level can increase pollutant concentrations in the breathing zone.

4.5.7 Maintenance, Cleaning, and Commissioning

Maintenance, cleaning, and commissioning of the HVAC system and building are generally thought to be significant determinants of indoor pollutant concentrations. Poor HVAC system maintenance may lead to poor control of indoor thermal comfort or outside air supply and to growth of microorganisms inside the HVAC system. Air filters may become sources of odors or a substrate for microbiological growth (e.g., Elixmann et al. 1990, Martikainen et al. 1990). HVAC system commissioning and air balancing help to assure that the system performs as intended. In a large study of office buildings with health complaints (Sieber et al. 1996), significantly increased prevalences of respiratory health symptoms were associated with poorer HVAC maintenance and less frequent building cleaning.

The methods and quality of building cleaning affects odor emissions from surfaces and the quantity of particles on surfaces that may become suspended in the air.

While increased maintenance and cleaning is generally considered beneficial, maintenance activities and products can be sources of indoor pollutants (e.g., cleaning compounds, waxes) and cleaning activities can be a source of resuspended particles.

4.6 Acute Non-Specific Health Symptoms and Building Related Illness

The general public is familiar with many of the health effects that may be influenced by IEQ (and by energy conservation measures), such as acute respiratory diseases, allergies, asthma, and cancer. This document will not discuss the nature of these health effects. Rather, this section will briefly describe two less familiar classes of building-related health effects: acute non-specific health symptoms associated with buildings and building related illness (BRI). More comprehensive discussions of the health effects associated with IEQ factors are provided in the published literature (e.g., Gammage and Berven 1996)

4.6.1 Non-Specific Health Symptoms

The most common health symptoms attributed by building occupants to their indoor environments are non-specific health symptoms that do not indicate a specific disease, such as irritation of eyes, nose, and skin, headache, fatigue, chest tightness, and difficulty breathing. These symptoms are commonly called sick building syndrome symptoms; however, we use the term non-specific health symptoms because the term sick-building syndrome can be misleading (i.e., the building is not sick and the building is not always the cause of symptoms). People commonly experience these non-specific health symptoms; however, their prevalence or severity varies considerably among buildings and, in some buildings, the symptoms coincide with periods of occupancy in the building. Buildings within which occupants experience unusually high levels of these symptoms are sometimes called sick buildings. Some non-specific health symptoms are experienced frequently by a substantial fraction of all office workers (e.g., Brightman et al. 1997, Fisk et al. 1993;

Nelson et al. 1995). The causes of non-specific health symptoms appear to be multifactorial and are not thoroughly understood. Although psychosocial factors such as the level of job stress are known to influence non-specific health symptoms, several characteristics of buildings and indoor environments are also known or suspected to influence these symptoms including: the type of ventilation system, type or existence of humidifier, rate of outside air ventilation, the chemical and microbiological pollution in the indoor air and on indoor surfaces, and indoor temperature and humidity (Mendell 1993; Sundell 1994). On average, occupants of sealed air-conditioned buildings report more symptoms than occupants of naturally ventilated buildings. Humidifiers increase the likelihood that occupants report these symptoms possibly because they can be a source of bioaerosols. Most studies have found that lower indoor air temperatures are associated with fewer non-specific health symptoms. Symptoms have been reduced through practical measures such as increased ventilation, decreased temperature, and improved cleaning of floors and chairs (Mendell 1993).

Non-specific health symptoms are a distraction from work and can lead to absence from work (Preller et al. 1990) and visits to doctors. When problems are severe and investigations of the building are required, there are financial costs to support the investigations and considerable effort is typically expended by building management staff, by health and safety personnel and by building engineers. Responses to non-specific health symptoms have included costly changes in the building.

4.6.2 Building-Related Illness

In contrast to non-specific health symptoms, the term building related illness (BRI) is sometimes used to describe a specific building-related health effect with known causes and objective clinical findings. Examples of BRIs include Legionnaires Disease, hypersensitivity pneumonitis, lung cancer from radon exposure, and health effects known to be a consequence of exposures to specific toxic compounds in buildings. Allergies and asthma are considered by some to be building related illnesses.

4.7 Sensitive Populations

Significant subsets of the total population have an increased sensitivity to indoor pollutants. Approximately 20% of people have environmental allergies and approximately 10% experience asthma (Committee on Health Effects of Indoor Allergens 1993). Peoples sensitivity to chemical irritants and their ability to detect odors also vary. To maintain low levels of building-related health complaints and health effects, the indoor environment must be maintained satisfactory for a substantial majority of occupants, many of whom are more sensitive than the average person to indoor pollutants.

A very small portion of the population report severe health effects when exposed to extremely low concentrations of a large variety of chemicals in the air. Their very high sensitivity to these chemicals may follow a period of sensitization caused by exposure to a higher concentration of one or more chemicals. The term multiple chemical sensitivity (MCS) is commonly used to describe this phenomenon. There is considerable uncertainty and controversy within the medical community about the concept of MCS. The current state of knowledge about MCS and its causes, physiological and psychological, is very limited. Owners and operators of buildings and building design and energy professionals usually do not have sufficient information to eliminate health symptoms in individuals with MCS.

4.8 Standards, Codes and Guidelines for Ventilation and Indoor Environmental Quality

A variety of standards, codes, or guidelines for minimum acceptable ventilation rates, lighting, thermal conditions, pollutant concentrations, tobacco smoking restrictions, pollutant sources, and building characteristics that influence IEQ have been adopted by national, state, regional, or municipal governments. Professional organizations also write voluntary or model standards or guidelines that are sometimes adopted, in whole or part, by code-making organizations. Some of these standards or codes constrain building and HVAC designs but do not strictly apply for building operation. A limitation of building design standards, applied at the time of new construction, is that these standards often fail to stimulate adjustments in building operation as building characteristics and building occupancy vary over time. However, failure to operate buildings in a manner that meets minimum design code requirements is considered poor practice and is likely to be a consideration in the event of IEQ-related litigation.

Thermal and lighting standards generally specify acceptable ranges for thermal and lighting conditions. Ventilation standards may specify minimum acceptable rates of outside air supply. Maximum pollutant concentrations are specified in some standards for a small number of air pollutants; however, at present there are no maximum concentration limits specified in standards for many of the pollutants present in indoor air.

IEQ-related codes and standards vary qualitatively and in their quantitative specifications. This document does not recommend specific standards to the exclusion of others because standards must reflect the regional climate, economic situation, and culture. This document does recommend that building professionals be familiar with all applicable standards and that the requirements in applicable standards be considered minimum requirements. In many situations, exceeding the minimum requirements is desirable. Examples of prominent codes or standards are listed and briefly described in *Table 1*.

4.9 Relationship of IEQ to Productivity

Improvements in IEQ have the potential to improve worker productivity, in part by reducing: a) costs for health care, b) sick leave, c) performance decrements at work caused by illness or adverse health symptoms; and d) costs of responding to occupant complaints and costs of IEQ investigations. Some characteristics of the indoor environment, such as temperatures and lighting quality, may also influence worker performance without impacting health. In many businesses, such as office work[1], worker salaries plus benefits dominate total costs; therefore, very small percentage increases in productivity, even a fraction of one percent, are often sufficient to justify expenditures for building improvements that increase productivity.

At the present time, the linkages between specific building and IEQ characteristics and productivity have not been well quantified. However, in a critical review and analysis of existing scientific information, Fisk and Rosenfeld (1997, 1998) have developed estimates of the potential to improve

1. In office buildings, salaries are typically about 100 times larger than building energy or maintenance costs.

Table 1: Examples of Standards, Codes, or Guidelines Pertinent to IEQ in Non-industrial, Commercial Buildings

Title	Organization	Primary Content
ASHRAE / ANSI Standard 55-1992, Thermal Environmental Conditions for Human Occupancy (ASHRAE 1992b)	ASHRAE[a] ANSI[b]	Acceptable range for temperature, humidity, and air velocity
ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality (ASHRAE 1989)	ASHRAE ANSI	Minimum acceptable rates of ventilation per occupant; Alternate IAQ performance path maintains selected pollutant concentrations below limits and subjective satisfaction to air above a limit; Includes a few pollutant concentration limits
ISO 7730: 1994 Moderate thermal environments determination of the PMV and PPD indices and specification of the conditions for thermal comfort (ISO 1994)	International Organization for Standardization (ISO)	Acceptable range for temperature, humidity, and air velocity
ANSI/IESNA —RP-1-1993	ANSI IESNA[c]	For office lighting, topics covered include office tasks, design process, lighting criteria for visual performance and comfort, luminous environmental factors, the lighting system, maintenance, light areas, energy and energy management
European concerted action, indoor air quality and its impact on man, report no. 11: guidelines for ventilation requirements in buildings (ECA 1992)	Commission of the European Communities, Directorate General for Science, Research, and Development	Minimum ventilation rates per unit of sensory indoor pollutant emission in olfs[d] to satisfy 70%, 80%, or 90% of people based on initial judgments when they enter space; Alternate minimum ventilation rate for protecting health
Air quality guidelines for Europe (WHO 1987)	WHO, Regional Office for Europe	Guideline concentrations for 25 chemicals, apply for outdoor and indoor air
Indoor climate-air quality: NKB publication no. 61e (NKB 1991)	Nordic Committee on Building Regulations (NKB)	General guidelines regarding: minimum quality of intake air; limiting spread of pollutants indoors (air recirculation is discouraged); use of low emission building materials, furnishings, processes and activities; assuring cleanability of buildings and HVAC; air balancing; minimum air change efficiency; necessary documentation and operation and maintenance. Also: minimum rates of outside air supply that are a sum of a minimum rate per unit floor area and a minimum rate per person
Law for Maintenance of Sanitation of Buildings, 1970 (Ministers 1970)	Ministers of Justice, Health and Welfare, Labor and Construction, Japan	Specifies limits or acceptable ranges for indoor temperature, relative humidity, air velocity, carbon dioxide concentration, carbon monoxide concentration, and suspended particle concentration. Specifies training and testing requirements for building sanitation engineers and oversight of building maintenance and management by building sanitation engineers. Requires maintenance of documents including those on state of regulation of air, management of water supply and wastewater, cleaning, and control of rodents, insects and other pests. Specifies fines for violations of law.

a. American Society of Heating, Refrigerating, and Air Conditioning Engineers
b. American National Standards Institute
c. Illuminating Engineering Society of North America
d. One olf is the rate of sensory pollutant emission from a standard person (non-smoker). The total sensory indoor pollutant emission rate, from people and other sources, is expressed in olfs

productivity in the U.S. through changes in indoor environments. The review indicates that building and HVAC characteristics are associated with prevalences of acute respiratory infections and with allergy and asthma symptoms and non-specific health symptoms. For the normal range of indoor lighting conditions, the effects of improved lighting on the performance of typical office work is poorly understood. Several studies have found performance to be affected only by unusually low lighting levels or have found performance to change only with small low contrast type (Fisk and Rosenfeld 1997). However, a recent laboratory study with computerized performance tests suggests that high frequency ballasts may increase performance (Veitch and Newsham 1998). There is evidence that improvements in lighting quality can improve the performance of work that is very visually demanding, such as mail sorting or detailed product inspections, by several percent. Finally, there is evidence that quite small changes in temperature, a couple of degrees centigrade, may increase or decrease the performance of office work; however, the optimal temperature varies with the type of work. Also, the optimal thermal conditions for work performance may differ from the optimal conditions for comfort. From analyses of existing scientific literature and calculations using statistical data, the estimated *potential annual nationwide benefits* of improvements in IEQ include the following:

- a 10% to 30% reduction in acute respiratory infections and allergy and asthma symptoms;
- a 20% to 50% reduction in acute non-specific health symptoms;
- a 0.5% to 5% increase in the performance of office work; and
- associated annual cost savings and productivity gains of $30 billion to $170 billion.

5 Best Practices for Maintaining IEQ

The recommended best practices for maintaining a high quality indoor environment vary throughout the world; however, there are several widely accepted elements of best practice. This section describes best practices that are widely accepted as beneficial.

5.1 Maintaining Good Indoor Air Quality

5.1.1 Limiting Pollutant Emissions from Indoor Sources

1 Limiting the rates of pollutant emission from indoor sources is essential to cost-effectively maintain good IAQ. While the rates of pollutant emission from occupants are not generally controllable, emissions from many other pollutant sources can be minimized by adhering to the following practices. Tobacco smoking should be restricted to enclosed and depressurized[1] smoking rooms from which air is exhausted to outdoors. Alternately, indoor smoking should be entirely eliminated.

