ASHRAE Guideline 45P

Public Review Draft

Measurement of Performance for Buildings Except Low-Rise Residential Buildings

Advisory Public Review (May 2025)
(Draft Shows Proposed New Guideline)

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Important Notes for Advisory Public Review (APR):

1. This document is in draft form, with some sections currently presented in a preliminary format. The purpose of ASHRAE's APR is to gather broad stakeholder feedback on the draft document prior to its formal Publication Public Review (PPR), providing an opportunity for early input in the review process.
2. Certain sections are labeled "To be completed." These sections will be revised and finalized before the PPR.
3. The GPC 45P is in the process of obtaining the necessary permissions to reproduce certain copyrighted figures and tables included in this draft. The Committee aims to secure all required permissions before the PPR.
4. All references, in-text citations, and capitalization will be thoroughly reviewed for accuracy and proper formatting before the PPR.

Measurement of Performance for Buildings Except Low-Rise Residential Buildings

Project Committee (PC): GPC 45P

Working Draft No. 01

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(This foreword is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

FOREWORD

Guideline 45 was developed by ASHRAE to address the need for a standardized set of procedures for measuring energy use, water use, thermal comfort, indoor air quality, lighting/visual environment, and acoustics/acoustical quality in all types of occupied buildings, except low-rise residential buildings. The intent is to provide guidance on metrics, measurement methods (including data integrity), and evaluation methods for benchmarking. Guideline 45 offers three levels of measurement (Basic, Intermediate, Advanced) in terms of accuracy and complexity.

The procedures do not include carbon metrics, rating methods, or quantitative measurement costs. Users of Guideline 45 who are interested in carbon metrics can refer to Informative Appendix A, which outlines ASHRAE standards for calculating and reporting carbon emissions over a building's life cycle, while those seeking cost information can consult Informative Appendix B, which presents one approach for estimating the costs associated with measuring and verifying energy savings in building retrofit projects, which may be a useful resource.

Prior to this guideline ASHRAE published the Performance Measurement Protocols for Commercial Buildings (PMP) in 2010. This was a joint effort between ASHRAE, the U.S. Green Building Council (USGBC), and The Chartered Institute of Building Services Engineers (CIBSE), aimed at providing guidance regarding the measurement and reporting of the performance of new and existing commercial buildings. In 2012, a follow-up best practices guide, Performance Measurement Protocols for Commercial Buildings: Best Practices Guide, was published to implement the PMP protocols by providing processes and tools that would make measurement, verification, and correction easier for facility managers and operators. Guideline 45 extends the work of the previous PMP documents into an ASHRAE Guideline to incorporate new technologies and advancements in building performance measurements, as well as updates in relevant standards and guidelines from the past 14 years, including but not limited to, occupancy and occupant behaviors.

It is also worth noting that in 2016, ASHRAE Technical Committee 7.6 sponsored a research project, 1702-RP Case Studies to Test Performance Measurement Protocols, to assess the validity, reliability, and practicality of ASHRAE PMP. Guideline 45 users can refer to Informative Appendix C for details.

The anticipated use of Guideline 45 is for projects where the standardized measurement of building performance plays a central role. Unlike many existing standards or guidelines that focus on a single aspect of building performance, Guideline 45 offers a comprehensive framework for conducting fundamental measurements across all six performance categories, along with the measurement of occupancy and occupant behaviors. Projects of greater complexity requiring advanced measurements are addressed to some extent in the guideline. However, readers may need to refer to additional documents, which are referenced in this guideline.

1. PURPOSE

The purpose of this document is to provide guidelines for measuring and evaluating building performance, including energy, water, and indoor environmental quality (IEQ), pertaining to occupied buildings, except low-rise residential buildings.

2. SCOPE

2.1 What Is Included. The procedures include:

a. IEQ (thermal comfort, indoor air quality, lighting/visual environment, and acoustics/acoustical quality);
b. energy, water, and on-site renewables;
c. occupancy and occupant behaviors;
d. metrics, measurement methods (including data integrity), and benchmarking/evaluation methods;

e. multiple levels of measurements (accuracy/complexity); and
f. all types of occupied buildings except low-rise residential buildings.

2.2 What Is Not Included. The procedures do not include:
a. greenhouse gas (GHG) and carbon metrics;
b. rating methods; or
c. quantitative measurement cost.

3. DEFINITIONS, ABBREVIATIONS, AND ACRONYMS

3.1 Definitions. Section 3 defines terms specific to this guideline. Terms not defined in this section either have meaning as defined on the ASHRAE Terminology website (terminology.ashrae.org) or carry their ordinarily accepted meaning within the context in which they are used. Ordinarily accepted meanings are based on American standard English language usage as documented in an unabridged dictionary.

3.1.1 Definitions: Section 5 Occupants

occupancy**:** occupancy is defined and quantified in terms of presence/vacancy (i.e., the binary state of occupancy of a space), number of occupants in space (e.g., expressed in absolute numbers or density, such as m^2/occupant or ft^2/occupant), or schedules (e.g., first arrival of occupants on a given day)

occupant behavior**:** building inhabitants' actions (or results of actions) on buildings and building systems that affect performance (in the current context), as energy use and indoor environmental quality

adaptive behavior**:** actions taken by building occupants in response to discomfort or in an attempt to improve comfort

non-adaptive behavior**:** actions taken by building occupants that are part of their routines, work tasks, etc. that are not taken to improve IEQ (e.g., turn on computer), but still affect building performance

3.1.2 Definitions: Section 6 Energy Use

baseline: pertaining to the baseline period.

baseline energy: energy use occurring during the baseline period without adjustments

calibrated simulation: (a) measurement and verification (M&V) approach where a simulation model is calibrated to baseline or post-retrofit energy use data; (b) process of reducing the uncertainty of a model by comparing the predicted output of the model under a set of conditions to the measured data for the same set of conditions. In both cases, calibration includes following defined procedures that identify which parameters of the instrument, meter, or model may be adjusted; determining what is an acceptable level of accuracy or uncertainty; and documenting the process and results.

coincident: occurring simultaneously or during the same interval.

constant: term used to describe a physical parameter that does not change during a period of interest. Minor variations may be observed in the parameter while still describing it as constant. The magnitude of variations that are deemed to be minor should be reported in the M&V plan.

energy efficiency measure (EEM): installation or modification of equipment, subsystems, or systems operations for the purpose of improving efficiency or reducing energy use and/or demand (and, therefore, energy and/or demand costs).

estimate: process of determining a parameter used in a savings calculation by methods other than measuring it in the baseline and reporting periods. For the purposes of this guideline, equipment performance tests that are not made where they are used during the reporting period are estimates.

facility: building or industrial site containing several energy using systems. A wing or section of a larger facility can be treated as a facility if it has meters that separately measure all of its energy use.

interactive effects: energy effects created by an EEM but not measured within the measurement boundary. Examples include the cooling energy savings and heating penalty that result when lighting energy use is reduced.

inverse method: approach to modeling energy use that develops an empirical relationship between a set of independent variables, such as weather and measured energy use, demand, and/or water use.

measure: to use an instrument or meter to determine a physical quantity.

measurement: (a) the act of collecting data using an instrument or meter; (b) data collected using an instrument or meter; (c) a calculated value that is derived directly from measurements.
measurement and verification (M&V): determination of energy, demand, and water savings achieved by one or more EEM. Savings cannot be directly measured because they represent the absence of energy use. Instead, savings are determined by comparing measured use before and after implementation of a project and making appropriate adjustments for changes in conditions.
meter: device used to measure energy use, demand, or water use. (See also *utility meter*.)
regression model: mathematical model based on statistical analysis of measured data.
savings: general term referring to reductions in energy use, demand, or water use or costs. (See also, *actual energy savings*.)
system: one or more pieces of equipment (e.g., fan, pump, motor) working together (e.g., heating system or electrical circuit).
uncertainty: range or interval of doubt surrounding a measured or calculated value, within which the true value is expected to fall within some degree of confidence. (See also *precision and accuracy.)*
utility: supplier of energy or water to a facility. For the purposes of this guideline, a utility includes all entities responsible for providing both the commodity (energy and/or water) and services related to delivering the commodity, which may include storage, transmission, distribution, and metering. This includes regulated utilities, commodities suppliers, and internal groups that supply steam, hot water, or chilled water.

3.1.3 Definitions: Section 7 Water Use

cycles of concentration (COC): is the ratio of chloride content of the cooling tower basin to the makeup water chloride content.
deionized water (DI): is clean water that has been demineralized by removing most of its ions. Ions are molecules that have a positive or negative electrical charge and are present in water as dissolved mineral salts. Deionized water is produced through an ion exchange process that removes dissolved particles like salt, minerals, carbon dioxide and organic contaminants. DI water is considered pure water and is used in the Medical, pharmaceutical, electronic manufacturing, food processing and other industrial processes. As pure water, DI water is very corrosive to metals.
flash steam: is steam released to the atmosphere when high pressure steam condensate water has its pressure reduced, which causes the condensate water to drop below its flash point and converts some water to steam.
fluid flow water meters: are meters used to measure the instantaneous water flow at a single point in time. These may be turbine meters, mag meters, transit time meters or other meters used in mechanical systems. These meters are not normally used in plumbing systems because of the difficulty in accurately accumulating total flow over a period of time that may have times of no-flow or very low flow.
gray water system: is a system that collects used potable water drainage that does not contain biological waste or other harmful or toxic material. Filtered gray water is used for non-potable water uses such as irrigation or other non -potable water uses.
positive displacement water meters: are positive displacement meters used to measure the total water used over time that do not provide instantaneous water flow amounts. These meters are used for plumbing system water flow because no-flow or very low flow does not affect the accuracy of the total water flow reading.
potable water: is water that is safe to drink. Drinking water is surface water or ground water that has been filtered or treated to ensure it is safe to drink.
rain water harvesting system: is a system that catches and stores rain water to be used for irrigation or other non-potable water uses. Stored rain water can also be filtered and treated to be used as potable water
reverse osmosis water (RO): is water that has been purified through the reverse osmosis process by forcing it through a semi-permeable membrane under high pressure that overcomes the natural osmotic pressure effectively removing impurities. RO water is clean and safe to drink, but since it is free from impurities it is also corrosive to metals.
steam boiler blowdown: is water released from either the water surface within a boiler or from the bottom of the boiler to remove contaminants to improve boiler efficiency and prevent any impurities from entering the steam flow.