2 Building materials, furnishings, office equipment, and cleaning and pest control products and practices with low VOC and odor emission rates

1. Smoking rooms should be maintained depressurized relative to adjoining rooms.

should be selected. In general, however, selection of low-emitting products is a difficult task because of limited information on VOC emissions, the lack of standard methods for determining emission rates, and because of the health effects resulting from exposures to many VOCs and VOC mixtures are poorly understood. Many cleaning, painting, and pest control activities should be performed when the building is unoccupied. Cleaning and pest control products must be properly diluted and applied.

3 To limit indoor growth of fungi and bacteria, water leaks from plumbing and the building envelope should be eliminated. Building materials that become wet should be dried rapidly (e.g., within 1—2 days) or removed and replaced. Construction materials, including concrete, should be dry before they are covered (e.g., with carpet) or enclosed (e.g., in a wall cavity).

4 To limit microbiological sources in HVAC systems, sources of moisture in HVAC systems must be controlled. The entry of water droplets and snow into outside air inlets must be restricted by proper design of the air intake system, e.g., use of rain-proof louvers and limiting of intake air velocities. Condensate drain pans must drain fully, be cleaned periodically, and have proper traps in the condensate drainage systems. Air velocities through cooling coils and humidifiers must be restricted to prevent water droplets from being entrained in the airstream and wetting downstream surfaces.

5 To limit microbiological sources in buildings, condensation of water vapor inside the building envelope and on interior building surfaces, including slab floors in contact with the soil, must be limited by controlling indoor humidity, proper use of moisture barriers and thermal insulation in the building envelope, and through control of indoor-to-outdoor pressure differences. Specific requirements will vary with climate.

6 A building should not be constructed on soil with unusual levels of hazardous contaminants (VOCs or radon) or special measures should be used to prevent soil gas from being drawn into the building. When building slabs are constructed on soils that are unusually wet, water proofing should be used to limit moisture transport from the soil into the slab.

7 Pollutants emitted from strong sources may need to be exhausted directly to outdoors. Combustion products from appliances should be vented to outdoors. The rates of air exhaust from janitor storage rooms and restrooms should be sufficient to maintain these rooms depressurized relative to surrounding rooms and the air should be exhausted directly to outdoors. Equipment with high emission rates of pollutants or odors should be isolated in rooms (e.g., copy machine rooms or kitchens) with high air exchange rates with air exhausted directly to outdoors. These rooms should also be maintained depressurized. Parking garages should be physically separated from occupied spaces and maintained under negative pressure relative to the adjoining occupied spaces.

8 Mechanical equipment rooms should not be used for storage of building materials, solvents, cleaning supplies, pesticides, adhesives, or other pollutant- or odor-emitting materials.

9 During building construction and major renovation projects, unusually strong sources of particles and VOCs may be present in the building. (Products or processes with low pollutant emissions should be employed when feasible.)

Occupants must be isolated from these sources of pollutants using temporary internal walls as necessary and by maintaining the air pressure in the construction area less than the pressure in the adjoining occupied spaces. Measures should be taken to ensure that ventilation systems serving the construction zone do not become contaminated by construction dusts, or the systems should be cleaned thoroughly prior to occupancy (SMACNA 1995). A short delay (e.g., few days to weeks) in the occupancy of newly constructed or renovated spaces can help to prevent odor and irritancy complaints associated with the VOC emissions of new materials.

10 Good housekeeping practices should be employed to limit the accumulation of pollutants on surfaces and to reduce the potential for microbiological growth on these surfaces.

5.1.2 Assuring Adequate Quality of Intake Air

Assuring adequate quality of intake air is essential. When possible, buildings should be located in areas with acceptable outdoor air quality. Outside air intakes should not be located near strong sources of pollutants such as combustion stacks, exhausts from fume hoods, sanitary vents, busy streets, loading docks, parking garages, standing water, cooling towers, and vegetation. The outside air intake must be separated sufficiently from locations where ventilation air is exhausted to prevent significant re-entrainment of the exhaust air.

Incoming air should be filtered to remove particles. The recommended minimum particle filtration efficiencies vary among IAQ and ventilation standards and guidelines; however, use of filters that exceed minimum requirements is an option to improve IAQ, often with a small or negligible incremental cost. If unacceptable concentrations of gaseous pollutants are present in outside air, gaseous air cleaning may be required.

5.1.3 Maintain Minimum Ventilation Rates

The minimum ventilation rates specified in the applicable code requirements should be maintained or exceeded. The HVAC system should be designed so that rates of outside air intake can be measured using practical measurement techniques. In buildings with variable air volume (VAV) ventilation systems, special controls may be needed to ensure the minimum outside air intake into the air handling unit is maintained during all operating conditions (Cohen 1994, Drees and Wenger 1992, Solberg et al. 1990).

In addition to maintaining the minimum rate of outside air intake into the building, the ventilation system must be designed and balanced to assure the proper air delivery to each major room or section of the building. In VAV systems, VAV control units must have a minimum open position[1] to ensure the required outside air supply to specific regions of the building.

When the air supply and return air registers are placed in or near the ceiling and the supply air is warmer than room air, the supply air may short circuit to the return registers resulting in poor ventilation at breathing level; i.e., a poor air change effectiveness (e.g., Fisk et al. 1997b, ASHRAE 1998). The ventilation system should be designed to assure a high air change effectiveness or the rate of outside air supply should be increased to correct for poor air change effectiveness.

1. When internal cooling loads are low, the supply air temperatures may need to be increased to prevent over-cooling of the conditioned space.

5.1.4 Recirculation of Indoor Air

Recirculation of indoor air is standard practice in some countries, such as the U.S., and discouraged in other countries such as those of Scandinavia. When air is recirculated, it should be filtered to remove particles. However, filters are often used only to prevent soiling and fouling of the HVAC equipment. These filters have a very low efficiency for respirable-size particles (smaller than 2.5 micrometers). Use of filters that exceed minimum requirements is an option to improve IAQ, often with a small or negligible incremental cost.

5.1.5 Maintenance of the HVAC System

Regular preventive maintenance of the HVAC system is necessary to assure proper delivery of outside air throughout the building and to limit growth of microorganisms in the system. A written plan for periodic maintenance should be developed and followed and maintenance activities should be documented. Elements of periodic maintenance that are important for maintaining good IEQ include changing of filters[1], cleaning of drain pans and cooling coils, checking fan operation, and checking dampers that influence air flow rates. Testing and balancing of an HVAC system may be necessary in the following circumstances: (a) after significant changes in the building, HVAC system, occupancy; or activity within the building (b) when control settings have been readjusted by maintenance personnel; and c) when accurate records are not available.

5.1.6 Integrated Approach to IEQ

It is widely recognized that an integrated or whole-building approach is the most effective means of saving energy in buildings because the energy performance of the building depends on the interactions of building systems and their control and operation. The IEQ performance of a building also depends on the interactions among building design, building materials, and building operation, control, and maintenance. Therefore, an integrated or whole building approach is recommended to maximize IEQ. Such an integrated approach may include the integrated consideration of the following: a) IEQ targets or objectives, b) occupancy and indoor pollutant sources and pollutant sinks and their variation over time, c) building and HVAC design, d) commissioning, e) training and education, and f) building operation and maintenance.

5.2 IEQ Management Plans and Related Programs

The establishment and implementation of IEQ management plans is recommended to help maintain high quality IEQ and a high level of occupant satisfaction with IEQ. Common elements of IEQ management plans include the following[2]:

1 Selecting an IEQ manager, responsible for management and coordination of all aspects of IEQ
2 Developing an IEQ profile of the building
3 Assigning responsibilities and training of staff
4 Development of an IEQ checklist
5 Periodic building and HVAC system inspections
6 Facility operation and maintenance practices to maintain IEQ
7 Specific procedures to record and respond to occupant complaints

---

1. Filters become sources of odors. Also, microorganisms may colonize filters.
2. For a more detailed description of elements in an IEQ management plan, see Building Air Quality Action Plan, U.S. EPA and NIOSH, http://www.epa.gov/IAQ/base/actionpl.html

8 Special practices to maintain IEQ during building renovation, painting, pesticide use, or other periods of high indoor pollutant generation

9 Maintaining IEQ documentation

In the US, an independent non-profit private sector program called the Building Air Quality Alliance (BAQA) offers recognition to building owners and managers who commit to maintaining IAQ primarily through implementation of a proactive management plan. BAQA (http://www.baqa.org) has a practical step-by-step protocol in checklist form that is reviewed annually with the assistance of an IEQ professional.

An IEQ insurance policy is becoming available for buildings that follow BAQA guidelines. Other IEQ insurance policies under development are not specifically linked to the BAQA process but reportedly will require an integrated building assessment.

The principles that underlie the BAQA process are derived substantially from a guidance document entitled Building Air Quality prepared by the US. EPA and NIOSH (EPA / NIOSH 1991; http://www.epa.gov/reg5oair/radon/healbld1.htm#bldgaqguinfo). The US EPA/NIOSH have also prepared and an accompanying Building Air Quality Action Plan (http://www.epa.gov/iaq/base/actionpl.html).

The US EPA / DOE (Department of Energy) Energy Star Program have recently announced a new Energy Star Building labeling program (http://www.epa.gov/buildinglabel). Based on current plans, commercial buildings whose energy performance is among the top 25% in the nation and which meet specific requirements for comfort and IEQ will be awarded and Energy Star Building Plaque.

Another private sector organization that promotes improved IEQ, as well as energy efficiency, is the US Green Buildings Council (http://www.usgbc.org). The Green Building Council has a building rating system called LEED (http://www.usgbc.org/programs/index.htm).

6 Linkages Between Energy Conservation Measures and IEQ

This section lists common energy conservation measures for commercial buildings, describes their potential influence on IEQ, and identifies precautionary actions or mitigations that can help to assure acceptable IEQ. The primary information is provided in *Table 2*. For many energy conservation measures, the cited references provide additional information on the IEQ impacts or on the related precautions and mitigations. The measures marked with "◆" in *Table 2* deserve special consideration because they will often simultaneously improve IEQ and save energy. Because of the growing interest in IEQ, energy efficiency proposals that are expected to protect or improve IEQ will have a competitive advantage relative to proposals that ignore IEQ.

The last column of *Table 2* links each energy conservation measure to the most directly relevant IEQ measurement and verification (M&V) alternatives provided subsequently in *Table 4*.

Table 2: List of Specific ECMs, Their Potential Influence on IEQ, and Related Precautions or Mitigation Measures

Energy Conservation Measure	**Potential Influence on IEQ**	**IEQ Precautions or Mitigations**	***Table 4* Rows**
Lighting			
◆ Energy efficient lamps, ballasts, fixtures (IES 1993)	Improved lighting quality is common if lighting system is properly designed and installed.	Emphasize lighting quality in design. Check lighting levels and reflected images in VDT screens. Provide task lighting. Ensure that lighting retrofits do not result in disturbance and release of asbestos, fiberglass, or irritating dusts.	18-20
Automated lighting controls: occupancy sensors, dimming (IES 1993)	Improved lighting quality possible. Improperly operating control systems can degrade lighting quality	Emphasize lighting quality in design. Commission control systems. Provide task lighting where practical.	18-20
Removing lamps and fixtures	Risk of insufficient local or overall lighting level.	Ensure appropriate light levels and distribution. Provide occupant controllable task lighting where appropriate.	18-20
Use of window, skylights, light shelves, and light tubes to provide natural lighting. (IES 1993)	Improved or degraded lighting quality are possible depending on placement and optical characteristics of building elements that provide daylight. There is some evidence that proximity to windows, even when they can not be opened, is associated with a decreased frequency of acute non-specific building-related health symptoms (Fisk et al. 1993).	Ensure proper design of natural lighting system to prevent lighting problems such as glare, or incorrect or uneven lighting levels. Check lighting levels. Provide occupant controllable task lighting.	18-20
Automatic and manually-adjustable shading controls, fixed shading, window films (IES 1993)	Improved lighting quality possible. Improperly operating shading controls can degrade lighting quality. Shading can reduce potential pollutant emissions from indoor materials caused (or increased) by exposure to direct sunlight.	Commission shading control systems to ensure proper operation. Provide occupant controllable task lighting.	18-20
HVAC energy conservation measures			
Improve efficiency of HVAC components (motors, pumps, fans, chillers)	Adverse influence on IEQ unlikely if components have sufficient capacity.	Commission HVAC system to ensure proper performance under full- and part-load in heating and cooling modes. (ASHRAE 1996c)	NA
◆ Heat recovery from exhausted ventilation air or other source of waste heat.	If heat recovery system allows increase in rate of outside air supply, IEQ will usually be improved. See outside air economizer discussion related to outdoor air pollutants. Some heat recovery systems transfer moisture or pollutants from exhaust to supply airstream. (ASHRAE 1992)	See outside air economizer discussion related to outdoor air pollutants. Ensure that heat recovery system does not transfer unwanted moisture or pollutants to supply airstream.	2, 4, 5, 8, 12, 13, 15, 21, 22

Table 2: List of Specific ECMs, Their Potential Influence on IEQ, and Related Precautions or Mitigation Measures

Energy Conservation Measure	Potential Influence on IEQ	IEQ Precautions or Mitigations	*Table 4* Rows
Reducing operating time of HVAC components (e.g., fans, chillers) to save energy or limit peak energy demand.	Risk of degraded indoor thermal environment and / or increased indoor air pollutant concentrations if components are not operated during periods of occupancy. Also, when HVAC systems are not operating, indoor pressure differences and the associated transport of pollutants between zones or between outdoors and indoors are not controlled.	Operating periods must be sufficient to ensure acceptable thermal comfort and ventilation during occupancy. Ventilation with outside air should precede occupancy to reduce concentrations of air pollutants emitted from building materials and furnishings during unoccupied / low ventilation periods. Minimize indoor pollutant sources to reduce the pollution burden on the ventilation system. Equipment shutdown to limit peak energy demands should be infrequent and of limited duration. Use energy efficient HVAC systems or thermal energy storage to limit peak energy demands without sacrificing thermal comfort. Sequencing the startup of HVAC equipment may also reduce peak demands, often without adverse influence on IEQ.	1-8, 21, 22
◆ Use of outside air economizer[a] for free cooling.	Generally, IEQ will improve due to the increase in average ventilation rate. (Seppanen et al. 1989; Mudarri et al. 1996) During periods of elevated outdoor pollutant concentrations, economizer use may increase indoor concentrations of outdoor pollutants. In humid climates, economizer use may increase indoor humidities and the potential moisture-related IEQ problems	Locate outside air intakes as far as practical from strong sources of pollutants such as vehicle exhausts, HVAC exhausts, trash storage, and restaurant exhausts. (ASHRAE 1996b) If outdoor air is highly polluted with particles, use high efficiency air filters. If outdoor air is highly polluted with ozone, consider checking indoor ozone levels and/or use of activated charcoal filters. Design and control HVAC economizer to prevent moisture problems. Economizer controls and associated minimum outside air flow rates should be regularly calibrated and maintained.	2, 4, 5, 8, 12, 13, 15, 21, 22
◆ Nighttime pre-cooling using outdoor air. (ASHRAE 1995)	Nighttime ventilation may result in decreased indoor concentrations of indoor-generated pollutants when occupants arrive at work. Nighttime ventilation with humid air may result in condensation on HVAC equipment or building components increasing the risk of growth of microorganisms.	Design and operate nighttime ventilation systems to prevent moisture problems. Often, controls prevent nighttime cooling when outdoor dew-point temperature is excessive.	2, 15, 21, 22

Table 2: List of Specific ECMs, Their Potential Influence on IEQ, and Related Precautions or Mitigation Measures

Energy Conservation Measure	**Potential Influence on IEQ**	**IEQ Precautions or Mitigations**	***Table 4* Rows**
Use of variable air volume (VAV) ventilation system in place of constant volume system.	Risk of insufficient outside air supply when indoor cooling or heating loads are low (Mudarri et al. 1996). See discussion of minimum outside air supply with VAV systems in *Section 4.1*. Particularly in HVAC systems with fixed outside air fraction, risk of excessive cooling and thermal discomfort when cooling loads are low if minimum outside air supply is maintained and supply air temperature is not increased. Increased risk of thermal comfort problems from supply air dumping[b].	Maintain outside air intake into air handler at or above minimum requirement for all supply air flow rates. (Solberg et al. 1990, Cohen 1994; Janu et al. 1995, Utterson and Sauer 1998) Avoid VAV control units that close fully when space temperatures are satisfied. Supply air temperatures may need to be increased when cooling loads are low. Check total and local outside air supply and indoor temperatures for a range of cooling loads. Use supply registers, minimum supply flow rates and temperatures that do not cause supply air dumping and thermal discomfort.	2, 3 — 5, 8, 21, 22
Use of variable speed drives in place of dampers for flow control.	No influence on IEQ expected.	Use flow controllers that depend on measured air flows rather than theoretical or design flows.	4, 5
Use of computerized digital HVAC control systems, Energy monitoring and control systems	Flexibility and ease of HVAC control are enhanced with properly operating control systems, hence, IEQ may be improved. Digital controls facilitate use of demand-controlled ventilation based on pollutant sensors.	Assure proper function of control system via commissioning (ASHRAE 1996c). Assure adequate training of building operators.	2-5, 8
Reduce air pressure drops and air leakage in duct systems.	May allow improved air supply and thermal control. May reduce noise generated in duct systems.	Air system balancing may be necessary after retrofits. Ensure quality of duct assembly to reduce noise.	2, 3
Use of hydronic radiant heating and cooling[c] with consequent fan energy savings	Mean radiant temperature is affected. Thermal comfort improvement or degradation are possible (e.g., the risk of draft from high air motion decreases but the risk of thermal discomfort from low air motion increases). Hydronic systems increase risk of water leaks or water condensation leading to microbiological growth. Average rate of outside air supply is reduced if radiant cooling precludes use of outside air economizer because of a reduction in capacity of fans and ducts.	Design, operating and maintenance practices of hydronic radiant heating and cooling systems should assure acceptable thermal comfort and outside air supply and low risks of water leakage and condensation. Periodic cleaning of radiant panels or radiators may be necessary. Water leaks should be immediately repaired. Water damaged materials must be quickly dried or replaced.	1 - 5, 8, 21, 22

Table 2: List of Specific ECMs, Their Potential Influence on IEQ, and Related Precautions or Mitigation Measures

Energy Conservation Measure	**Potential Influence on IEQ**	**IEQ Precautions or Mitigations**	***Table 4* Rows**
Reduction in average or minimum rate of outside air supply, (especially closure of outside air dampers).	Primary effect is that concentrations of indoor-generated air pollutants will increase potentially leading to complaints and adverse health effects even though indoor concentrations of pollutants from outdoor air may be reduced (especially pollutants like ozone and particles that react with or deposit on indoor surfaces). In air conditioned buildings, indoor humidity may also be reduced.	Maintain rates of outside air supply specified in applicable codes and standards. Do not fully close outside air dampers during occupancy. Minimize indoor pollutant sources to decrease pollution burden on ventilation system. Use improved particle and gaseous air cleaning.	4, 5, 8, 21, 22
◆ Increase supply air temperature when cooling space (may decrease chiller energy but increase fan energy).	Higher supply air temperatures in VAV ventilation systems will increase supply air flow rates. In many VAV systems, outside air flow rates will also increase leading to reduced concentrations of indoor-generated air pollutants. Increasing chilled water temperatures often reduces the moisture removal by the HVAC system resulting in higher indoor humidities.	Maintain chilled water temperatures sufficiently low for control of indoor humidity.	1 - 3, 4, 5, 8
Increasing thermostat setpoints during periods of space cooling or decreasing thermostat setpoints during periods of space heating to save energy or limit peak energy demand. (ASHRAE 1992b, ISO 1994).	Air temperatures near or outside of the boundaries of locally applicable thermal comfort zones are likely to increase complaints of thermal discomfort, especially in air-conditioned buildings without provisions for occupant control. Occupants' perceived acceptability of air quality decreases as temperature increases between 18 °C and 28 °C (Fang et al. 1997). Increased air temperature is associated with increased prevalences of acute building related health symptoms in some studies (Mendell 1993)	Maintain temperatures within the bounds of applicable thermal comfort standards. Provide occupant-controllable fans and space heaters . Thermally efficient windows and walls may help to maintain thermal comfort (see Energy Efficient Building Envelope). Resetting of space temperature to limit peak energy demands should be infrequent and of limited duration. Use energy efficient HVAC systems or thermal energy storage to limit peak energy demands without sacrificing thermal comfort.	1 -3
Increase interior or exterior thermal insulation of piping and duct systems	Increased insulation will usually have negligible influence on IEQ. Potential for improved thermal comfort if insulation enables HVAC system to satisfy peak thermal loads. Increased insulation with vapor barriers can reduce moisture condensation and potential for microbiological growth. Potential increase in irritation symptoms if fibers or particles from insulation enter occupied space or if insulation releases VOCs at a high rate. Interior insulation in ducts can reduce fan noise (ASHRAE 1995). Interior insulation in ducts can be colonized by microorganisms (Morey 1991) potentially resulting in increased indoor concentrations of bioaerosols and microbiological VOCs.	Ensure that fibrous insulation is isolated from indoor air. Minimize fiber or particle release during installation of insulation and perform space cleanup prior to occupancy. Use insulation products with low emission rates of VOCs, especially of odors. The surface of insulation installed on the interior of ducts should prevent release of fibers or particles and not degrade. Interior duct insulation should not be located where it is likely to become wet or damaged. Promptly remove or repair damaged or wet insulation.	1 - 3

Table 2: List of Specific ECMs, Their Potential Influence on IEQ, and Related Precautions or Mitigation Measures

Energy Conservation Measure	Potential Influence on IEQ	IEQ Precautions or Mitigations	*Table 4* Rows
CO_2 - based demand controlled ventilation (DCV). (Carpenter 1996; De Almeida, and Fisk 1997, International Energy Agency 1990, 1992; Emmerich and Persily 1997, Persily 1993, ASTM 1998)	IEQ may improve or degrade depending on the reference condition and on the outside air control strategy used for DCV. Improved IEQ is most likely in spaces with high occupancy where occupant-generated pollutants dominate. DCV systems that provide outside air only after CO_2 concentrations exceed a setpoint may lead to substantially increased indoor concentrations of pollutants from building components and furnishings during the first few hours of occupancy	Avoid CO_2 - based DCV when building has strong pollutant emissions from sources other than occupants. Ventilate prior to occupancy to reduce concentrations of pollutants from non-occupant sources. CO_2 measurement locations must provide data representative of concentrations in occupied spaces. Consider advanced DCV control strategies that supply outside air in proportion to the indoor CO_2 generation rate, which is a better surrogate for occupancy than the CO_2 concentration (Federspiel 1996). Periodically check calibration of CO_2 sensors.	4, 5, 8, 15, 21, 22
◆ Displacement ventilation (Displacement ventilation systems usually supply 100% outside air with improved IEQ as the main goal. The addition of heat recovery system may be necessary to achieve energy savings relative to some other methods of HVAC.)	Generally, concentrations of indoor-generated air pollutants at breathing zone are reduced. (Seppanen et al. 1989; Yuan et al. 1998) Reduced transport of pollutants from sources to other rooms. Reduced risk of thermal drafts. Increased risk of thermal discomfort due to large vertical gradients in air temperature. Potential increased indoor concentrations of pollutants from outdoors, especially pollutants like ozone and particles that react with or deposit on indoor surfaces.	See outside air economizer discussion related to outdoor air pollutants. Design and operate displacement ventilation systems to avoid drafts in vicinity of supply diffusers and to avoid excessive gradients in air temperature. Displacement ventilation, without radiant cooling panels, may be effective only with internal heat generation less than 40 W m^{-2}.	1 — 5, 8, 21, 22
◆ Use of natural ventilation with operable windows as a substitute for air conditioning. (Olgyay 1963, Koenigsberger et al. 1973; Watson and Labs 1983, Awbi 1991, Givoni 1997, Busch 1992)	In some climates, thermal acceptance of environment may increase because occupants in naturally ventilated buildings are tolerant of a wider range of thermal conditions (De Dear and Brager 1998). Thermal comfort may decrease because of elevated indoor temperatures and humidities. On average, occupants of buildings with natural ventilation and operable windows report fewer acute non-specific health symptoms. Open windows admit sounds from outdoors, potentially degrading the indoor acoustic environment.	Building design, e.g., size, layout, openings for outside air, position of openings, and shading must assure adequate natural ventilation and thermal conditions throughout building. Generally, cross-ventilation is desirable. Occupant - controllable fans can enhance thermal comfort. Openable windows should not be located near concentrated outdoor sources of pollutants or annoying sounds.	1 — 3, 6, 8, 21, 22

Table 2: List of Specific ECMs, Their Potential Influence on IEQ, and Related Precautions or Mitigation Measures