3.1.4 Definitions: Section 8 Thermal Comfort

adaptive model: a model that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters.

air speed: the rate of air movement at a point, without regard to direction.

air speed, average (Va): the average air speed surrounding a representative occupant. The average is with respect to location and time. The spatial average is for three heights as defined for average air temperature ta. For an occupant moving in a space, the sensors shall follow the movements of the occupant. The air speed is averaged over an interval not less than one and not greater than three minutes. Variations that occur over a period greater than three minutes shall be treated as multiple different air speeds.

comfort zone: a zone whose boundaries enclose sets of environmental and personal conditions that provide thermal satisfaction according to the standard.

corrective power: the ability of a personal comfort system (PCS), expressed in degrees (°C [°F]), to correct thermal conditions toward the comfort zone, measured as the difference between two operative temperatures at which equal thermal sensation is achieved—one a temperature in the comfort zone with no PCS, and one with PCS in use, with all other environmental factors held constant.

direct-beam solar radiation: solar radiation from the direction of the sun, expressed in W/m^2 ($Btu/h \cdot ft^2$). Does not include reflected or diffuse solar radiation. Also known as "direct normal insolation" (Idir).

draft: the unwanted local cooling of the body caused by air movement.

environment, satisfactory thermal: a thermal environment that a substantial majority (more than 80%) of the occupants find thermally satisfactory.

environment, thermal: the thermal environmental conditions that affect a person's heat loss.

exceedance hours: the number of occupied hours within a defined time period in which the environmental conditions in an occupied space are outside of the comfort zone.

humidity: a general reference to the moisture content of the air. It is expressed in terms of several thermodynamic variables, including vapor pressure, dew-point temperature, wet-bulb temperature, humidity ratio, and relative humidity. It is spatially and temporally averaged in the same manner as air temperature. (Informative Note: Any one of these humidity variables must be used in conjunction with dry-bulb temperature in order to describe a specific air condition.)

insulation, clothing (clo): the resistance to sensible heat transfer provided by a clothing ensemble, expressed in units of clo. (Informative Note: The definition of clothing insulation relates to heat transfer from the whole body and, thus, also includes the uncovered parts of the body, such as head and hands.)

local thermal discomfort: the thermal discomfort caused by locally specific conditions such as a vertical air temperature gradient between the feet and the head, by radiant temperature asymmetry, by local convective cooling (draft), or by contact with a hot or cold floor.

metabolic rate (met): the rate of transformation of chemical energy into heat and mechanical work by metabolic activities of an individual, per unit of skin surface area (expressed in units of met) equal to 58.2 W/m^2 ($18.4\ Btu/h \cdot ft^2$), which is the energy produced per unit skin surface area of an average person seated at rest.

occupant, representative: an individual or composite or average of several individuals that is representative of the population occupying a space for 15 minutes or more.

occupant-controlled naturally conditioned spaces: those spaces where the thermal conditions of the space are regulated primarily by occupant-controlled openings in the envelope.

occupied zone: the region normally occupied by people within a space. In the absence of known occupant locations, the occupied zone is to be between the floor and 1.8 m (6 ft) above the floor and more than 1.0 m (3.3 ft) from outside walls/windows or fixed heating, ventilating, or air-conditioning equipment, and 0.3 m (1 ft) from internal walls.

personal comfort system (PCS): a device, under the control of the occupant, to heat and/or cool individual occupants directly, or heat and/or cool the immediate thermal environment of an individual occupant, without affecting the thermal environment of other occupants.

personal environment: the thermal environment immediately surrounding an occupant.

predicted mean vote (PMV): an index that predicts the mean value of the thermal sensation votes (self-reported perceptions) of a large group of persons on a sensation scale expressed from –3 to +3 corresponding to the categories "cold," "cool," "slightly cool," "neutral," "slightly warm," "warm," and "hot."
predicted percentage of dissatisfied (PPD): an index that establishes a quantitative prediction of the percentage of thermally dissatisfied people determined from PMV.
radiant temperature asymmetry: the difference between the plane radiant temperature tpr in opposite directions. The vertical radiant temperature asymmetry is with plane radiant temperatures in the upward and downward directions. The horizontal radiant temperature asymmetry is the maximum radiant temperature asymmetry for all horizontal directions. The radiant temperature asymmetry is determined at waist level, 0.6 m (24 in.) for a seated occupant and 1.1 m (43 in.) for a standing occupant. (See ASHRAE Handbook—Fundamentals 1, Chapter 9 for a more complete description of plane radiant temperature and radiant asymmetry.)
temperature, air: the temperature of the air at a point.
temperature, air average (ta): the average air temperature surrounding a representative occupant. The average is with respect to location and time. The spatial average is the numerical average of the air temperature at the ankle level, the waist level, and the head level. These levels are 0.1, 0.6, and 1.1 m (4, 24, and 43 in.) for seated occupants; 0.1, 1.1, and 1.7 m (4, 43, and 67 in.) for standing occupants, and the mean height of the body for horizontal occupants. Time averaging is over a period not less than three and not more than 15 minutes.
temperature, floor (tf): the surface temperature of the floor where it is in contact with the representative occupants' feet.
temperature, long-wave mean radiant (trlw): radiant temperature from long-wave radiation from interior surfaces expressed as a spatial average of the temperature of surfaces surrounding the occupant, weighted by their view factors with respect to the occupant. (See ASHRAE Handbook—Fundamentals 1, Chapter 9.)
temperature, mean daily outdoor air (tmda(out)): any arithmetic mean for a 24-hour period permitted in Section 5.4 of the standard. Mean daily outdoor air temperature is used to calculate prevailing mean outdoor air temperature tmda(out).
temperature, mean radiant (tr): the temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual surroundings. It is a single value for the entire body and accounts for both long-wave mean radiant temperature trlw and short-wave mean radiant temperature trsw.
temperature, operative (to): the uniform temperature of an imaginary black enclosure, and the air within it, in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment; calculated in accordance with Normative Appendix A of the ASHRAE Standard 55-2023. (See ASHRAE Handbook—Fundamentals, Chapter 9, for further discussion of operative temperature.)
temperature, plane radiant (tpr): the uniform temperature of an enclosure in which the incident radiant flux on one side of a small plane element is the same as in the existing environment.
temperature, prevailing mean outdoor air (tpma(out)): when used as an input variable in Figure 5-9 for the adaptive model, this temperature is based on the arithmetic average of the mean daily outdoor temperatures over some period of days as permitted in Section 5.4.2.1 of ASHRAE Standard 55-2023.
temperature, short-wave mean radiant (trsw): radiant temperature from short-wave direct and diffuse solar radiation expressed as an adjustment to long-wave mean radiant temperature trlw using the calculation procedure in Normative Appendix C of ASHRAE Standard 55-2023.
temperature, standard effective (SET): the temperature of a hypothetical isothermal environment at 50% rh, <0.1 m/s (20 fpm) average air speed Va, and tr = ta, in which the total heat loss from the skin of an imaginary occupant wearing clothing, standardized for the activity concerned, is the same as that from a person in the actual environment with actual clothing and activity level.

thermal comfort: that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.
thermal zone: an area of a building designated by the designer such that the comfort zone is maintained within the occupied zone by local controls for its representative occupant(s).

3.1.5 Definitions: Section 10 Visual Environment

absorption: a general term for the process by which incident flux is converted to another form of energy, usually and ultimately to heat.
blinds: a light controlling shading device consisting of overlapping thin slats which can be varied in angle and deployment.
circadian: relating to or showing rhythmic behavior with a period of 24 hours.
clear sky: a sky that has less than 30 percent cloud cover.
color fidelity: the degree to which an object's color looks similar to its appearance under a reference illuminant.
contrast: the relationship between the luminances of an object and its immediate background.
daylight: direct, diffuse, and/or reflected light that originates at the sun.
daylighting: the use of controlled natural light to illuminate architectural space.
daylight availability: the luminous flux from sun plus sky at a specific location, time, date, and sky condition.
daylight harvesting: the reduction of electric lighting power in a space in response to daylight illumination.
dimming: the ability to change the luminous flux of one or more lamps or luminaires.
direct glare: glare resulting from high luminances or insufficiently shielded light sources in the field of view.
direct sunlight: the contribution from the collimated solar beam that is neither reflected nor diffused.
disability glare: the effect of stray light in the eye whereby the contrast of the retinal image is reduced and, consequently, whereby visibility and visual performance may also be reduced. A direct glare source that produces discomfort may also produce disability glare by introducing a measurable amount of stray light in the eye.
emittance (or emissivity): the ratio of radiance in a given direction (for directional emittance) or radiant exitance (for hemispherical emittance) of a sample of a thermal radiator to that of a blackbody radiator at the same temperature.
fenestration: (1) commonly used to refer to any opening, usually glazed, in a building envelope, windows. Examples include windows, plastic panels, clerestories, skylights, glass doors that are more than one-half glass, and glass block walls. (2) in an external wall of a building, any area that allows light to pass.
fluorescent lamp: a low-pressure mercury electric-discharge lamp in which a fluorescing coating (phosphor) transforms some of the ultraviolet energy generated by the discharge into light.
footcandle: a unit of illuminance. One footcandle is one lumen per square foot (lm/ft^2).
glare: the sensation produced by luminances within the visual field that are sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance or visibility.
High Intensity Discharge (HID) lamps: an electric discharge lamp in which the light-producing arc is stabilized by bulb wall temperature and in which the arc tube has a bulb wall loading in excess of 3 W/cm^2. HID lamps include groups of lamps known as mercury, metal halide, and high-pressure sodium.
illuminance: the areal density of the luminous flux incident at a point on a surface.
Lambertian surface: a surface that emits or reflects light in accordance with Lambert's cosine law. A Lambertian surface has the same luminance regardless of viewing angle.
lamp: a generic term for a manufactured source created to produce optical radiation.
lamp lumen depreciation (LLD): the ratio of lamp lumen output after an extended period of operation under rated operating conditions to its initial lumen output under the same operating conditions.
LED (Light Emitting Diode): a p-n junction semiconductor device that emits incoherent optical radiation when forward biased. The optical emission may be in the ultraviolet, visible, or infrared wavelength regions.