Energy Conservation Measure	Potential Influence on IEQ	IEQ Precautions or Mitigations	*Table 4* Rows
◆ Preventive maintenance of HVAC system	Preventive maintenance will help to assure proper HVAC operation, sometimes also saving energy and improving IEQ. Preventive maintenance measures that may save energy and improve IEQ include calibration of temperature and humidity sensors, periodic replacement of air filters, maintenance of airflow and pressures control systems, balancing of airflows to provide proper air distribution, and cleaning of coils and other components to reduce airflow resistance and pollutant sources in the HVAC system.	Ensure that preventive maintenance does not disturb or release asbestos fibers (asbestos is present in mechanical rooms of many older buildings).	2, 3, 21, 22
Energy efficient building envelope:			
Increased thermal insulation in building envelope.	Often negligible influence on IEQ. Potential increase in thermal comfort because insulation helps HVAC system satisfy thermal loads and because of reduced radiant heat transfer between occupants and building envelope. Potential increase in irritation symptoms if fibers or binders from insulation enter occupied space or if insulation releases VOCs at a high rate.	Assure that fibrous insulation is isolated from indoor air. Minimize fiber or particle release during installation of insulation and perform space cleanup prior to occupancy. Use insulation products with low emission rates of VOCs, especially of odors.	1 - 3
Light color roof and walls to reduce solar loads	Often negligible influence on IEQ. Potential increase in thermal comfort because reduced loads help HVAC system satisfy thermal loads and because of reduced radiant heat transfer between occupants and envelope.	NA	1 - 3
◆ Thermally efficient windows	Improvements in thermal comfort possible from reductions of drafts and reduced radiant heat exchange between occupants and windows (ASHRAE 1995b, Heiselberg 1994, Heiselberg et al 1995). Reduces risk of condensation on windows and associated risks from growth of microorganisms. Thermally efficient windows help to isolate the indoor space from outdoor sounds.	NA	1 - 3

Table 2: List of Specific ECMs, Their Potential Influence on IEQ, and Related Precautions or Mitigation Measures

Energy Conservation Measure	Potential Influence on IEQ	IEQ Precautions or Mitigations	*Table 4* Rows
Reduce air leakage through building envelope (e.g., install infiltration barriers)	Thermal comfort may increase due to reduced entry of unconditioned air. Reducing air leakage may help to isolate the indoor space from outdoor sounds. Reducing envelope leakage facilitates room or building pressure control via the HVAC system. Indoor concentrations of outdoor pollutants or pollutants from adjoining spaces (e.g., parking garages) may decrease because leakage of outdoor pollutants to indoors decreases. Improperly placed infiltration and vapor barriers can lead to condensation and associated microbiological problems in building envelope. Reduced infiltration of outside air will generally increase concentrations of indoor-generated air pollutants; however, magnitude of increase may be insignificant, particularly if adequate outside air ventilation is provided mechanically.	Ensure adequate mechanical or intentional natural ventilation. Infiltration and vapor barriers should be located near warm side of building envelope.	1 — 3, 8, 21, 22
Reducing indoor heat generation or heat gain through building envelope			
Reduced indoor heat generation through use of energy efficient lighting and equipment or through reduced heat gain through building envelope.	Increased thermal comfort possible if measures enable HVAC system to provide adequate cooling. Decreased thermal comfort possible if building has inadequate heating system. In buildings with VAV ventilation systems, supply air flow rates will decrease when building is being cooled; in turn, rate of outside air supply may decrease (see prior information and references on VAV systems). Reduced heat loads without compensating changes in supply flows may lead to increased indoor humidity because control systems may increase cooling coil discharge temperatures. Excessive cycling and control problems with oversized refrigeration systems may cause discomfort.	Use a control system that maintains outside air intake into air handler at or above minimum requirement for all supply air flow rates. Avoid VAV control units that close fully. Check total and local outside air supply and indoor temperatures for a range of cooling loads. Check for and eliminate control system problems associated with oversized refrigeration systems.	1 — 5, 8

a. To save energy, economizer systems automatically increase the rate of outside air supply above the minimum setpoint during mild weather.

b. The term supply air dumping refers to the tendency for the jet of cool supply air exiting a supply register located at ceiling level to drop toward the floor without sufficient mixing between the jet and the warm air within the room. Supply air dumping, which is more common with low supply flow rates, lower supply temperatures, and certain supply diffuser designs, is a source of thermal discomfort.

c. A hydronic radiant heating or cooling system uses a heated or chilled liquid to create a heated or cooled radiant panel or surface. The occupants thermal comfort is determined, in part, by radiant heat exchange between occupant and the radiant panel.

7 Influence of Energy Conservation Measures on IEQ in Specific Buildings

7.1 Background

Many of the energy conservation measures in *Table 2* have multiple potential impacts on IEQ. When considering the application of these measures in specific buildings, energy conservation professionals may be faced with three important questions:

1 Which of the potential IEQ outcomes will occur in this building and what is the expected magnitude of the changes in IEQ?

2 Will the change in IEQ significantly affect occupants health, comfort, or productivity?

3 Can the impacts on IEQ be assessed with measurements?

A working knowledge of IEQ and its effects on occupants is an essential first step in addressing these questions. *Section 4* summarizes much of the critical background information. This section addresses the first two questions. IEQ measurements are reviewed in *Section 8*.

7.2 Identifying the Probable IEQ Outcomes and Predicting Their Magnitude

The impact of an energy conservation measure on IEQ may depend on several factors including the climate, outdoor air quality, characteristics of the building, and the details of implementation of the energy conservation measure.

Warm humid climates increase certain IEQ risks associated with high indoor humidity. In humid climates, energy conservation measures that increase the rate of outside air supply, such as openable windows or a poorly-controlled economizer system, are more likely to result in unacceptable indoor humidities. Also, reducing the capacity of HVAC equipment and increasing temperatures at cooling coils can result in insufficient moisture removal and excess indoor humidity. Condensation of water vapor on radiant cooling panels is much more likely in high humidity climates. Maintaining thermal comfort with natural ventilation is much more difficult in warm humid climates.

In cold climates, thermally efficient windows, high levels of thermal insulation in the building envelope, and measures that reduce air infiltration are more likely to significantly improve thermal comfort by reducing drafts and radiant heat losses from occupants to walls and windows. The potential to have very low indoor humidities is also increased in cold climates.

Elevated levels of pollutants in the outdoor air increase certain IEQ risks. Energy conservation measures that increase outside air supply, will generally improve IEQ by reducing concentrations of indoor-generated air pollutants. However, when outdoor air quality is poor, e.g., when outdoor pollutant concentrations exceed applicable standards, these same energy conservation measures may increase the indoor concentration of outdoor pollutants.

Characteristics of the building and building HVAC system also influence the IEQ outcomes from energy conservation. Only a few of the many possible interactions are described here. The magnitude of indoor pollutant emission rates is one consideration. If the building contains strong indoor sources of air pollutants, energy conservation measures that reduce outside air supply are much more likely to result in elevated concentrations of these indoor-generated pollutants. (The converse is also true.) Similarly, if a building has a low rate of outside air supply, pollutants emitted from energy conservation products such as sealants are more likely to significantly degrade indoor air quality. Energy conservation measures that reduce outside air ventilation are more likely to lead to IEQ problems if the initial rate of outside air supply is low.

Proper implementation of the energy conservation measures can prevent many of the potential adverse impacts on IEQ. Most of the possible implementation errors are obvious: faulty design, installation, calibrations, control methods, commissioning, operation, or maintenance of the energy conservation systems or practices can lead to IEQ problems. Proper design, training of users, etc. can prevent problems.

Engineering calculations and computer modeling are the primary tools for predicting levels of IEQ or the magnitude of changes in IEQ. Indoor temperatures are determined from energy balances, and indoor humidity and pollutant concentrations from mass balances. Algorithms for equipment performance are often required. The ASHRAE handbooks (e.g., ASHRAE 1992, 1995, 1997) are one source for many of the engineering calculations. Simple steady state and transient mass balance calculations for estimating pollutant concentrations in a single well-mixed zone can be implemented by the user. Several computer programs, as reviewed by National Laboratories (1997), are available for predicting air infiltration rates, airflows between zones, and indoor pollutant concentrations. Proper use of these models generally requires considerable expertise in IEQ and experience with the model. The difficulties in obtaining model inputs are a major obstacle to IEQ modeling in multizone buildings.

7.3 Significance of Predicted Changes in IEQ

Once an expected change in IEQ is identified and, to the degree possible, quantified, the resulting influence on occupants health, comfort, or productivity should be considered. The main approach for evaluating the significance of predicted (or measured) changes in IEQ parameters is to compare the initial and final values of these parameters to the values listed as acceptable in the applicable standards or guidelines (see *Table 1*). When assessing significance, the following points should be kept in mind: 1) Small changes in indoor temperature, on the order of 1°C, may significantly influence thermal comfort, the prevalence of acute non-specific building-related health symptoms experienced by workers, and perceptions of air quality. 2) Occupants satisfaction with thermal conditions may be estimated using thermal comfort models (e.g., ASHRAE 1992b, Fountain and Huizenga 1996, ISO 1994); however, recent research suggests that these models are imperfect because they do not account for peoples behavioral, physiological, or psychosocial adaptations to their thermal environments. 3) Changes in lighting are much more likely to influence work performance if the work is unusually visually demanding.

For many pollutants, there are no published maximum concentration limits for non-industrial work places. The pollutant concentration limits published for industrial workplaces, such as the Threshold Limit Values (TLVs) of the American Conference of Governmental Industrial Hygienists (ACGIH 1998), should not be directly applied to non-industrial settings and workers.

In assessments of the significance of changes in IEQ, the sensitivity of occupants to IEQ is a consideration. Older workers tend to have more stringent thermal comfort requirements and the vision of older workers is more likely to be adversely affected by low lighting levels. Women report non-specific health symptoms more frequently than men do (Mendell 1993, Menzies and Bourbeau 1997). Workers in buildings with prior or ongoing IAQ or thermal comfort problems may be more likely to respond negatively to small decrements in IEQ.

8 Measurement And Verification Alternatives for IEQ[1]

8.1 Background

As indicated in *Table 2*, most of the impacts of energy projects on IEQ relate to thermal comfort or ventilation. Therefore, the most common parameters subject to IEQ M&V will be thermal comfort parameters (e.g., temperatures and humidities) and ventilation rates. For lighting retrofits, lighting-related M&V may sometimes be warranted. Occasionally, M&V of other IEQ parameters may be warranted. Such situations include, for example, building retrofits which move the outside air intake close to an outdoor pollutant source or measures, such as installation of an economizer, that cause a large increase of ventilation rate in a building located in a heavily polluted region. In such situations, M&V for specific pollutants (e.g., ozone, particles, carbon monoxide, or VOCs) may be desirable. Many IEQ measurements are expensive. Measurements should be performed only when there are clear objectives and the capabilities and intent to interpret the measurement results.

8.2 Goals of IEQ M&V

The appropriate M&V approach will depend on the goals of the IEQ M&V. Therefore, a definition of the M&V goals is a critical first step. Examples of IEQ M&V goals follow:

Goal 1: To ensure that the energy conservation measures have no adverse influence on IEQ.

Goal 2: To quantify the improvements in IEQ resulting from implementation of energy conservation measures.

Goal 3: To verify that selected IEQ parameters satisfy the applicable IEQ guidelines or standards.

8.3 Context for IEQ M&V

This document can be applied under two basic M&V contexts. The first basic context, and the primary focus of this volume, is the implementation of energy conservation retrofits in existing commercial buildings. Generally, in this situation, pre-retrofit and post-retrofit IEQ measurements are compared. A broad range of M&V approaches may be applied (e.g., measurements, modeling, and surveys).

---

1. IEQ measurement and verification (M&V) activities may be hazardous due to the potential for pollutant exposures, falls, and contact with high voltage or rotating equipment. Staff performing IEQ M&V should receive training in safe work practices. Reference documentation is available in the US EPA Orientation to Indoor Air Quality: Instructor Kit (or Student Manual). Ordering information can be found at http://www.epa.gov/iaq/base/baqapp2.html. These documents may also be purchased from the National Technical Information Service (NTIS), US Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161 (telephone 1-800-553-6847). The NTIS reference numbers are AVA19276SS00 and AVA 19277B00 for the Instructor Kit and Student manual, respectively.

The second basic context[1] is the anticipated future application of energy conservation features in new commercial building construction. For this second context, when M&V goal 1 or goal 2 are selected, it is necessary to define the relevant characteristics of a reference building without the energy conservation features and to define the relevant characteristics of the building with the energy conservation features implemented. Modeling is the only approach available prior to construction to estimate changes in IEQ (M&V goals 1 and 2). After construction is completed, measurements may be performed to verify that IEQ parameters satisfy applicable codes or standards (M&V goal 3).

8.4 M&V Procedure

Table 3 presents a recommended basic procedure for IEQ M&V. The M&V Approaches and M&V Alternatives referenced in this table are described later.

Table 3: The M&V Procedure

Steps in the M&V Procedure	Comments
1. Define M&V goals	See *Section 8.2*
2. Select M&V staff	a) Staff performing measurements must have necessary skills and knowledge; outside consultants with IEQ expertise are generally available. b) Owner should consider whether or not measurement staff should be independent of the organization (e.g., ESCO) that benefits financially from positive findings or if there should be independent oversight.
3. Select general M&V approach	See *Section 8.5*
4. Select specific IEQ parameters and M&V alternatives for measuring and predicting values of these parameters	See *Section 4*, *6*, and *8.6*
5. Establish plans for interpreting M&V data	a) Generally, measured IEQ data or predictions are compared to data or predictions from another time period, to baseline data from a representative set of buildings, or to values listed in standards. b) See *Section 4*, *8.3*, *8.5*
6. Define requirements for M&V accuracy and quality control procedures for measurements	Often the required accuracy depends on the expected magnitude of the change in IEQ.

1. A building with occupants that have excessive health or comfort complaints is a third potential context for IEQ M&V. However, this document is not intended as a guide for diagnosis or investigations of the causes of such complaints. Several existing documents may be consulted for such situations (e.g., EPA / NIOSH 1991; ISIAQ 1996 (in draft), ECA 1989, Weekes and Gammage 1990, Raferty 1993, Nathanson 1995). Usually, a phased investigative approach is recommended. Early phases include building inspections and discussions with building occupants. Expensive measurements are recommended only if necessary in subsequent phases of the investigation. These guides point out the importance of maintaining open channels of communication about the complaints, about IAQ, and about the investigation.

Table 3: The M&V Procedure

7. Select measurement or assessment periods	a) Often, pre-retrofit values of IEQ parameters are compared to post-retrofit values. b) Many IEQ parameters change with time because of changes in building operation, indoor pollutant emission rates, or outdoor air quality. Measurements should take place under the relevant conditions (e.g., minimum outside air supply) or they should average over the range of conditions. If weather, outdoor air quality, or occupancy differ significantly between the pre- and post-retrofit measurement periods, a comparison of pre-retrofit and post-retrofit measurements may not accurately indicate the effect of the energy conservation on IEQ. c) Indoor thermal conditions and pollutant concentrations in buildings do not respond instantly to changes in the controlling factors. d) Instantaneous measurements of temperatures, humidities, and air pollutant concentrations will often not be valuable.
8. Select measurement locations	a) Thermal comfort standards provide guidance for measurement locations. b) Measurement locations should yield data representative of conditions experienced by occupants. Worst-case locations may also be monitored. c) The breathing zone is most important location for air pollutant measurements. d) Pollutant concentrations in HVAC return airstreams may approximately represent average concentration in section of building from which the return air is drawn (except with displacement ventilation).
9. Define acceptable M&V costs	Expenditure should generally be small compared to expected savings from energy conservation measures.
10. Select M&V instrumentation	Instrumentation must satisfy accuracy, cost, and data logging requirements
11. Inform occupants of M&V plans	Unexplained measurements may cause occupants concern about IEQ.
12. Implement measurements, surveys, or modeling	Methods employed should meet accuracy, space, and temporal specifications and cost constraints.
13. Analyze and report results	Results should generally be available to occupants.

8.5 Basic M&V Approaches

This section identifies basic approaches for IEQ M&V and identifies situations for which each general approach may be applicable.

8.5.1 Approach 1: No IEQ M&V

Table 2 lists several energy conservation measures (e.g., chiller upgrades) that are either unlikely to affect IEQ or that are likely to have only a beneficial influence on IEQ. In general, no IEQ M&V will be necessary when the energy conservation measures are judged highly unlikely to result in a significant adverse IEQ impact. However, IEQ M&V may still be performed if the M&V goal is to quantify an anticipated improvement in IEQ.

8.5.2 Approach 2: IEQ M&V Based on Modeling

IEQ modeling is usually the only method available to predict the magnitude of changes in IEQ associated with implementation of energy conservation measures during new construction. Additionally, modeling may be appropriate to estimate changes in indoor pollutant concentrations associated with changes in ventilation rates or when measurement methods are too expensive or not available.

Very simple mass balance models for single zones with well-mixed air can provide a useful estimate of the change in indoor pollutant concentrations that are expected when ventilation rates or indoor pollutant emission rates are modified. Many scientific papers describe such models which can be implemented using spreadsheet software (e.g., Persily and Dols 1990, Nazaroff et al. 1993, Fisk and de Almeida. 1998). Several much more complex multi-zone models are available (National Laboratories 1997, Chapter 3). Many of the complex models require extensive model inputs and considerable IEQ modeling expertise.

Lighting simulation tools such as the Radiance program (Ward and Rubinstien 1998) can model the resultant luminance distribution from most lighting and daylighting systems; however, only a few lighting quality parameters, such as glare, are computed by these tools. Extensive model inputs and considerable modeling expertise are required.

8.5.3 Approach 3: Short Term Measurements of Selected IEQ Parameters

Short term measurements of IEQ parameters (e.g., measurements for a month or less) may be used for IEQ parameters that do not vary significantly with season or with the mode of building operation. Examples of such parameters are light levels in core zone of building and minimum outside air flow rates in constant volume HVAC systems. Short term measurements may also be appropriate when the outcome of interest is an IEQ parameter for a defined set of climatic and building operating conditions, such as conditions that leads to worst case IEQ. In this instance, short-term measurements can be performed only under these conditions.

8.5.4 Approach 4: Long-term Continuous Measurements of Selected IEQ Parameters

Long-term continuous measurements are often affordable and useful for tracking selected IEQ parameters including indoor temperatures and humidities, carbon dioxide concentrations, carbon monoxide concentrations, and rates of outside air intake into air handlers. For most other IEQ parameters, long-term continuous measurements are prohibitively costly or unavailable. The costs of sensors, and sensor maintenance and calibration may be lower in continuous monitoring systems that use single sensors to analyze samples drawn sequentially from multiple locations. However, drawing some pollutants, e.g., particles and many VOCs, through long sampling tubes will lead to substantial measurement errors.

8.5.5 Approach 5: Surveys to Assess Occupant Perceptions and Ratings of IEQ

In many instances, occupant perceptions determined in a survey are as relevant an outcome as measured IEQ conditions. Survey costs can be lower or higher than costs of physical measurements.

There are two basic uses of surveys in the context of IEQ M&V. First, administration of a survey before and after implementation of an energy conservation measure can provide information on the perceived change in IEQ and occupant reports of health symptoms[1]. The second method of using surveys in the context of IAQ M&V is to perform a one-time survey and to compare the results to baseline data obtained previously in other buildings with the same survey instrument.

Survey data are subjective; hence, these data may be influenced by psychosocial factors such as job satisfaction. A portion of the occupants may express dissatisfaction even when IEQ is above average. Additionally, surveys can only assess the responses to IEQ that are sensed by the human sensory systems. IEQ exposures that increase the risk of some chronic health effects, such as lung cancer from radon exposures, will not be detected using surveys.

The survey design and methods of administration can affect the outcome; therefore, surveys should be based on established questionnaires and on survey administration methods developed by staff with suitable expertise. High response rates (e.g., > 80%) to surveys are necessary to reduce risk of bias (e.g., a higher response rate from unhappy occupants could bias the overall results).

Well-established survey methods are available for thermal comfort. Thermal sensation is commonly assessed using a seven-point scale (e.g., ASHRAE 1992b, ISO 1994). Baseline data are being compiled by de Dear and Brager (1998) from thermal comfort surveys performed throughout the world.

Several survey instruments (questionnaires) have included broad assessments of the level of satisfaction with, or perception of, multiple IEQ parameters such as lighting level, lighting quality, acoustical quality, air movement, acceptability of indoor air quality, ventilation, etc. These same surveys have generally collected data on the prevalence or severity of non-specific health symptoms experienced by office workers.

A U.S. EPA-supported survey is collecting data on non-specific symptoms from 100 office buildings in the US (EPA 1994; Brightman et al. 1997). A European Audit Project has collected symptom data from 56 office buildings (Bluyssen et al. 1996). Stenberg et al. (1993) and Sundell (1994) describe similar data obtained from approximately 5000 office workers in 210 buildings in Sweden.

Questionnaires to evaluate occupant satisfaction with lighting are available (Collins et al. 1990, Dillon and Vischer 1987, Eklund and Boyce 1995, Hygge and Lofberg 1998) although customization for specific applications may be required.

8.6 M&V Alternatives for Specific IEQ Parameters

In tabular form, this section identifies M&V alternatives for specific IEQ parameters and provides comments on these alternatives. The M&V alternatives for thermal comfort and ventilation are listed first because energy conservation retrofits more often affect these IEQ parameters. The tables do not include all possible M&V alternatives. The alternatives judged to be the most practical and valuable are marked with "◆". General guidance for measurement of indoor air pollutant concentrations is available in several publications (e.g., ACGIH 1995, Nagda and Harper 1989)

1. There is evidence that responses to surveys of non-specific health symptoms tend to vary even with no apparent change in building conditions or IEQ. Often, occupants report fewer building-related health symptoms on a second of two surveys administered a week or two apart in time. Thus, it may be necessary to correct the change in survey results obtained from the space with the energy conservation retrofit by subtracting the change in survey results from a control population.

Table 4: Specific M&V Alternatives for IEQ Parameters.

Row	IEQ Parameter / M&V Alternative	Comments
Thermal comfort		
1	Alternative 1. Multi-parameter measurements specified in thermal comfort standards (ASHRAE 1992b, ISO 1994)	a) Generally one measures air temperature, mean radiant temperature, relative humidity, and air velocity at multiple heights in multiple (e.g., 20 - 30) workspaces. b) Measurement system cost is at least US $5K. The system may be moved between locations (e.g., see De Dear and Fountain 1994). c) This method provides only short-term data at each location. d) Thermal comfort instruments are commercially available.
2	◆ Alternative 2. Multipoint measurement and logging of air temperatures and/or humidities using portable or permanent inexpensive instrumentation	a) In many common situations air temperature measurements at a single height (without air velocities, humidity, and mean radiant temperature) are adequate. b) This alternative is not appropriate for situations with high air velocities (e.g., fans used for cooling), high temperature stratification (e.g., displacement ventilation) or large radiant heat gains or losses (e.g., near cold windows). c) Temperature sensor accuracy should be ~ 0.25 °C because temperature differences < 1 °C may significantly influence thermal comfort. d) Humidity sensor accuracy should be ~ 5% RH. e) The cost of battery powered sensor with data logger for a single point measurement is ~ US$100 to $200.
3	◆ Alternative 3. Thermal comfort surveys (Schiller et al. 1988, De Dear and Fountain 1994)	a) In many instances, surveys are the best alternative. b) Surveys may ask about current level of thermal comfort or about thermal comfort during prior extended period.
Outside air ventilation rate		
4	Alternative 1. Outside airflow into air handler measured using anemometry (ASHRAE 1988, SMACNA 1993, Utterson and Sauer 1998, Solberg et al 1990)	a) Accuracy is often questionable when measurements are made near outside air louvers or dampers. b) ◆ Better accuracy obtained if measurements can be made in sufficient length of straight outside air duct.
5	◆ Alternative 2. Outside airflow into air handler measured based on HVAC supply flow and% outside air (Drees et al. 1992)	a) Supply air flow is typically from balometers (airflow hoods), pitot tube or hot wire anemometer traverses in supply airstream, or permanently-installed supply airflow measurement stations. b) Percent outside air is determined from carbon dioxide or tracer gas mass balance. c) The temperature method of determining percent outside air is often inaccurate.
6	Alternative 3. Outside air ventilation rates determined using tracer gas methods (ASTM 1995, NORDTEST 1982, 1988, Lagus and Persily 1985, ASHRAE 1998, Faulkner et al. 1998, Charlesworth 1988)	a) Procedures include tracer gas decays, stepups, and methods based on continuous release of tracer to indoors. b) Measurements can account for both natural and mechanical ventilation. c) Reasonable (e.g., 15-25%) accuracy is possible in many buildings. d) For most tracer gas methods, ventilation rates must be reasonably stable during the measurement period. e) Measurements are often expensive and require considerable expertise (instrumentation costs usually > US $10000). f) Most procedures give ventilation rates representative of a short (few hour) time period; some provide an average effective ventilation rate for an extended period.
7	Alternative 4: Outside air ventilation rates determined using outside air flow measurement stations in air handlers	a) Usually airflow straighteners and multiple point velocity sensors are installed in vicinity of outside air inlet dampers / louvers. b) Commercially available products are relatively new; therefore, limited performance data are available.