light adaptation: the process by which the retina becomes adapted to a luminance greater than about 3.4 cd/m^2 (0.32 cd/ft^2; 1.0 fL).
light loss factor (LLF): the ratio of illuminance (or exitance or luminance) for a given area to the value that would occur if lamps operated at their (initial) rated lumens and if no system variation or depreciation had occurred.
light meter: a common name for an illuminance meter. An instrument for measuring illuminance on a plane.
lumen: SI unit of luminous flux. Radiometrically, it is determined from the radiant power (see luminous flux). Photometrically, it is the luminous flux emitted within a unit solid angle (one steradian) by a point source having a uniform luminous intensity of one candela.
Lumen method: a procedure used to determine the relationship between the number and types of lamps and luminaires, the room characteristics, and the average level of illuminance on the work plane. It takes into account both direct and reflected flux.
luminaire dirt depreciation (LDD): the ratio of lumens emitted from a luminaire with dirt accumulated to the lumens emitted from the same luminaire when clean.
luminance ratio: the ratio between the luminances of any two areas in the visual field.
luminous efficacy of a source: the total emitted luminous flux divided by the total source electrical input power; expressed in lumens per watt (lm/W).
luminous exitance: the areal density of luminous flux leaving a surface at a point. Formerly, luminous emittance (deprecated).
luminous flux: The time rate of flow of radiant energy, evaluated in terms of a standardized visual response.
luminous intensity: the luminous flux per unit solid angle in the direction in question.
matte surface: a surface from which the reflection is predominantly diffuse, with or without a negligible specular component.
occupancy sensor: a device that detects the presence or absence of people within an area and that causes lighting, equipment, or appliances to be regulated accordingly.
opaque medium: a medium that transmits no radiation in the spectral range of interest.
orientation: the position of a building with respect to compass directions.
overcast sky: a sky that has 100% cloud cover; the sun is not visible.
reflectivity/reflectance: (1) portion of the incident radiation on a surface that is reflected from the surface. Note: for an opaque surface, the sum of the reflectance and the absorptance is unity at equilibrium. Absorptances and reflectances are of various types, as are emittances. (2) the ratio of the light reflected by a surface to the light incident upon it.
Rf (fidelity index): A variation of a color produced by adding white to it, which lowers saturation and increases lightness.
Rg (gamut index): A measure of the average change in chroma produced by a test illuminant relative to a standardized reference illuminant for the 99 color evaluation samples specified in ANSI/IES TM-30-24, Technical Memorandum: IES Method for Evaluating Light Source Color Rendition (IES, 2024c)
solid angle: a measure of that portion of space about a point bounded by a conic surface whose vertex is at the point. It is defined as the ratio of intercepted surface area of a sphere centered on that point to the square of the sphere’s radius. It is expressed in steradians.
spectroradiometer: an instrument for measuring radiant flux as a function of wavelength.
spectral tuning: adjustment of a light source spectrum in response to task, space, or occupant needs.
specular reflection: that process by which incident flux is redirected at the specular angle.
spot: the narrowest beam possible from a luminaire that can be focused.
transmission: a general term for the process by which incident flux leaves a surface or medium on a side other than the incident side, without change in frequency.
tunable white: a form of spectral tuning used to vary the correlated color temperature (CCT) of a white light source.
veiling reflections: reflections (most often specular) that are superimposed upon diffuse reflections from an object, or the view through clear glazing, that partially or totally obscure the details to be seen by reducing contrast. This sometimes is called reflected glare.

visual acuity: a measure of the ability to distinguish fine details, usually measured with optotypes of different sizes when not constrained by contrast.
visual field: the locus of objects or points in space that can be perceived when the head and eyes are kept fixed. Separate monocular fields for the two eyes may be specified or the combination of the two.
visual task: conventionally designates those details and objects that must be seen for the performance of a given activity, and includes the immediate background of the details or objects.
window shades: Continuous planar material (translucent or opaque; woven, mesh or film; interior or exterior) which can be deployed/retracted along the plane of the glazing to control solar heat gain, visible transmittance, view, and/or visual privacy.

3.1.6 Definitions: Section 12 Evaluating the Impact of Interdependent IEQ Factors on Occupants

(To be completed)

3.2 Abbreviations and Acronyms

3.2.1 Abbreviations and Acronyms: Section 5 Occupants

AHU	air handling unit
BAS	building automation system
BIM	building information modeling
HVAC	heating, ventilation, and air conditioning
IAQ	indoor air quality
IEQ	indoor environmental quality
IoT	Internet of things
KPI	key performance indicator
PIR	passive infrared
RFID	Radio-frequency identification

3.2.2 Abbreviations and Acronyms: Section 6 Energy Use

4-P	four-parameter
BAS	building automation system
BPD	LBNL Building Performance Database
Btu	British thermal unit
CO_2	carbon dioxide
CBECS	Commercial Building Energy Consumption Survey
CDD	cooling degree days
CIBSE	Chartered Institution of Building Services Engineers
DHW	domestic hot water
DOE	U.S. Department of Energy
EERE	Energy Efficiency and Renewable Energy
EEM	energy efficiency measure
ELF	electric load factor
EMS	energy management systems
EV	electric vehicle
EVO	Efficiency Valuation Organization
EUI	energy use intensity
FEMP	USDOE Federal Energy Management Program
HDD	heating degree days
HVAC	heating, ventilating, and air conditioning
IEA	International Energy Agency
IMT	inverse model toolkit
IPMVP	International Performance Measurement and Verification Protocol
kW	kilowatt
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LCCA	life-cycle cost analysis

M&V	measurement and verification
MJ	megajoule
NCEI	National Centers for Environmental Information
NEMVP	North American Measurement and Verification Protocol
NOAA	National Oceanic and Atmospheric Administration
NO_X	oxides of nitrogen
NWS	National Weather Service
O&M	operation and maintenance
OLF	occupancy load factor
PNNL	Pacific Northwest National Laboratory
PRISM	Princeton scorekeeping method
PV	photovoltaics
RP	research project
SHW	service hot water
TES	thermal energy storage
USDOE	U.S. Department of Energy
USEIA	U.S. Energy Information Administration
USEPA	U.S. Environmental Protection Agency
USGBC	U.S. Green Building Council
VAV	variable air volume
VBDD	variable-base degree-day
yr	year

3.2.3 Abbreviations and Acronyms: Section 7 Water Use

BD	CT blow down
CE	controller efficiency
COC	cycles of concentration of solids in the condenser water
CT	cooling tower
D	CT drift – mist ejected from the tower
ET_O	evapotranspiration rate
ET_L	evaporation rate
IE	irrigation type
K_D	density factor
K_L	landscape factor
K_{MS}	microclimate factor
K_S	species factor
kW	kilowatt = 3412.142 Btu/h
fpd	flushes per day
fpdpp	flushes per day per person
fte	full time equivalent = 1 for one person per 8-hour shift. Visitors are calculated as daily average visitors
gpd	gallons per day
gpf	gallons per flush
gpm	gallons per minute
gpu	gallons per use
gpv	gallons per visit
lm	liters per minute
lpd	liters per day
lpf	liters per flush
lpu	liters per use
lpv	liters per visit
MPU	minutes per use

SCADA	supervisory control and data acquisition
therm	100 ft^3 of gas or 100,000 Btu
ton	12,000 Btu/h
TWA	total water applied
TPWA	total potable water applied
UPD	use per day
W	watt
WCM	water conservation measure
Wh	watt-hour
WUI	water use intensity
µS/cm	microSiemens per centimeter

3.2.4 Abbreviations and Acronyms: Section 8 Thermal Comfort

Idir	direct normal insolation
Icl	insulation, clothing
met	metabolic rate
PCS	personal comfort system
PMV	predicted mean vote
PPD	predicted percentage of dissatisfied
SET	temperature, standard effective
ta	temperature, air average
tf	temperature, floor
tdp	temperature, dew-point
trlw	temperature, long-wave mean radiant
tmda(out)	temperature, mean daily outdoor air
trsw	temperature, short-wave mean radiant
Tsol	solar transmittance, total
TSENS	thermal sensation
Va	air speed, average

3.2.5 Abbreviations and Acronyms: Section 9 Indoor Air Quality

AHU	air-handling unit
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
ASME	American Society of Mechanical Engineers
ASTM	ASTM International
BUS	Building Utilization Survey
CBE	Center for the Built Environment
cfm	cubic feet per minute
CIBSE	The Chartered Institution of Building Services Engineers
CoC	contaminants of concern
HVAC	heating, ventilation, and air-conditioning
IAQ	indoor air quality
IEQ	indoor environmental quality
ISO	International Organization for Standardization
MERV	minimum efficiency reporting value
NAAQS	National Ambient Air Quality Standards
NIOSH	National Institute of Occupational Safety and Health
NIST	National Institute of Standards and Technology
OA	outdoor air
OEHHA	Office of Environmental Health Hazard Assessment
SBS	sick building syndrome
USEPA	U.S. Environmental Protection Agency

WHO	World Health Organization
VAV	variable air volume

3.2.6 Abbreviations and Acronyms: Section 10 Visual Environment

2-D	two dimension
3-D	three dimension
ANSI	American National Standards Institute
ASE	annual sunlight exposure
BREEAM	Building Research Establishment Environmental Assessment Methodology
°C	degrees Celsius
CBE	Center for the Built Environment
CCT	correlated color temperature
cd/m^2	candelas per square meter
CEN	European Committee for Standardization
CRI	color rendering index
CS	circadian stimulus
CU	coefficient of utilization
DGP	daylight glare probability
DGPs	daylight glare probability simplified
DSLR	digital single-lens reflex
EH	horizontal illuminance
EML	equivalent melanopic lux
EN	European Norm
°F	degrees Fahrenheit
fc	footcandle
FI	flicker index
ft	feet
ft2	square feet
HID	high-intensity discharge
HDR	high dynamic range
Hz	hertz
IES	Illuminating Engineering Society
in	inch
IP	inch-pound
IWBI	International WELL Building Institute
LED	light emitting diode
LEED	Leadership in Energy and Environmental Design
LLF	light loss factor
LM	lighting manual
m	meters
m^2	square meters
Mp	flicker perception metric
MEDI	melanopic equivalent daylight illuminance
nm	nanometers
PBM	person-bound measurement
PF	percent flicker
Rg	gamut index
Rf	fidelity index
RP	recommended practice
sDA	spatial daylight autonomy
SI	systéme international
SPD	spectral power distribution

SVA	spatial view access
SVM	stroboscopic visibility measure
TC	technical committee
TLM	temporal light modulation
TM	technical memorandum
TMY	typical meteorological year
UDI	useful daylight illuminance
UGR	unified glare rating
USGBC	United States Green Building Council
UV	ultraviolet
WWR	window-to-wall ratio

3.2.7 Abbreviations and Acronyms: Section 11 Acoustical Quality

(To be completed)

3.2.8 Abbreviations and Acronyms: Section 12 Evaluating the Impact of Interdependent IEQ Factors on Occupants

(To be completed)

4. INTRODUCTION AND OVERVIEW

4.1 Introduction to Guideline 45. As stated in the Executive Summary of the Performance Measurement Protocols for Commercial Buildings (PMP) (ASHRAE 2010): *Although there are many buildings in the United States and United Kingdom, and elsewhere that claim to be "green", "low energy", or "high performance", it is rarely clear on what evidence or data these claims are based. Such claims of high performance cannot be credible without standardized protocols that are applied consistently to the assessment of building performance. If claims of superior building performance are to be believed, it is essential that a common set of measurements be used and the results reported against meaningful and consistent benchmarks. Such protocols are also needed to give useable feedback to building designers and operators when measured performance does not match design intent and expectations.*

Prior to this guideline ASHRAE published the PMP in 2010. This was a joint effort between ASHRAE, the U.S. Green Building Council (USGBC), and The Chartered Institute of Building Services Engineers (CIBSE), aimed at providing, for the first time, a standardized, consistent set of protocols, for a range of detailed inquiry, to facilitate the appropriate and accurate comparison of measured energy, water, and indoor environmental quality (IEQ) – thermal comfort, indoor air quality, lighting, and acoustics – characteristic of the performance of commercial buildings. Energy and water savings need to be accomplished while maintaining acceptable levels of building service for the occupants. Benchmarks facilitate appropriate comparison to peer buildings.

These protocols identify what to measure, how it is to be measured, and how often it is to be measured. For each of the six performance categories listed above, protocols are presented at three levels – Basic, Intermediate, and Advanced – providing choices for realistic characterization of the building stock. Information is provided to describe the measurement parameters, instrumentation types (including both subjective methods like occupant surveys and objective methods like metering), analysis and evaluation methods, standards and benchmarks, and limitations as to application of the measurement tools. A range of costs for staff time and instrumentation is given for each category.

Two years later ASHRAE published the follow-up document Performance Measurement Protocols for Commercial Buildings: Best Practices Guide (ASHRAE 2012). This document is a working guide to help users implement the protocols presented in the 2010 publication, by providing tools and techniques for measuring, managing, and improving the performance of a facility, as demonstrated by its energy and water use, as well as IEQ. Thus, it provides best practices for facility managers and operators to evaluate and improve the performance of commercial buildings. It also is intended to support integrated commissioning (Cx), and all activities of the building's operation and maintenance team.

The guide presents step-by-step procedures for three process levels of performance, which are intended to match the level of cost and intensity of effort for a range of types and sizes of facilities: Basic Evaluation, Diagnostic Measurement, and Advanced Analysis. The guide covers all energy-using and water-using systems within facilities, and systems that affect IEQ. Appendices include measurement and instrumentation specifics, detailed procedures, and examples of forms, worksheets, and checklists.

Now, over a decade later, Guideline 45 expands on the work of the 2010 and 2012 documents, brings them up-to-date, and formalizes them in a peer-reviewed ASHRAE Guideline. The performance categories are expanded from six to seven with the addition of occupants. Additionally, Informative Appendix D provides guidelines on sensor quality and calibration. While Guideline 45 offers comprehensive guidance for reliably measuring whole-building performance except low-rise residential buildings, many other recent documents, standards, and guidelines address selected performance measurement categories and/or dimensions/characteristics, and/or provide selected guidance, methods, or benchmarks. Several of those are summarized below.

a. ASHRAE Standard 105-2021 (Standard Methods of Determining, Expressing, and Comparing Building Energy Performance and Greenhouse Gas Emissions) and Standard 211-2018 (Standard for Commercial Building Energy Audits) both address only energy use and don't address instrumentation or benchmarks, whereas ASHRAE Guideline 14-2023 (Measurement of Energy, Demand, and Water Savings) addresses both energy and water use, as well as instrumentation and cost, but does not provide benchmarks.
b. The Efficiency Evaluation Organization (EVO) has published multiple documents addressing International Performance Measurement and Verification Protocols (IPMVP), primarily addressing only energy use; these focus on verifying energy use in the context of building evaluation and rebate programs.
c. In the UK, CIBSE has published multiple Technical Manuals for energy assessment and reporting methods in 2006 (TM22), building energy metering in 2009 (TM39), and energy benchmarks in 2008 (TM46).
d. The International Standards Organization (ISO), the American Society of Testing Materials (ASTM), and the Acoustical Society of America (ASA) address ergonomic instruments and analytic methods, test methods, or design requirements and evaluation criteria.
e. Finally, the US Green Building Council has developed and implemented the LEED rating systems that cover all six of the performance categories included in Guideline 45.

4.2 Ethics/Appropriateness in Data Privacy and Liability. Because Guideline 45 is an ASHRAE Guideline, it is required to be written in non-mandatory language. Since Guideline 45 specifies "what to measure, how it is to be measured, and how often it is to be measured", users are neither required nor expected to divulge any measured data, whether public or private. However, if Guideline 45 is applied to a specific building or facility, the data collected during its performance measurement would normally be owned by the building owner. It would be the owner's responsibility to decide whether to divulge or release the data associated with the performance evaluation and/or determination. Publishing or sharing such data without the express consent of the building owner would subject the distributor of that data to legal liability.

When poor building performance poses serious health issues, transparency is critical to ensure the safety and well-being of occupants. Building owners and managers should consider carefully how to communicate these findings and take prompt corrective actions. Ethical considerations suggest that occupants have a right to know about conditions that may affect their health. This can sometimes create a tension between maintaining confidentiality and the need for disclosure to protect public health. Balancing these interests requires careful judgment and, where appropriate, consultation with legal and health professionals to determine the best course of action.

4.3 Intended Users. The intended users of Guideline 45 include:

a. Building owners (or their representatives)
b. Building architects, designers, or building service engineers
c. Building operators or facility managers
d. Tenants/occupants

e. Technical consultants
f. Auditors and raters
g. Utilities
h. Manufacturers/product suppliers
i. Government agencies/judicial authorities
j. Energy service companies
k. Commissioning specialists
l. Researchers

Depending on their roles and the specific performance categories described in Section 4.1, these users will either generate or use the performance data to varying degrees: frequently, occasionally, or rarely.

4.4 Differentiating Three Levels of Protocols. Guideline 45 offers three levels of protocols, which vary, based on the level of detail required and the available resources, including funds, staff time, and instrumentation. Essentially, all buildings and facilities should conduct a performance evaluation at Level 1 (Basic Evaluation). Level 1 measurements are intended to be simple, low-cost measures for gaining an initial insight into the performance of the building, as indicated by characterizing and quantifying the aspects of each measurement category. Where these reveal issues or cause for further investigation, Level 2 (Diagnostic Measurement) protocols provide more detailed data to support corrective measures. Lastly, Level 3 (Advanced Analysis) protocols offer a very detailed analysis for those building owners or managers wishing to gain the deepest insight into building performance. The level chosen is the decision of the building owner or his/her representative.

4.5 Occupant Surveys. The objective of Guideline 45 is to measure and evaluate the operation of buildings to optimize their performance. A key tool to facilitate this process is occupant surveys. Building occupants can provide quantifiable insights about the performance of the indoor environment they inhabit. Their direct experience with their workspace allows them to evaluate subjectively how well the building supports or hinders them in carrying out their activities. These evaluations are usually provided through surveys referred to as post occupancy evaluations (POEs).

Post-occupancy evaluations are a systematic process of evaluating the occupant experience in a building. They are a common tool in measuring the success of workspace designs (Li et al. 2018; Graham et al. 2021) and informing the operation and management of buildings by providing feedback for diagnostic purposes. Of the different POE methods for soliciting occupant feedback (Dykes and Baird 2013), the survey is most widely used because it is simple and cost-effective (Heinzerling et al. 2013). There are two basic types of surveys used for different purposes: ‘Occupant Satisfaction’ surveys and ‘Point-in-Time’ surveys.

4.5.1 Occupant Satisfaction Surveys. Occupant satisfaction surveys ask occupants for their evaluations of the environment as experienced over an extended period (e.g., months, season, year). The length of the desired evaluation period might be specified in the question or left to the occupant’s discretion. This type of survey is used to obtain directly the bottom-line satisfaction of the occupants with various aspects of the building, including indoor environmental quality. Surveys need to ask questions in a manner such that responses are unbiased and systematically quantified. Psychometric scales that have been developed and tested over years should be used where possible. Occupant responses to satisfaction questions are typically measured on a seven-point Likert scale (see Figure 4.1) that is recoded to some numeric value for later analysis: e.g., 1 = very satisfied, 7 = very dissatisfied. Examples of such surveys used in research are given in Leaman and Bordass (2001), Zimmerman and Martin (2001), Zagreus et al. (2004), and Candido et al. (2016).

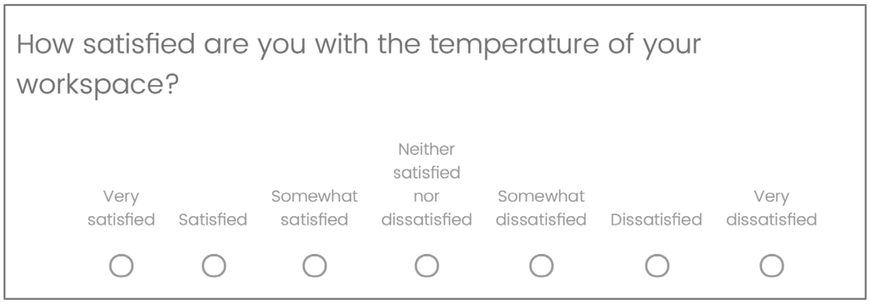


Figure 4.1 An Example Satisfaction Question Using a Seven-Point Likert Scale.

Occupant satisfaction surveys are generally constructed with multiple sections that each contain a set of related questions. Each section is designed to target different aspects of an occupant's space. For example, the first section might address occupant demographics (e.g., age, gender, type of work) and general experiences with the workspace (e.g., how many hours per week they work, how long they have resided in their workspace). Occupants may identify their location in the building, along with the type of workspace (e.g., private office, shared office, low/high cubicle, etc.). These contextual factors can be important when later analyzing and interpreting the responses (Dutta et al. 2020; Xiong et al. 2024). A sequence of sections targeting occupant perceptions of the indoor environment might follow. These could include satisfaction with office layout, furnishings, thermal comfort, indoor air quality, lighting, acoustics, cleanliness, and maintenance. Figure 4.2 represents the survey flow of the CBE Occupant Survey developed by the Center for the Built Environment (CBE) at the University of California, Berkeley. Additional sections could focus on aspects like health outcomes or sick building syndrome (Roulet et al. 2006). The Occupant Survey is presented in Informative Appendix E1.