Table 4: Specific M&V Alternatives for IEQ Parameters.

Carbon dioxide concentrations		
8	◆ Alternative 1. Real time CO_2 infrared analyzers with output logged over time (Persily and Dols 1990; Persily 1993, ASTM 1998)	a) Peak or time average carbon dioxide concentrations are useful indicators of how effectively occupant-generated bioeffluents are controlled by ventilation and may be fair indicator for other pollutants associated with occupancy. b) Several procedures have been used (and often misused) to estimate ventilation rates from measured carbon dioxide concentrations. In many buildings, it is difficult to accurately determine the rate of outside air supply from carbon dioxide data because of uncertainties and temporal variations in occupancy, uncertain rates of carbon dioxide generation by occupants, and because concentrations change slowly after changes in ventilation or occupancy. c) The cost of a carbon dioxide analyzer is typically US $700 to $3000.
Carbon monoxide concentrations		
9	Alternative 1. Real time infrared analyzer with output logged over time	a. Elevated indoor carbon monoxide concentrations, relative to outdoor concentrations, may indicate failure of the venting of a combustion appliance or leakage of auto exhaust into the building. b) Typical instrumentation cost is a few thousand dollars US.
10	◆ Alternative 2. Use of low cost carbon monoxide alarms.	a. Elevated indoor carbon monoxide, relative to outdoor concentrations, may indicate failure of the venting of a combustion appliance or leakage of auto exhaust into the building. b) Typical alarm cost is ~ US $100.
Ozone concentrations		
11	Alternative 1. Use real time electrochemical analyzer with data logger	a) May be useful in high-ozone cities to determine if energy conservation measures that change ventilation rates significantly influence indoor-outdoor ozone concentration ratios or time average indoor ozone concentrations. b) Indoor and outdoor concentrations are highly variable with time. c) Measurement equipment is relatively expensive, > US $6000, so measurement will often be impractical.
Particle concentrations		
12	Alternative 1. Real time particle counting using light scattering instruments.	a) Indoor particle concentrations may be compared to limits specified in standards or the influence of the energy conservation measure on the indoor-outdoor concentration ratio may be assessed. b) Outdoor air is a significant, sometimes dominant, source of indoor particles. c) Indoor and outdoor concentrations vary over time. d) Real—time instruments typically cost at least a few thousand dollars (US).
13	Alternative 2. Draw air samples through filters at constant and known rates and weigh filters using precision balance to determine collected particle mass. (ACGIH 1993)	a) Indoor particle concentrations may be compared to limits specified in standards or the influence of the energy conservation measure on the indoor-outdoor concentration ratio may be assessed. b) Outdoor air is a significant, sometimes dominant, source of indoor particles. c) Indoor and outdoor concentrations vary over time. d) Sampling instrumentation costs ~ US $1000 for a single measurement site. Precision balance may cost a few thousand dollars (US). Substantial sample handling costs.

Table 4: Specific M&V Alternatives for IEQ Parameters.

Bioaerosol concentrations		
14	Alternative 1. Use single or multi-stage impactor to collect samples on culture media, incubate and count and identify microbial colonies (ACGIH 1990, 1995b, 1995c)	a) Measurements are expensive; concentrations may vary a great deal with time while sample collection periods are less than 15 minutes. b) Measurement results depend on culture media and incubation conditions. c) Culture based methods do not detect non-culturable (e.g., dead) organisms that may elicit health effects. d) High level of expertise required.
Airborne volatile organic compounds		
15	◆ Alternative 1: Collect samples on solid sorbents and have samples analyzed in a laboratory for TVOC using gas chromotography with a flame ionization detector or gas chromotography—mass spectrometry (Hodgson 1995, ECA 1997)	a) See comments in *Section 3* on use of TVOC data. b) Cost of sampling equipment for a single measurement site is usually < US $1000. c) Analysis cost for TVOC is ~ US $100 per sample.
16	Alternative 2. Use sensitive (e.g., photo acoustic) infrared analyzer to measure TVOC concentration (Hodgson 1995)	Value of TVOC measurements made with infrared analyzers is uncertain because analyzer response varies depending on the mixture of compounds in the air.
17	Alternative 3: Collect samples on solid sorbents and have samples analyzed in a laboratory using gas chromotography — mass spectrometry for concentrations of several individual VOCs (e.g., quantify the most abundant VOCs or those from known sources) (Hodgson 1995, ECA 1997, ASTM 1994, 1994b, 1994c, 1995b, 1996, 1997, 1998b)	a) See comments in *Section 3* VOCs. b) Cost of sampling equipment for a single measurement site is usually < US $1000. Analysis cost for a set of 10 to 15 VOCs is ~ US $500 per sample.
Lighting parameters and satisfaction		
18	Alternative 1: Light intensity measurements made in accordance with existing standards (IES 1993)	a) One time measurements of lighting intensity (illuminance at task height) and uniformity in typical spaces. b) Instrumentation (light meter) is relatively inexpensive (~ US $200 to $400). c) Expertise required to determine which spaces are typical and to perform measurements correctly.
19	Alternative 2: Multi-parameter measurements made in accordance with existing standards (IES 1993)	a) Measurements of luminance distribution (obtainable with an image capture system) in typical spaces. b) Existing image capture systems are still in infancy. Some software is available to analyze images after capturing; however, existing analysis tools do not directly compute lighting quality parameters from luminance data. c) Measurements of direct glare from sources in field of view (both electric light and daylight). Requires luminance meter. Difficult to document exact location of luminance measurements, thus reproducibility is questionable. d) Some light sources (e.g., daylight) are time variant.
20	◆ Alternative 3. Occupant comfort or satisfaction with lighting assessed via a survey (Collins et al. 1990, Dillon and Vischer 1987, Eklund and Boyce 1995, Hygge and Lofberg 1998)	a) Often the least expensive method. b) Survey results can integrate over time. c) A well-designed survey can assist occupants in identifying particular sources of lighting problems.

Table 4: Specific M&V Alternatives for IEQ Parameters.

Occupant satisfaction with IEQ		
21	◆ Assess using survey (see *Section 8.5.5*)	a) See comments on surveys in *Section 8.5.5*. b) Survey results can integrate over time. c) High satisfaction with air quality does not assure that pollutants do not pose a health risk. d) Occupants sometimes attribute problems to an incorrect source or to unrelated environmental conditions (e.g., noise from computers attributed to lighting system ballasts).
Prevalence or severity of acute non-specific health symptoms		
22	◆ Assess using survey (see *Section 8.5.5*)	a) See comments on surveys in *Section 8.5.5*. b) Survey results can integrate over time. c) Low level of self-reported health symptoms does not assure that pollutants do not pose a health risk.

9 Implementing the Guideline

To implement this guideline, the following actions are recommended:

1 Develop a general knowledge of IEQ through a review of *Section 4* and *5* or equivalent documentation.

2 For the energy conservation measures that will be implemented, use *Table 2*, *Section 7*, and supplemental information as necessary to determine: a) the potential impacts of the energy conservation measures on IEQ; and b) the associated precautions or mitigation measures.

3 Select a goal for IEQ M&V from *Section 8.2*.

4 Based on the energy conservation measures and goal, select an IEQ M&V approach from *Section 8.5*.

5 Assuming that the selected IEQ M&V approach is not Approach 1 (no IEQ M&V), select and implement an IEQ M&V alternative from *Table 4*. During implementation, utilize, as appropriate, steps 4-10 of the M&V procedure described in *Table 3*. If *Table 4* does not include an acceptable IEQ M&V Alternative, other alternatives may be developed and utilized.

6 Prepare and distribute written documentation of the IEQ M&V process that includes descriptions and justifications of important decisions and procedures plus a summary and interpretation of findings.

10 Concluding Remarks

Awareness of the significant influences of IEQ on the comfort, health, satisfaction and productivity of building occupants is increasing. The implementation of energy conservation projects in commercial buildings will often influence IEQ positively or negatively; therefore, IEQ should be considered during the selection and implementation of energy conservation measures. For many projects, IEQ problems are easily avoided through proper implementation of the energy conservation measures and the application of general knowledge about IEQ. In some situations, IEQ M&V is warranted to assure that IEQ remains acceptable or to quantify improvements in IEQ. This document serves to educate building energy professionals about the most relevant aspects of IEQ and also provides guidance on IEQ M&V.

11 References

1 ACGIH (1990) *Guidelines for the assessment of bioaerosols in the indoor environment, Publication 3180*, American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH

2 ACGIH (1993) *Aerosol measurement: principles, techniques, and applications*, Klaus Willeke and Paul A. Baron, Eds. American Conference of Governmental Industrial Hygienists, Inc., Publication 9400, Cincinnati, OH

3 ACGIH (1998) 1998-1999 *Threshold limit values for chemical substances and physical agents and biological exposure indices.* American Conference of Governmental Industrial Hygienists, Cincinnati.

4 ACGIH (1995) *Air sampling instruments*, 8th Ed., Publication 0030, American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH

5 ACGIH (1995b) *Bioaerosols*, Harriet Burge, Ed., Publication 9612, American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH

6 ACGIH (1995c) *Bioaerosols handbook*, Christopher S. Cox and Christopher M. Wathes, Eds., Publication 9611, American Conference of Governmental Industrial Hygienists, Inc., Cincinnati, OH

7 Andersson, K.; Bakke J.V., Bjorseth, O., Bornehag, C._G., Clausen, G., Hongslo, J.K., Kjellman, M., Kjaergaard, S., Levy, F., Molhave, L., Skerfving, S., and Sundell, J. (1997) TVOC and health in non-industrial indoor environments: report from a Nordic Scientific Consensus Meeting at Langholmen in Stockholm, 1996 , *Indoor Air 7*(2): 78-91.

8 Arens, E and Baughman, A. (1996) Indoor humidity and human health, part 2: buildings and their systems , *ASHRAE Transactions 102*(1): 212-221.

9 Arens, E.A. Bauman, F.S., Johnston, L.P., and Zhang, H. (1991) Testing of localized ventilation systems in a new controlled-environment chamber , *Indoor Air 1*(3), pp. 263-281.

10 ASHRAE (1988) *ASHRAE / ANSI Standard 111-1988, Practices for measurement, testing, adjusting, and balancing of building heating, ventilating, and air-conditioning systems*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta.

11 ASHRAE (1989) *ASHRAE standard 62-1989, ventilation for acceptable indoor air quality*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

12 ASHRAE (1992) *1992 ASHRAE handbook, HVAC systems and equipment*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

13 ASHRAE (1992b*) ASHRAE / ANSI Standard 55-1992, Thermal environmental conditions for human occupancy*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

14 ASHRAE (1995) *1995 ASHRAE handbook, HVAC applications*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

15 ASHRAE (1995b) *ANSI/ASHRAE Standard 55a-1995, Addendum to thermal environmental conditions for human occupancy*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

16 ASHRAE (1996) *1996 ASHRAE Handbook, HVAC Systems and Equipment*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

17 ASHRAE (1996b*) ASHRAE Standard 62-1989 Ventilation for acceptable indoor air quality, public review draft*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

18 ASHRAE (1996c) *Guideline 1-1996 - The HVAC commissioning process*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

19 ASHRAE (1997) *1997 ASHRAE handbook, fundamentals*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

20 ASHRAE (1998) *ASHRAE Standard 129, measuring air change effectiveness*, To be published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., Atlanta.

21 ASTM (1994) *ASTM Standard D 5014-94, standard test methods for measurement of formaldehyde in indoor air (passive sampler methodology),* American Society for Testing and Materials, West Conshohocken, PA.

22 ASTM (1994b) *ASTM Standard D 4947-94, standard practice for chlorodane and heptachlor residues in indoor air*, American Society for Testing and Materials, West Conshohocken, PA.

23 ASTM (1994c) *ASTM Standard D 4861-94a, standard practice for sampling and selection of analytical techniques for pesticides and polychlorinated biphenyls in indoor air*, American Society for Testing and Materials, West Conshohocken, PA.

24 ASTM (1995) *ASTM Standard E 741-95, standard test methods for determining air change in a single zone by means of a tracer gas dilution*, American Society for Testing and Materials, West Conshohocken, PA.

25 ASTM (1995b) *ASTM Standard D 5466-95, standard test method for determination of volatile organic compounds in atmospheres (canister sampling methodology)*, American Society for Testing and Materials, West Conshohocken, PA.