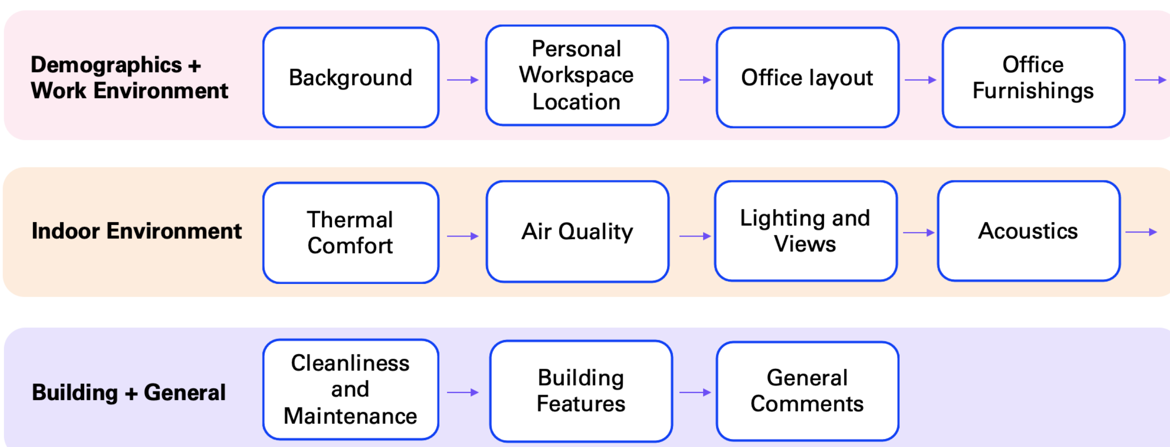


Figure 4.2 Survey Flow of the CBE Occupant Survey.

The results from occupant satisfaction surveys can be used in several ways. For example, they have traditionally been used for diagnostic purposes. Dissatisfied occupants can identify issues (Kent et al. 2021; Parkinson et al. 2023) that may have gone unnoticed and can assist building managers in pinpointing the reasons why spaces do not meet expectations. Such causes might be physical attributes of the building, or policies or procedures being followed in the workplace. When respondents indicate some degree of dissatisfaction with any one of these questions, they are presented a set of diagnostic branching questions to gain detailed and specific feedback on the causes for the dissatisfaction (see Figure 4.3). The branching questions are checkbox and open-ended response types that attempt to cover all the likely sources of dissatisfaction for a given IEQ category. If respondents indicate neutral or positive satisfaction with an IEQ category, they do not see the branching questions for that category. This shortens the survey's completion time and minimizes survey fatigue.

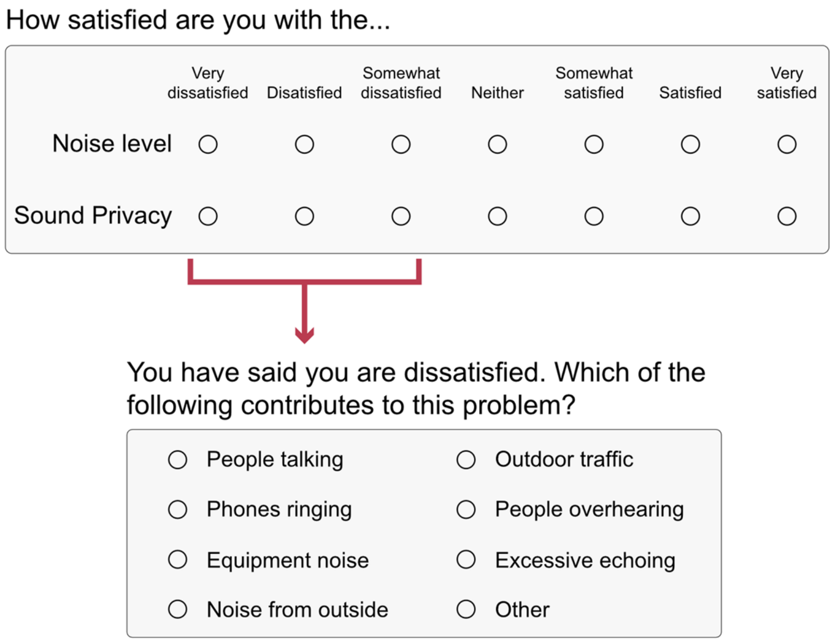


Figure 4.3 An Example of a Diagnostic Branching Question.

Another common reason to conduct occupant satisfaction surveys is because they are recommended as a 'basic' instrument for subjective data collection in building performance evaluation protocols such as PMP or building certification systems like LEED. The WELL building rating system has tested and approved several surveys with different emphases and applications. Increasingly common is the use of surveys to better understand how occupants perceive their workspace in the context of broader topics like health and wellness, interior design, and organizational psychology. A feedback loop established through POE can improve the fit between buildings and their users (Zimmerman and Martin 2001) by focusing on occupant needs, in addition to objective metrics of building performance (e.g., energy, water, waste). These reflect broader trends in the commercial office sector motivated in part by schemes like WELL that take a more holistic approach to workspace performance.

The end user will expect some kind of reporting of the survey responses in most cases. This might take the form of a report summarizing the survey measurements, comparison to benchmarks from accumulated building performance datasets, evaluation of performance results, and diagnostic identification of causes of dissatisfaction. Informative Appendix E2 presents an example survey report for the CBE Occupant Survey, which exhibits the types of evaluation provided by a satisfaction survey in an office building. There may also be metrics and formats that are required of the resulting datasets for submission to performance rating schemes. Practitioners are encouraged to familiarize themselves with these requirements to ensure compliance.

4.5.2 Point-in-Time Surveys. Point-in-time surveys ask occupants for their immediate evaluation of the space at the time of questioning. This is often a repeated sampling technique that is used in a research context. It is common in disciplines such as environmental psychology, where it is referred to as 'ecological momentary assessment' (Shiffman 2008). However, these surveys are also useful for testing building systems to determine how the conditions produced by these systems are affecting occupants. Such surveys may be used to tune settings in a building's HVAC, lighting, fenestration, and acoustical systems.

The distribution of point-in-time surveys may be triggered by physical measurements near the occupants, which presents novel solutions to collecting more balanced and complete datasets (Duarte et al.

2020). Other approaches involve the development of an open-source survey platform for wearable devices like smartwatches (Jayathissa et al. 2019) for crowdsourced data. Alternatively, apps or kiosks can display surveys or forms for continuous input. This allows occupants to log comments about the environment and request changes in system settings at any time. Such systems have the potential to collect large datasets of occupant responses that can yield important insights, especially when combined with other device data and concurrent building system settings.

4.5.3 Benchmarking. One of the applications of occupant satisfaction surveys is a comparison of satisfaction rates in a particular building to several other buildings in a database to contextualize performance. It is important to have as many previous building surveys as possible against which to compare (or benchmark) the present building's results, since there is no objective basis for establishing acceptable levels of occupant satisfaction.

Benchmarking requires that the previous surveys used the same or very similar question scales to allow consistent comparison. Standardized POE databases enable comparisons between buildings, organizations, or design features that often form the basis of performance metrics and benchmarks. The CBE at the University of California, Berkeley developed one of the first digital post-occupancy surveys in 1999. Known as the CBE Occupant Survey, this web-based tool has been used in many PMP roles; facility management, LEED and WELL building accreditation, design evaluation, and diagnostics. As of 2020, there are over 90,000 responses from occupants in about 800 buildings from across the US, as well as from Australia, Canada, China, Italy, India, Japan, Mexico, Singapore, United Arab Emirates (UAE), and the UK. Other databases exist in both a commercial and research context.

These survey databases have been extensively analyzed by researchers to generate a snapshot of occupant satisfaction in buildings. Some examples include green and non-green buildings (Altomonte et al. 2017; Altomonte and Schiavon 2013), different heating, ventilation, and air-conditioning (HVAC) system types (Brager and Baker 2009; Karmann et al. 2017; Kim and de Dear 2012), different spatial configurations (Kim and de Dear 2013; Leder et al. 2016), determinants of overall satisfaction (Frontczak et al. 2012), and occupant demographics (Choi et al. 2010; Kim et al. 2013). Careful consideration should be given to data governance and participant anonymity; regulations and requirements may change with jurisdiction.

4.5.4 Sampling. It is possible to get a reliable representation of the satisfaction of the entire population by sampling a random group of occupants. But a random selection of occupants might lead to a non-representative sample due to challenges like self-selection bias. A more focused strategy might be pursued where certain occupants are targeted based on their location or other attributes. For example, emphasis might be given to occupants in some HVAC zones or fenestration configurations that are most critical in determining the quality of the environment. This normally requires a deep understanding of the space and is therefore difficult for a survey provider to advise on.

Since the distribution of such problem configurations within a building is hard to determine in advance, some surveys (like the BUS survey, Leaman and Bordass 2001) aim at sampling all the occupants. This usually involves administering the surveys in person on site and can achieve response rates approaching 90%. Web-based surveys typically have lower response rates around 40%, depending on the building and occupancy. If the focus of the survey is IEQ diagnostics, a self-selected group of respondents may be sufficient since these people are likely to be the ones who have experienced problems and feel strongly enough to report them. This approach directly addresses the performance diagnostic function of surveys; it does not attempt to statistically represent the satisfaction of all the building occupants.

5. OCCUPANTS

5.0 Overview

5.0.1 Introduction. At the basic level of occupant measurement, we introduce definitions of occupancy and occupant behavior, and describe basic procedures for directly or indirectly measuring key occupant-related parameters, without significant investment in human resources, software, or equipment. Given that occupants are a relatively new focus of building performance measurement (Burpee et al. 2016), we begin by asking: why measure occupancy and occupant behavior as part of building performance? The objectives of measuring occupants in the context of building performance measurement include the following.

a. **Assess and quantify occupant-centric key performance indicators (KPIs)** to gain insights that may be concealed by traditional KPIs.
b. **Benchmark** buildings against each other with regard to occupancy. For example, occupant utilization (e.g., measured by peak occupant density) can be used to assess buildings' utility.
c. **Improve operations** (e.g., align schedules with actual occupancy, provide more comfortable conditions during occupied periods)
d. **Support measurement of other areas of building performance measurement** (e.g., knowledge of occupancy is an important context for measuring IAQ, water use, contaminant exposure, and ventilation adequacy)
e. **Generate new knowledge** that can be used to improve the operation or retrofit of existing buildings and the design of new buildings (e.g., explain underperformance resulting from unexpected occupant behaviors).

5.0.2 Key Definitions. First, we divide occupant measurement into two complementary categories: occupancy and occupant behavior. We hereby define occupancy as the presence of occupants. Occupant behavior is defined as the building performance-related actions that occupants take.

Occupancy can be described and quantified in terms of presence/vacancy (i.e., the binary state of occupancy of a space), number of occupants in space (e.g., expressed in absolute numbers or density, such as m^2/occupant[1] or ft^2/occupant), or schedules (e.g., first arrival of occupants on a given day). In some instances, it may be useful to have demographic information about occupants, such as gender (which could have implications for restroom demand) or age (which could have implications for metabolic rate, IEQ preferences, and vulnerability). The spatial scale of occupancy quantification could range from workstation to building or even a cluster or portfolio of buildings. Notably, beyond the direct importance of measuring occupancy, it is usually an important context for occupant behavior (unless systems can be remotely controlled by occupants). Occupancy is often expressed as a diversity profile over 24 hours, such as the example in Figure 5.1.

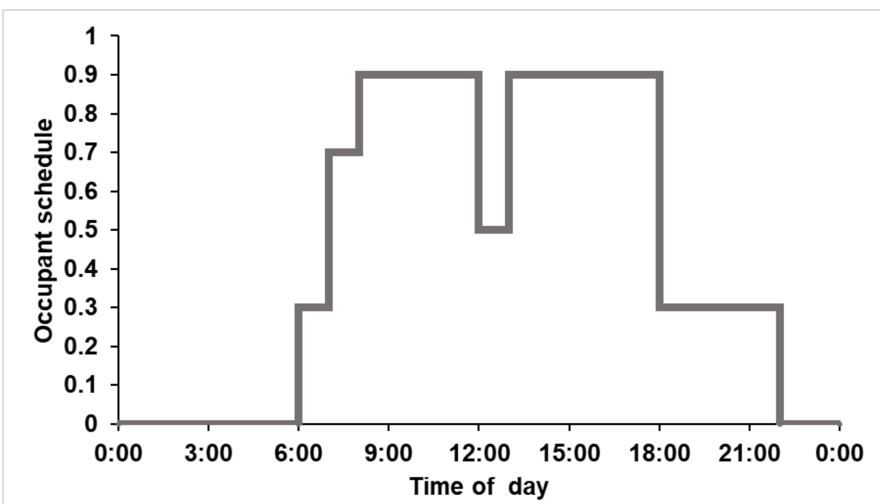


Figure 5.1 Sample of 24-Hour Profile for Occupancy in a Typical Office Building, Where 1 Represents Full Capacity (Often Defined by Some Standard Occupant Density) and 0 Represents an Unoccupied Building.

[1] Note that occupant density is often defined inversely to occupants divided by floor area, in part to yield more convenient numerical values.

Occupant behaviors can be divided into adaptive and non-adaptive categories. Adaptive behaviors are those for which the pursuit of comfort (often triggered by discomfort) is the major motivator. These include actions like adjusting thermostats, opening windows, turning on ceiling fans, and turning on lights. In contrast, non-adaptive behaviors are those which are driven by factors other than comfort, such as habits, performing tasks (e.g., computer work), or to save energy (e.g., turning off a light before departure from a space). A wide selection of key behaviors is summarized in Table 1. Actions are categorized as adaptive or non-adaptive, but note that some systems are turned on for adaptive purposes and off for non-adaptive, or vice versa (see examples in Table 5.1).

Table 5.1 Examples of Systems That Occupants May Have Access to and That Affect Building Performance.

System acted on	Adaptive or non-adaptive	Common triggers	Impacts of actions
Thermostats, thermostatic valves, manual dampers, etc.	Adaptive (to improve comfort) or non-adaptive (to save energy)	Indoor air temperature too warm or cold	Energy use (electricity, gas, etc.) and thermal comfort
Operable windows	Adaptive	Indoor air temperature too cold or warm or air is stale	Increased heat and moisture transfer, IAQ
Movable solar shading (e.g., window blinds/shades, awnings, shutters)	Adaptive	Daylight glare or need for privacy/views to outdoors	Glare/visual comfort and resulting lighting energy use, solar gains and resulting HVAC energy use
Overhead and task lights	Adaptive (on/brighter/dimmer) and non-adaptive (off)	Conditions too dark or too bright	Electricity use and sensible heat gains
Ceiling/desk fans	Adaptive	Indoor temperature too warm or stale air; conditions too drafty	Thermal comfort and electricity use
Office equipment and appliances	Non-adaptive	The need to perform task using equipment	Energy use and heat gains
Sinks, showers, toilets	Non-adaptive	Hygiene or dishwashing	Water use and latent heat gains
Clothing level	Adaptive	Indoor temperature too warm or cold	Thermal comfort and implications for preferred temperature

5.0.3 Objective of Measuring Occupants. There are a multitude of objectives related to measuring occupancy and occupant behavior, including to inform operations, to optimize controls, to inform space management and retrofits, to understand and measure energy and comfort-related behavior, to manage security, and to manage and improve occupant exposure to the indoor environment. These are outlined in more detail in Table 5.2.

Table 5.2 Objectives of Measuring Building Occupancy and Occupant Behavior.

Objective	Description
Building operations	Measure and predict occupancy schedules to fine-tune HVAC schedules and sequences of operation.
Building controls	Measure and predict occupancy and occupant preferences at the room/zone level to fine-tune zone-level HVAC schedules and setpoints, and lighting controls.
Space management	Measure and predict occupancy at the room or floor level to quantify space use. This may allow for a redistribution of occupants and space uses, or even reduce total floor area (e.g.,

	reduce leased space). Adapt space usage (e.g., consolidation of occupants, hot-desking/hoteling[2]) to improve space use and adjust HVAC and lighting controls accordingly.
Retrofits	Measure occupancy and occupant behaviors to inform retrofit decisions, including optimized space utilization and programming, provision of adaptive opportunities (e.g., operable windows, ceiling fans).
Energy- and comfort-related behavior	Measure and analyze occupants' energy- and comfort-related behaviors to understand impact on performance and act accordingly (e.g., smart plugs and lighting controls, signage, etc.)
Occupant exposure to indoor environment	Measure occupancy in conjunction with indoor environmental quality parameters to evaluate occupant exposure (i.e., dose and duration)

5.1 Level 1: Basic Evaluation.

5.1.1 Level 1: Objective. At the basic level, the objective is to characterize high-level occupant-related parameters, including the type of occupants, basic schedule parameters, and the adaptive opportunities. This is the simplest method to evaluate occupancy. The following sections comprise measurement methods, performance metrics, and benchmarking. These map on to each other as summarized in Figure 5.2, which are subsequently described in the following three sections.

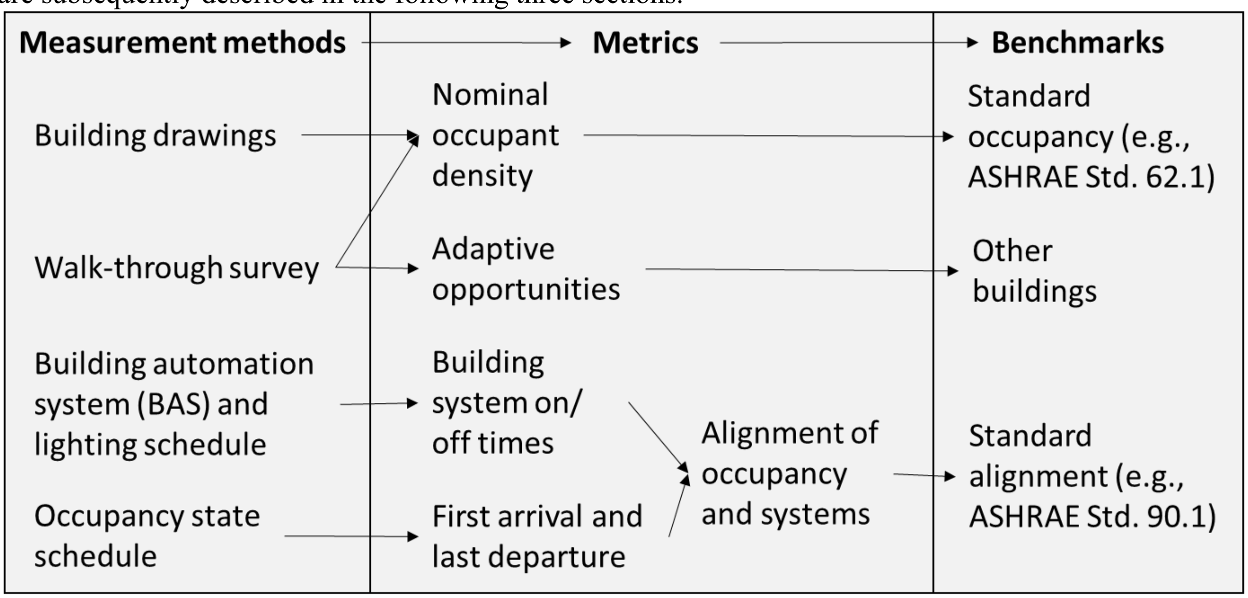


Figure 5.2 Summary of Level 1 Measurement Methods, Metrics, and Benchmarks.

5.1.2 Level 1: Metrics. At the basic level, we recommend the following building performance metrics for occupancy.

a. **Nominal design occupancy or occupant density**: This is a tabulated database of room, floor, and building level occupant capacity. Note this is not actual occupancy, but rather design occupancy.
b. **Time of first arrival and last departure (as a function of day type)**: The time of day for the first occupant arrival and last occupant departure occurs for each major day type (e.g., weekdays, Saturday, Sunday, holidays) and each major occupant type, if applicable (e.g., staff, customers, technicians, etc.). For some buildings, operations may be continuous (i.e., 24 hours per day) or overnight.

[2] Hot-desking (AKA hoteling) is a method to manage office space whereby each occupant does not have a permanently assigned desk, but rather than it changes every day or week. This approach can be significantly more space efficient for workplaces whereby employees are not present every day.

c. **Operating schedule for the air-handling unit, lighting, and other building-level systems**: The time that a building transitions from unoccupied mode (or occupied-standby mode) to occupied mode or vice versa is defined by ASHRAE Standard 62.1. Depending on the building type, these times may be a function of day type and system type (air-handling unit fans, outdoor air damper, lighting, etc.). Moreover, some buildings may not have an occupied mode scheduled or may be in occupied mode permanently.

d. **Alignment of occupancy and building systems schedules**: A measure of the effectiveness of HVAC and lighting schedules compared to occupancy. Ideally, most time is spent in the top left or bottom right of Table 5.3. Table 5.4 illustrates the alignment between occupancy and HVAC schedules. The result of this example is that HVAC is on for 8 hours (one third of the day) when occupants are not present, indicating a significant opportunity for improved operations.

e. **Number and type of adaptive opportunities for occupants in the building, including but not limited to the following list**. For comparative purposes, these could be normalized to the number of occupants or to floor area. It could also be separated for different floors or parts of the building. A summary is provided in Table 5.5

Table 5.3 Summary of Four Possible States for a Building for Overlapping Periods between Systems and Occupancy. Systems Can Refer to HVAC, Lighting, or Other Systems.

Occupied and systems on	Occupied and systems off
Unoccupied and systems on	Unoccupied and systems off

Table 5.4 Example Alignment Between Occupancy and HVAC, Whereby 10 Hours Are Occupied with HVAC On, 8 Hours Are Unoccupied with HVAC On, and 6 Hours Are Unoccupied with HVAC Off.

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Occupancy																								
HVAC																								

Table 5.5 Energy-, Water-, and Comfort-Related Systems to Which Occupants Have Access. Additional Rows and Items Should Be Added as Needed.