26 ASTM (1996) *ASTM Standard D 5075-96E01 standard test method for nicotine and 3-ethenylpyridine in indoor air*, American Society for Testing and Materials, West Conshohocken, PA.

27 ASTM (1997) *ASTM Standard D 5197-97 standard test method for formaldehyde and other carbonyl compounds in air (active sampler methodology),* American Society for Testing and Materials, West Conshohocken, PA.

28 ASTM (1998*) ASTM Standard D 6245-98, standard guide for using indoor carbon dioxide concentrations to evaluate indoor air quality and ventilation*, American Society for Testing and Materials, West Conshohocken, PA.

29 ASTM (1998b) *ASTM Standard D 6306-98, standard guide for placement and use of diffusion controlled passive monitors for gaseous pollutants in indoor air*, American Society for Testing and Materials, West Conshohocken, PA.

30 Awbi, H.B. (1991) *Ventilation of buildings*, Chapman & Hall, Northway, Andover, Hants, United Kingdom.

31 Baughman, A. and Arens, E (1996) Indoor humidity and human health, part 1: literature review of health effects of humidity-influenced indoor pollutants , *ASHRAE Transactions* 102(1): 193-211.

32 Bauman, F., Baughman, A., Carter, G., and Arens, E. (1997) A field study of PEM (Personal Environment Module) performance in Bank of America s San Francisco office buildings , CEDR-01-97, University of California, Berkeley (cedr@ced.berkeley.edu).

33 Bauman, F.S., Zhang, H., Arens, E.A., and Benton, C. (1993) Localized comfort control with a desktop task conditioning system *ASHRAE Transactions 99*(2), pp. 733-749.

34 Bearg, D.W. (1993) *Indoor air quality and HVAC systems*, Lewis Publishers, Chelsea, MI

35 BEIR VI (1998) *Health effects of exposure to radon: BEIR VI, Committee on the Biological Effects of Ionizing Radiation (BEIR VI)*, National Research Council, National Academy Press.

36 Berman, S.M. (1992) Energy efficiency consequences of scotopic sensitivity , *Journal of the Illuminating Engineering Society* 21(1): 3-14

37 Bluyssen, P.M., de Oliveira Fernandes, E., Groes, L., Clausen, G., Fanger, P.O., Valbjorn, O., Bernhard, C.A., and Roulet, C.A. (1996) European indoor air quality audit project in 56 office buildings , *Indoor Air 6*(4): 221-238.

38 Brightman, H.S., Womble, S.E., Girman, J.R., Sieber, W.K., McCarthy, J.F., Buck, R.J., and Spengler, J.D. (1997) Preliminary comparison of questionnaire data from two IAQ studies: occupant and workspace characteristics of randomly selected buildings and complaint buildings , *Proceedings of Healthy Buildings / IAQ 97,* vol. 2, pp. 453-458, Healthy Buildings/ IAQ 97 Washington DC

39 Brunekreef, B. (1992) Damp housing and adult respiratory symptoms , Allergy 47: 498-502.

40 Busch, J. (1992) A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand , *Energy and Buildings* 18: 235-249.

41 California EPA (1997) *Health effects of exposure to environmental tobacco smoke, final report September 1997*, California Environmental Protection Agency, Sacramento, CA.

42 Carpenter, S.E. (1996) Energy and IAQ impacts of CO2 -based demand-controlled ventilation , To be published in *ASHRAE Transactions* 102(2): 80-88.

43 Charlesworth, P.S. (1988) *Air exchange rate and airtightness measurement techniques — an application guide*Air Infiltration and Ventilation Centre, Coventry, Great Britain.

44 Cohen, T. (1994) Providing constant ventilation in variable air volume systems , *ASHRAE Journal* 36(5): 38-40.

45 Collins, B.L., Fisher, W., Gillette, G. and Marans, R.W. (1990) Second —level post-occupancy evaluation analysis , *Journal of the Illuminating Engineering Society* 19(2): 21-44

46 Committee on Health Effects of Indoor Allergens (1993) *Indoor allergens: assessing and controlling adverse health effects*, Pope, A.M., Patterson, R., and Burge, H. editors, National Academy Press, Washington, D.C.

47 Daisey, J.M., Hodgson, A.T., Fisk, W.J., Mendell, M.J., Ten Brinke, J.A. (1994) "Volatile organic compounds in twelve california office buildings: classes, concentrations, and sources", *Atmospheric Environment* 28(22), pp. 3557-3562.

48 Dales, R.E.; Burnett, R.; and Zwanenburg, H. (1991) Adverse health effects among adults exposed to home dampness and molds , *American Review of Respiratory Disease* 143: 505-509.

49 De Almeida, A.T. and Fisk, W.J. (1997) Sensor based demand controlled ventilation , LBNL-40599, Lawrence Berkeley National Laboratory, Berkeley, CA.

50 De Dear, R. and Brager, G.S. (1998) Developing an adaptive model of thermal comfort and preference , to be published in *ASHRAE Transactions* 104(1).

51 De Dear, R. and Fountain M. (1994) Field experiments on occupant comfort and office building thermal environments in hot-humid climate , *ASHRAE Transactions* 100(2): 457-475.

52 Dillon, R. and Vischer, J. (1987) *Derivation of the tenant survey assessment method: office building occupant survey data analysis*, Public Works Canada, Ottawa.

53 Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health (1984), Outbreaks of respiratory illness among employees in large office buildings -- Tennessee, District of Columbia , *MMWR* 33(36): 506-513.

54 Drees, K.H., Wenger, J.D., and Janu, G. (1992) Ventilation air flow measurement for ASHRAE Standard 62-1989 , *ASHRAE Journal* 34(10): 40-45.

55 ECA (1989) Report No. 4, *Sick building syndrome- a practical guide, European Collaborative Action Indoor Air Quality and its Impact on Man* , COST Project 613, Office for Official Publications of the European Communities, Luxembourg.

56 ECA (1992) *Report no. 11: guidelines for ventilation requirements in buildings*, EUR 14441 EN, European collaborative action, indoor air quality & its impact on man, Office for Official Publications of the European Communities, Luxembourg.

57 ECA (1997) *Report 19, total volatile organic compounds (TVOC) in indoor air quality investigations*, European collaborative action, indoor air quality & its impact on man, Office for Official Publications of the European Communities, Luxembourg.

58 Eklund, N.H. and Boyce, P.R. (1996) The development of a reliable, valid, and simple office lighting survey , *Journal of the Illuminating Engineering Society* 25(2): 25-40.

59 Elixmann, J.H., Schata, M., and Jorde W. 1990. "Fungi in filters of air conditioning systems cause the building related illness." *Proceedings of the Fifth International Conference on Indoor Air Quality and Climate*, Toronto, vol. 1, pp. 193-202. Published by the International Conference on Indoor Air Quality and Climate, Inc., 2344 Haddington Crescent, Ottawa, Ontario, K1H 8J4.

60 Emmerich, S.J. and Persily, A.K. (1997) Literature review on CO2 — based demand controlled ventilation, *ASHRAE Transactions* 103(2): 229-243.

61 EPA (1992) *Respiratory health effects of passive smoking: lung cancer and other disorders*, EPA/600/6-90/006F, US Environmental Protection Agency, Washington, DC.

62 EPA (1994) *A standardized EPA protocol for characterizing indoor air quality in large office buildings*, Office of Research and Development and Office of Air and Radiation, U.S. Environmental Protection Agency.

63 EPA (1996) *Air quality criteria for particulate matter, volume II of III*, EPA/600/P-95/001bF, US Environmental Protection Agency.

64 EPA / NIOSH (1991) *Building air quality: a guide for building owners and facility managers*, US Environmental Protection Agency and National Institute for Occupational safety and Health, EPA/400/1-91/033, Superintendent of Documents, PO Box 37195, Pittsburgh, PA 15250

65 Fang, L.; Clausen, G.; and Fanger, P.O. (1997) Impact of temperature and humidity on acceptability of indoor air quality during immediate and longer whole-body exposures , *Proceedings of Healthy Buildings* / IAQ 97, vol. 2: 231-236, Healthy Buildings/ IAQ 97 Washington DC

66 Fanger, P. O. (1970): *Thermal comfort analysis and applications in environmental engineering*. McGraw-Hill, New York.

67 Faulkner, D.; Fisk, W.J.; Sullivan, D.P.; and Thomas, J.M. Jr. (1998) Characterizing building ventilation with the pollutant concentration index: results from field studies , To be published in the *proceedings of IAQ and Energy 98*, October 24 — 27, New Orleans, ASHRAE, Atlanta

68 Federspiel, C.C. (1996) On-demand ventilation control: a new approach to demand-controlled ventilation , *Proceedings of Indoor Air 96,* vol. 3, pp. 935-940. SEEC Ishibashi, Inc., Japan.

69 Federspiel, C.C. (1998) Statistical analysis of unsolicited thermal sensation complaints in commercial buildings , *ASHRAE Transactions* 104(1): 912-923

70 Fisk, W.J. and de Almeida, A.T. (1998) Sensor based demand controlled ventilation: a review , LBNL- 41698, Lawrence Berkeley National Laboratory, Berkeley, CA, *to be published in Energy and Buildings*.

71 Fisk, W.J. and Rosenfeld, A.H. (1997) Estimates of improved productivity and health from better indoor environments , *Indoor Air 7*(3): 158-172.

72 Fisk, W.J. and Rosenfeld, A.H. (1998) Potential nationwide improvements in productivity and health from better indoor environments , *Proceedings of the ACEEE 1998 Summer Study on Energy Efficiency in Buildings*, Energy Efficiency in a Competitive Environment , August 23-28, Asilomar, CA, pp. 8.85-8.97.

73 Fisk, W.J., Faulkner, D., Sullivan, D., and Bauman, F (1997). Air change effectiveness and pollutant removal efficiency during adverse mixing conditions , *Indoor Air 7*: 55-63

74 Fisk, W.J., Mendell, M. J., Daisey, J. M., Faulkner, D., Hodgson, A.T., Nematollahi, M., and Macher, J. (1993) "Phase 1 of the California Healthy Building Study: a summary" *Indoor Air 3*(4): 246-254.

75 Fountain, M.E. and Huizenga, C. (1996): "A thermal comfort prediction tool," *ASHRAE Journal* 38(9): 39-42.

76 Gammage, R.B. and Berven, B.A., eds. (1997) *Indoor air and human health*, second edition. Lewis Publishers, Boca Raton, FL.

77 Givoni, B. (1997) *Passive and low energy cooling of buildings*, John Wiley & Sons, New York

78 Hanley, J.T., Ensor, D.S., Smith, D.D., and Sparks, L.E. (1994) Fractional aerosol filtration efficiency of in-duct ventilation air cleaners , *Indoor Air 4*(3): 169-178.

79 Heiselberg, P. (1994) Draught risk from cold vertical surfaces , *Building and Environment* 29: 297-301.

80 Heiselberg, P., Overby, H., and Bjorn, E. (1995) Energy-efficient measures to avoid downdraft from large glazed facades , *ASHRAE Transactions* 101(2): 1127-1135.

81 Hodgson, A.T. (1995) A review and limited comparison of methods for measuring total volatile organic compounds in indoor air , *Indoor Air 5*(4): 247-257.

82 Hygge, S. and Loftberg, H. (1998) User evaluation of visual comfort in some buildings of the daylight Europe project , *Proceedings of the 4th European Conference on Energy Efficient Lighting*, vol. 2, pp. 69-74, DEF Congress Service, Coppenhagen

83 IES (1993) *Lighting handbook, reference & application*, M.S. Rea Ed., Illuminating Engineering Society of North America, New York

84 International Energy Agency (1990) *Demand-controlled ventilating systems: state of the art review*, (editor W. Raatschen) Published by the Swedish Council for Building Research, Stockholm.

85 International Energy Agency (1992), *Demand controlled ventilation systems - source book*, Energy Conservation in Buildings and Community Systems Programme, Swedish Council for Building Research, Stockholm.

86 ISIAQ (1996) ISIAQ guidelines: Task Force II - general principles for the investigation of IAQ complaints (DRAFT - May 31, 1996) , International Society for Indoor Air Quality and Climate, Ottawa (http://www.isiaq.org)

87 ISO (1994) *ISO 7730:1994 Moderate thermal environments -- determination of the PMV and PPD indices and specification of the conditions for thermal comfort,"* International Organization for Standardization

88 Jaakkola, J.K.; Heinonen, O.P.; and Seppanen, O. (1991) Mechanical ventilation in office buildings and the sick building syndrome. An experimental and epidemiological study , *Indoor Air* 2: 111-121.