	Accessible to occupants?	Type of control/ interface?	Automation system/ override?	Total number of systems in building	Number of systems per floor area or occupant
Operable windows					
Window blinds/shades					
Ambient lighting					
Task lighting					
Thermostats and other central HVAC control					
Ceiling/desk fans					
Space heaters					

Sinks, showers, and water closets					
Other					

5.1.3 Level 1: Measurement Methods. At the Basic level (Level 1), occupancy and occupant behavior measurement is focused on leveraging existing information without installing a new sensing system or processing any data. While aimed to be low in effort, the Basic level comes with limited accuracy and resolution.

5.1.3.1 Building Drawings. If they are available, building drawings, or even building information models (BIMs), can be investigated to efficiently obtain several key occupant-related parameters: space types and areas (which can be used to estimate occupancy using standard densities), direct indication of number of occupants (e.g., based on number of chairs or workstations), and adaptive opportunities (e.g., light switches, operable windows). This information could be mapped onto Table 5.6. If information or evidence for the number of occupants is unavailable, standard density values can be used at a room-by-room level or building level, e.g., from (ANSI/ASHRAE/IES) Standard 62.1 or 90.1 or Deru et al. (2011). Note that a recent trend towards much greater telework and the associated drop in occupancy in many office spaces should be considered for estimating building use.

Table 5.6 Sample Template for Space Inventory Based on Building Drawings, BIMs, or Walk-Through Surveys.

Room number/floor	Primary space use	Floor area	Standard occupant density	Estimated nominal occupancy	Expected occupied hours (weekdays, weekend, holiday, etc.)	Number and type of adaptive opportunities
101	*Classroom*	*80 m² (800 ft²)*	*35 occ/100 m² (35 occ/1000 ft²)*	*28*	*8:30-15:30 weekdays only*	*1 light switch; 8 operable windows with manual windows shades; 1 desktop computer*
…	…	…	…	…	…	…
Building total		**(sum)**	**(average)**	**(sum)**		

5.1.3.2 Walk-Through Survey. Supplementing information available on drawings (or by observation if drawings are unavailable), a walk-through survey may be performed whereby artefacts are observed and recorded on a per-room basis. Key information that can be obtained from walk-throughs includes manual inspection of nominal occupancy (e.g., number of workstations, seats, beds), or as indicated by signage (e.g., posted maximum capacity). Schedules may also be obtained from building managers, owners, and/or operators.

Many adaptive opportunities are not shown on drawings or the full context is not shown. For example, operable windows or thermostats may be locked. Thus, using a table like Table 5.6, all major adaptive opportunities and occupant interfaces/equipment (e.g., desktop computers) can be recorded.

5.1.3.3 Building Automation System Schedule. Building automation systems can be used to obtain building- or campus-wide schedules for HVAC units, lighting, and other centrally controlled building systems. Both HVAC (and terminal unit) and lighting schedules are often conservative relative to anticipated occupancy, while HVAC schedules are particularly conservative (i.e., turned on well before anticipated occupancy) to ensure the building is conditioned to the occupied setpoint and to flush accumulated contaminants. Note that sometimes master schedules are locally overridden, so portfolio-/campus-level schedules may not accurately reflect building-level schedules.

5.1.3.4 Occupancy Schedule Estimation. The objective here is to estimate the first arrival and last departure of the day (see Section 5.1.1) at the building or HVAC system level. This could be obtained by examining occupancy schedules (e.g., work shifts, class schedules, worker schedules) or a bottom-up, room-by-room approach, as illustrated in Table 5.7. A walk-through site visit or discussion with facility managers may be necessary to complement documented information. The coarsest method to estimate the occupancy schedule is to rely on a generic schedule (e.g., Table 5.8).

Note the important distinction between occupancy and number of occupants. For HVAC and lighting schedules, occupancy is the most critical metric because their operations are independent of the number of occupants. In contrast, ventilation rate can be made dependent on the number of occupants in a space. In the Intermediate and Advanced Levels, more sophisticated and accurate methods are described.

Table 5.7 Room and Building Schedule, Where the Building Occupancy Schedule is Defined as the First Arrivals and Last Departures in Any Given Individual Room.

Hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Classroom																								
Cafeteria																								
Staff office																								
Gym																								
Building																								

5.1.4 Level 1: Performance Evaluation and Benchmarks. Many occupancy-related parameters require comparison to other buildings and norms for meaningful interpretation. Broadly, two approaches are recommended: 1) comparison to ASHRAE standards and other recognized sources or 2) comparison between similar buildings in a portfolio. For example, the building's operating schedule and occupancy schedule can be compared to that of ASHRAE Standard 90.1 for a particular building type (as shown in Table 5.8). Similarly, the measured occupancy density can be compared to the nominal occupancy densities in ASHRAE Standard 62 (Table 5.9). The context of standardized values should be considered, as they are often designed to be conservative or the upper expected limit.

a. Occupant density: Occupant density can be benchmarked against standardized values or other buildings within a portfolio or class of buildings. Table 5.9 provides the default occupant density values by space type in ASHRAE 62.1, which can serve as a benchmark for a wide variety of building types.
b. Adaptive opportunities: Unfortunately, standardized values for adaptive opportunities do not exist in most cases. A suitable starting point is to compare multiple spaces or buildings. For some system types, the measured values can be compared to building codes or standards. For example, ASHRAE Standard 90.1-2022 9.4.1.1.(a) requires that each lighting control device (e.g., light switch) control an area that does not exceed 230 m^2 (2,500 ft^2). Building type plays a critical role in the type and density of adaptive opportunities. In transient and public spaces, where occupants play little role in controlling the comfort of spaces, we expect significantly fewer such opportunities, compared to spaces where the occupants own the buildings (e.g., homes) or spend significant time (e.g., offices). Moreover, the building design and operating strategy will play a major role in the type and number of adaptive opportunities.
c. Alignment of occupancy and systems: Similar to occupant density, benchmarking can be achieved using default values in standards, e.g., ASHRAE Standard 90.1 or with other buildings in the portfolio. Table 5.8 shows the ASHRAE Standard 90.1 Appendix G schedules for a variety of building types. For example, for lighting in assembly buildings (first row in Table 5.8), is on for hours 6 to 23 on weekdays. Table 5.10 provides a further example for assembly buildings.

Table 5.8 ASHRAE Standard 90.1 Appendix G Schedules by Building Type. (Wd = Weekday). Note That the Original Schedule Values, Which Vary Between 0 and 100%, Were Converted to Binary Such That Values That Are 10% or Above Are Assumed to Be Occupied or On.

Building type	Nominal density (people/ft²; people/m²)	Occupancy schedule			Lighting schedule			HVAC schedule		
		Wd	Sat	Sun	Wd	Sat	Sun	Wd	Sat	Sun
Assembly	0.0200; 0.2152	8-22	8-23	8-23	6-23	7-22	7-23	5-23	6-23	6-23
Health/ institutional	0.0050; 0.0528	8-22	7-23	7-18	-	8-22	-	Always on		
Hotel/motel	0.0040; 0.0430	Always on	0-2; 5-24	0-2; 6-24	Always on			Always on		
Light manufacturing	0.0013; 0.0143	7-18	7-22	8-17	-	8-12	-	6-22	6-18	-
Office	0.0036; 0.0391	7-18	7-22	8-12	-	8-12	-	6-22	6-17	-
Parking garage	NA				Always on			Based on use		
Restaurant	0.0100; 0.1076	0-2; 10-24	7-24	7-24	10-24	0-2; 10-24	0-2; 11-24	0-3; 7-24	0-3; 9-24	0-3; 10-24
Retail	0.0033; 0.0359	8-21	6-21	9-21	10-19	8-21	10-18	6-21	6-22	10-19
School	0.0133; 0.1435	8-5; 18-21	7-22	8-13	-	-	-	7-22	8-13	-
Warehouse	0.00007; 0.0072	7-17	7-18	9-12	-	8-12	-	7-17	8-16	-

Table 5.9 Standard Occupancy Density Values by Space Type (ASHRAE Standard 62.1-2022).

Occupancy Category	Occupant density #/1000 ft² (#/100 m²)
Art classroom	20
Auditorium seating area	150
Bank vaults/safe deposit	5
Banks or bank lobbies	15
Barbershop	25
Barracks sleeping areas	20
Bars, cocktail lounges	100
Beauty and nail salons	25
Bedroom/living room	10
Booking/waiting	50
Bowling alley (seating)	40
Break rooms (General)	50
Break rooms (Office)	50
Cafeteria/fast-food dining	100
Cell	25
Classrooms (age 9 plus)	35
Classrooms (ages 5–8)	25
Coffee stations	20

Occupancy Category	Occupant density #/1000 ft² (#/100 m²)
Laundry rooms within dwelling units	10
Laundry rooms, central	10
Lecture classroom	65
Lecture hall (fixed seats)	150
Legislative chambers	50
Libraries	10
Lobbies	150
Lobbies/prefunction	30
Main entry lobbies	10
Mall common areas	40
Media center	25
Multipurpose assembly	120
Multi-use assembly	100
Museums (children's)	40
Museums/galleries	40
Music/theater/dance	35
Occupiable storage rooms for liquids or gels	2
Occupiable storage rooms for dry materials	2

Coin-operated laundries	20
Common corridors	
Computer (not printing)	4
Computer lab	25
Conference/meeting	50
Corridors	0
Courtrooms	70
Daycare (through age 4)	25
Daycare sickroom	25
Dayroom	30
Disco/dance floors	100
Dwelling unit	2
Freezer and refrigerated spaces (<50°F)	0
Gambling casinos	120
Game arcades	20
General manufacturing (excludes heavy industrial and processes using chemicals)	7
Guard stations	15
Gym, sports arena (play area)	7
Health club/aerobics room	40
Health club/weight rooms	10
Kitchen (cooking)	20

Office space	5
Pet shops (animal areas)	10
Pharmacy (prep. area)	10
Photo studios	10
Places of religious worship	120
Reception areas	30
Restaurant dining rooms	70
Sales (except as below)	15
Science laboratories	25
Shipping/receiving	2
Sorting, packing, light assembly	7
Spectator areas	150
Stages, studios	70
Supermarket	8
Swimming (pool & deck)	0
Telephone closets	0
Telephone/data entry	60
Transportation waiting	100
University/college laboratories	25
Warehouses	0
Wood/metal shop	20

Table 5.10 Matrix of Alignment Between Occupancy and Lighting for the Assembly Type of Buildings (All Values in Hours).