89 Janu, G.; Wenger, J., and Nesler, C. (1995) Outdoor air flow control for VAV systems , *ASHRAE Journal* 37(4): 62-68.

90 Katzev, R. (1992) The impact of energy-efficient office lighting strategies on employee satisfaction and productivity , *Environment and Behavior* 24(6): 759-778.

91 Koenigsberger, Ingersoll, Mayhew, Szokolay (1973) *Manual of tropical housing and building; part 1, climatic design*, 320 pp., Longman Group Limited, London and New York.

92 Lagus, P. and Persily, A.K. (1985) A review of tracer gas techniques for measuring airflows in buildings , *ASHRAE Transactions* 91(2b): 1075-1087.

93 Martikainen, P.J., Asikainer, A., Nevabiner, A., Jantunen, M., Pasanen, P., and Kalliokski, P. (1990) "Microbial growth on ventilation filter materials" *Proceedings of the Fifth International Conference on Indoor Air Quality and Climate*, Toronto, vol. 3, pp. 203 - 206. Published by the International Conference on Indoor Air Quality and Climate, Inc., 2344 Haddington Crescent, Ottawa, Ontario, K1H 8J4.

94 Mendell, M.J. (1993) Non-specific health symptoms in office workers: a review and summary of the epidemiologic literature , *Indoor Air* 3(4): 227-236.

95 Menzies, D.; Tamblyn, R.; Farant, J.; Hanley, J.; Nunes, F.; and Tamblyn, R. (1993) The effect of varying levels of outdoor-air supply on the symptoms of sick building syndrome , *The New England Journal of Medicine* 328(12): 821-827.

96 Ministers (1970) *Law for maintenance of sanitation in buildings*, Ministers of Justice, Health and Welfare, Labor, and Construction, Japan

97 Molhave, L., Bach, B., and Pedersen, O.F. (1986) Human reactions to low concentrations of volatile organic compounds , *Environment International* 12: 167-175.

98 Molhave, L., Lui, Z., Jorgensen, A.H., Pedersen, O.F., and Kjaergaard, S.K. (1993) Sensory and physiological effects on humans of combined exposures to air temperatures and volatile organic compounds , *Indoor Air* 3(3), pp. 155-169.

99 Morey, P.R. and Williams, C.M. (1991) "Is porous insulation inside an HVAC system compatible with a healthy building?" *Proceedings of IAQ '91: Healthy Buildings*, pp. 128 - 135. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

100 Mudarri, D.; Hall, J.D.; and Werling, E. (1996) Energy cost and IAQ performance of ventilation systems and controls , *Proceedings of IAQ 96*, pp. 151-160, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

101 Nagda, N. and Harper, J., (eds.), 1989, *Design and protocol for monitoring indoor air quality*, ASTM STP 1002, ASTM, West Conshohocken, PA.

102 Nathanson, T. (1995) *Indoor air quality in office buildings: a technical guide*, A report of the Federal-Provincial Advisory Committee on Environmental Health, Health Canada, available from Communications Branch, Health Canada, Tunney's Pasture, Ottawa, Ontario, Canada K1A0K9

103 National Laboratories (1997) Survey and discussion of models applicable to the transport and fate thrust area of the Department of Energy Chemical and Biological Nonproliferation Program , available from the National Technical Information Service, US Department of Commerce, Springfield VA.

104 Nazaroff, W.W., Gadgil, A.J., and Weschler, C.J. (1993) Critique of the use of deposition velocity in modeling indoor air quality , In *American Society of Testing and Materials Standard Technical Publication* 1205, ASTM, Philadelphia.

105 Nelson, N.A.; Kaufman, J.D.; Burt, J.; and Karr, C. (1995) Health symptoms and the work environment in four nonproblem United States office buildings , *Scand. J. Work Environ. Health* 21(1): 51-59

106 NKB (1991) *Indoor climate-air quality: NKB publication no. 61e*, Nordic Committee on Building Regulations, Espoo, Finland (ISBN 951-47-5322-4)

107 NORDTEST (1982) *Standard NT BUILD 232, buildings: rate of ventilation in different parts of a building*, Edition 2, NORDTEST, Espoo, Finland

108 NORDTEST (1988) *Standard NT VVS 019, buildings - ventilation air: local mean age*, Edition 2, NORDTEST, Espoo, Finland

109 NRC (1981) *Indoor pollutants*, Committee on Indoor Pollutants, National Research Council, National Academy of Sciences, National Academy Press.

110 Owen, MK, DS Ensor, and LE Sparks (1992) Airborne particle sizes and sources found in indoor air , *Atmospheric Environment* 26A(12): 2149-2162

111 Persily, A. and Dols, W.S. (1990) The relation of CO2 concentration to office building ventilation , *ASTM Special Technical Publication 1067-1990*, pp. 77-91, American Society for Testing and Materials, West Conshohocken, PA.

112 Persily, A., (1993) "Ventilation, carbon dioxide and ASHRAE Standard 62-1989", *ASHRAE Journal*, 35(7): 40-44.

113 Preller, L.; Zweers, T.; Brunekreef, B.; and Boleij, J.S.M. (1990) Sick leave due to work-related complaints among workers in the Netherlands , *Proceedings of the Fifth International Conference on Indoor Air Quality and Climate*, vol. 1: 227-230, International Conference on IAQ and Climate, Ottawa.

114 Raferty, P.J. (1993) *The industrial hygienist's guide to indoor air quality investigations*, Stock # 144-EQ-93, American Industrial Hygiene Association, Fairfax, VA.

115 Schiller, G., E. Arens, F. Bauman, C. Benton, M. Fountain, and T. Doherty. (1988). "A field study of thermal environments and comfort in office buildings." *ASHRAE Transactions*, Vol. 94(2): 280-308.

116 Seppanen, O., Fisk, W.J., Eto, J., and Grimsrud, D.T. (1989) "Comparison of conventional mixing and displacement air conditioning and ventilating systems in U.S. commercial buildings." *ASHRAE Transactions* 95 (2): 1028-1040.

117 Sieber, W.K., Petersen, M.R., Staynor, L.T., Malkin, R., Mendell, M.J., Wallingford, K.M., Wilcox, T.G.,, Crandall, M.S., and Reed, L. (1996) Associations between environmental factors and health conditions:, *Proceedings of Indoor Air 96*, vol. 2, pp. 901-906. SEEC Ishibashi, Inc., Japan.

118 Skov, P., Valbjorn, O., Pedersen, B. V. and DISG (1989) "Influence of the indoor climate on the sick building syndrome in an office environment", *Scand. J Work. Environ. Health* 16, pp. 1-9.

119 SMACNA (1993) *HVAC systems- testing, adjusting, and balancing*, Sheet Metal and Air Conditioning Contractors National Association, Chantilly, VA

120 SMACNA (1995) *IAQ guidelines for occupied buildings under construction*, Sheet Metal and Air Conditioning Contractors National Association, Chantilly, VA

121 Smedje, G.; Norback, D.; Wessen, B.; and Edling, C. (1996) Asthma among school employees in relation to the school environment , *Proceedings of Indoor Air 96*, vol. 1: 611-616, Seec Ishibashi, Inc. Japan

122 Solberg, D.; Dougan, D., and Damiano, L. (1990) Measurement for the control of fresh air intake , *ASHRAE Journal* 32(1): 46-51.

123 Spengler, J., Neas, L., Nakai, S., Dockery, D., Speizer, F., Ware, J., and Raizenne, M. (1993) "Respiratory symptoms and housing characteristics", *Proceedings of Indoor Air '93*, The 6th International Conference on Indoor Air Quality and Climate, vol. 1: 165 - 170., Published by *Indoor Air* '93, Helsinki.

124 Stenberg, B., Hansson, Mild, K.H., Sandstrom, M., Sundell, J., and Wall, S. (1993) A prevalence study of sick building syndrome (SBS) and facial skin symptoms in office workers , *Indoor Air* 3(2): 71-81.

125 Sundell, J. (1994) On the association between building characteristics, some indoor environmental exposures, some allergic manifestations and subjective symptom reports *Indoor Air Supplement 2*.

126 Ten Brinke, J. (1995) Development of new VOC exposure metrics and their relationship to sick building syndrome symptoms , Lawrence Berkeley National Laboratory Report, LBL-37652, Berkeley, CA.

127 U.S. Environmental Protection Agency (1996) Air quality criteria for particulate matter, vol ume II of III, EPA/600/P-95/001bF.

128 Utterson, E. and Sauer, H.J. Jr. (1998) Outside air ventilation control and monitoring , *ASHRAE Journal* 40(1): 31-35.

129 Vedal, S. (1985) Epidemiological studies of childhood illness and pulmonary function associated with gas stove use , Chapter 23 in *Indoor Air and Human Health*, Proceedings of the Seventh Life Sciences Symposium, October 29-31, Knoxville, TN, Lewis Publishers, Chelsea, MI.

130 Veitch, J.A. [ed.] (1994) Full-spectrum lighting effects on performance, mood, and health, IRC-IR-659, pp. 53-111, National Research Council of Canada, Institute for Research in Construction, Ottawa, http://www.nrc.ca/irc/light

131 Veitch, J.A. and Newsham, G.R. (1998) Determinant of lighting quality I: state of the science , *Journal of the Illuminating Engineering Society* 27(1): 92-106.

132 Veitch, J.A. and Newsham, G.R. (1998) Lighting quality and energy-efficiency effects on task performance, mood, health, satisfaction, and comfort , *Journal of the Illuminating Engineering Society.* 27(1), 107-129.

133 Victor Olgyay, V. (1963) *Design with climate; bioclimatic approach to architectural regionalism*. 236 pp., Princeton University Press, Princeton, NJ.

134 Ward, G. and Rubinstein, F.M. (1988) A new technique for computer simulation of illuminated spaces , *Journal of the Illuminating Engineering Society* 17(1).

135 Watson, D. and Labs, K. (1983) *Climatic design; energy-efficient building principles and practices*, 280 pp. McGraw-Hill Book Company, New York.

136 Weekes, D.M. and Gammage, R.B. (1990) The practitioner's approach to indoor air quality investigations , *Proceedings of the Indoor Air Quality International Symposium*, Stock # 145-EQ-90, American Industrial Hygiene Association, Fairfax, VA.

137 Weschler, C.J. and Shields, H.C. (1997) Is the importance of ventilation partially explained by indoor chemistry , *Proceedings of Healthy Buildings / IAQ 97*, vol. 1, pp. 293-298, Healthy Buildings/ IAQ 97 Washington DC

138 Wilkins, A.J., Nimmo-Smith, I., Slater, A.I., and Bedocs, L. (1988) "Fluorescent lighting, headaches and eyestrain." *Proceedings of the CIBSE National Lighting Conference*, Cambridge (UK), pp. 188-196.

139 World Health Organization (1987) Air quality guidelines for Europe, WHO Regional Publications, European Series No. 23, Copenhagen.

140 Wyon, D.P. (1992) "Sick buildings and the experimental approach", *Environmental Technology* 13: 313 - 322.

141 Wyon, D.P. (1996) Indoor environment effects on productivity , *Proceedings of IAQ 96*, pp. 5-15, American Society of Heating, Refrigerating, and Air Conditioning Engineers, Atlanta.

142 Yuan, X.; Chen, Q.; and Glicksman, L.R. (1998) A critical review of displacement ventilation , to be published in *ASHRAE Transactions* 104(1).

Index

R

S

T

V

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE Revised March 2002	3. REPORT TYPE AND DATES COVERED Technical Report

4. TITLE AND SUBTITLE
International Performance Measurement & Verification Protocol Volume II: Concepts and Practices for Improved Indoor Environmental Quality

5. FUNDING NUMBERS
IS414140

6. AUTHOR(S)
International Performance Measurement & Verification Protocol Technical Committee

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/TP-710-31601

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Energy

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOE/GO-102002-1517

11. SUPPLEMENTARY NOTES
Technical coordinator: Satish Kumar, Lawrence Berkeley National Laboratory, 202-646-7953

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This protocol serves as a framework to determine energy and water savings resulting from the implementation of an energy efficiency program. It is also intended to help monitor the performance of renewable energy systems and to enhance indoor environmental quality in buildings.

14. SUBJECT TERMS
buildings, energy savings, water savings, energy efficiency, indoor environmental quality

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY
U.S. DEPARTMENT OF ENERGY

DOE/GO-102002-1517

Printed with a renewable source ink on paper containing at least 50% wastepaper, including 10% postconsumer waste.