	Occupied-on	Occupied-off	Unoccupied-on	Unoccupied-off
Weekdays	14	0	3	7
Saturday	14	0	2	8
Sunday	14	0	2	8
Overall	14	0	2.7	7.3

5.2 Level 2: Intermediate Measurement

5.2.1 Level 2: Objective. For the basic level, Level 1, the scope of occupant measurement was limited to leveraging commonly available building information to make simple inferences about occupancy and occupant behavior. At the intermediate level, Level 2, the objective is to obtain a sufficiently accurate occupancy profile to reveal new insights – at the floor and building level - to understand how the building is being used and quantitatively to estimate how occupants impact building performance. The intermediate level requires a larger investment in time than the basic level, but with the benefit of increased accuracy and granularity of measurements. Note that the Intermediate level focuses on occupancy (i.e., occupant presence) rather than behavior. A high-level mapping of measurement methods to performance metrics and benchmarks is summarized in Figure 5.3.

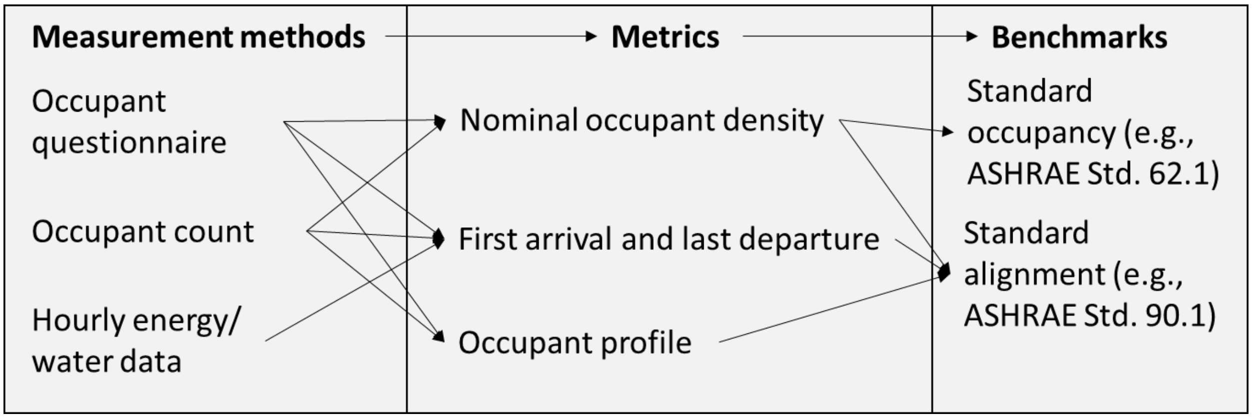


Figure 5.3 Summary of Level 2 Measurement, Metrics, and Benchmarks.

5.2.2 Level 2: Metrics. The Intermediate metrics are mostly the same as the Basic level except for the addition of an occupancy profile. Those repeated from the Basic level are the nominal/design occupancy and first arrival/last departure. Occupancy profiles are represented by time series graphs spanning one or more days (e.g., weekdays, Mondays, Saturdays, all days). An example is shown in Figure 5.4. They can either represent fractional occupancy (relative to the nominal/design occupancy) or the absolute number of occupants.

Any of the measurement methods could be used to generate occupancy profiles, though with varying levels of data post-processing.

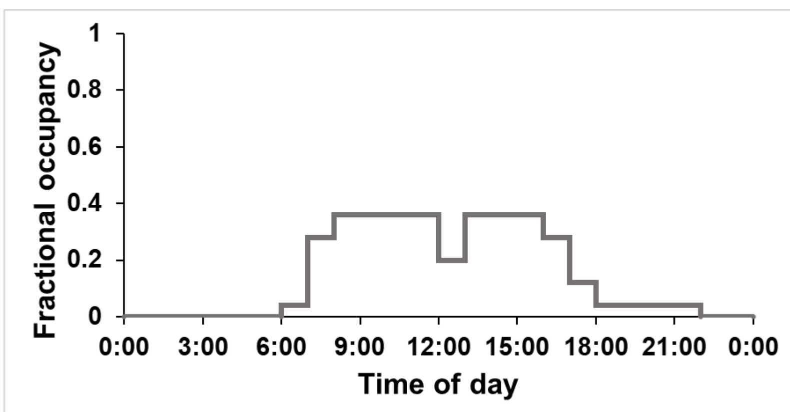


Figure 5.4 Example of Occupancy Profile, Where the Y-Axis Represents the Measured Occupancy Fraction with Respect to the Nominal or Maximum Occupancy (e.g., the Building Never Exceeds 40% of Maximum Occupancy).

5.2.3 Level 2: Measurement Methods. At the intermediate level, occupant measurement is focused on leveraging existing data sources and performing spot checks and surveys. This level provides incrementally higher accuracy, resolution, and effort, while not requiring any investment in new building equipment. These measurement methods can be further combined to improve accuracy and provide validation. Technologies exist to automate much of these measurement methods, but that is left for the advanced level, Level 3.

5.2.3.1 Occupant Questionnaire. The first recommend measurement method is to survey occupants about their typical occupancy. Key topics to ask about are: typical arrival and departure times, extended breaks, and days of the week or year during which occupancy (or vacancy occurs). Questions should be tailored to the building type. For example, an office building may focus on asking about schedules for typical weekdays, since they are likely to have repeating routines. Another question may ask about occupants' location(s) in the building to gain a higher resolution understanding. Occupancy-related questions can be added to questionnaires focused on other performance areas (e.g., thermal comfort) to reduce effort and/or to correlate responses (e.g., identify times or locations that are frequently uncomfortable). Some sample questions follow.

a. Check off which of the following days you are typically in building X.
   □ Monday □ Tuesday □ Wednesday □ Thursday □ Friday □ Saturday □ Sunday
b. On average, what time of day do you first arrive in building X? __________
c. Which room number in building X do you spend the majority of your time? ________

However, one must be aware of biases. For example, for places of employment, employees may exaggerate their working hours. This can be partially mitigated by ensuring that the questionnaire is anonymous and communicating that to participants. Another source of error relates to the sampling method. For example, if paper questionnaires are distributed as occupants arrive in the building, there will be bias towards occupants who are present more often. This can be avoided by targeting a large and random sample via email or through mathematical correction (i.e., include null results using knowledge about total number of occupants in a building).

Inevitably, a sample less than 100% of the building population will be achieved. In general, larger samples will improve accuracy, notwithstanding the aforementioned biases. The responses associated with schedules (e.g., arrival time) can be used to estimate building population schedules. Sampled responses can also be cautiously extrapolated to estimate occupancy and occupant density (refer to the Basic level), but this requires knowledge of the response rate.

The above method works best for buildings with long-term occupants (e.g., office workers, household residents) where the responses can be expected to be valid for an extended period (years). If recruitment is done by email or other mass communication, it is important that the building owner/operator have access to occupant information (e.g., database of email addresses). This would not be the case for shopping mall customers, hospital patients, etc. It can also be applicable to multi-tenant buildings. The following method would be more suitable for such cases.

5.2.3.2 Occupant Count Survey. Much as vehicle traffic is studied, building occupants can be tracked by observing all occupants who pass through doorways or other lines of sight. For rooms with single points of entry, this is a straightforward process. Larger spaces and buildings with multiple entrances may require more advanced methods and more observers to be simultaneously deployed.

This method involves using mechanical counters, pen and paper, or other methods to count each occupant that passes through a line. Normally the associated time of day, and possibly the occupant type (e.g., student vs. teacher), is also of interest and should be recorded. For occupants entering or exiting different doorways, measurement at each passage should ideally be recorded simultaneously. As an example, in a mid-sized seven-story 6,000 m^2 (65,000 sq. ft.) academic building, the building had two main ground-level lobby doors, two stairwells, and one underground exit to a tunnel system. Despite the modest size of the building, five people would need to be stationed to get an accurate count.

Given the effort required for manual observations (e.g., a minimum of one person for one day), sampling is needed to extrapolate and generalize findings. The number of days required depends on the variability between days of the week and year. For example, office buildings may have consistent occupancy on most weekdays, lower occupancy (and shorter workdays) on Fridays, and then even less occupancy on Saturdays and Sundays. Such circumstances would necessitate a minimum of four days of sampling. Teleworking schemes (e.g., most people avoid in-person work on Mondays and Fridays) could further inflate the required measurement period. Large seasonal variations (e.g., in universities or office buildings occupied by accountants) could necessitate sampling at various times of year. In general, more measurement days can improve accuracy and confidence.

The outcome of this measurement method results in an occupancy profile (e.g., Figure 5.5), from which other metrics can be extracted, such as first daily arrival and last daily departure, and occupant density. Refer to Basic level for metric definition.

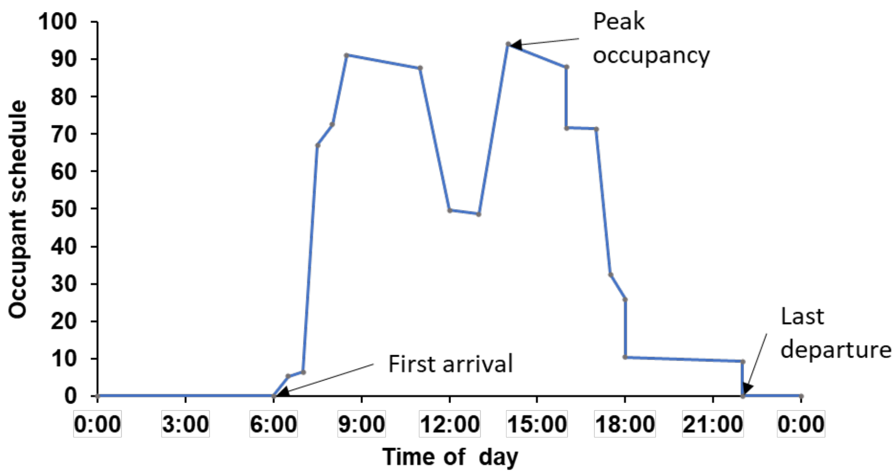


Figure 5.5 Example Occupancy Profile.

5.2.3.3 Hourly Energy Data. Depending on the building type and available data, inferences about occupancy may be drawn from energy and water data – particularly if it is hourly or subhourly. For building types for which energy use are sensitive to occupancy, utility (electricity, gas, etc.) data can be used as a proxy for occupancy. The most suitable building types for this approach have relatively high occupancy density and relatively low process loads. For example, office buildings are normally densely occupied and those occupants have significant impact on utilities (e.g., plug loads, appliances, lighting, showers, sinks, laundry, etc.). In contrast, a factory or hospital has utility use that is dominated by process loads will not be sensitive to occupancy.

Among common building types, hotels/motels, offices, and schools are most suitable for estimating occupancy from hourly or subhourly utility data. Consider Figure 5.6, which shows the electricity use and estimated occupancy profile for a day for an office building. The electricity use profile closely follows the occupancy profiles – including the midday dip. When analyzing utility data, one must be cautious about other high-load operations, such as the activation of HVAC units. In many commercial/institutional buildings, HVAC units are turned on several hours before anticipated occupancy. As such, care must be taken using this method and sources of errors should be acknowledged.

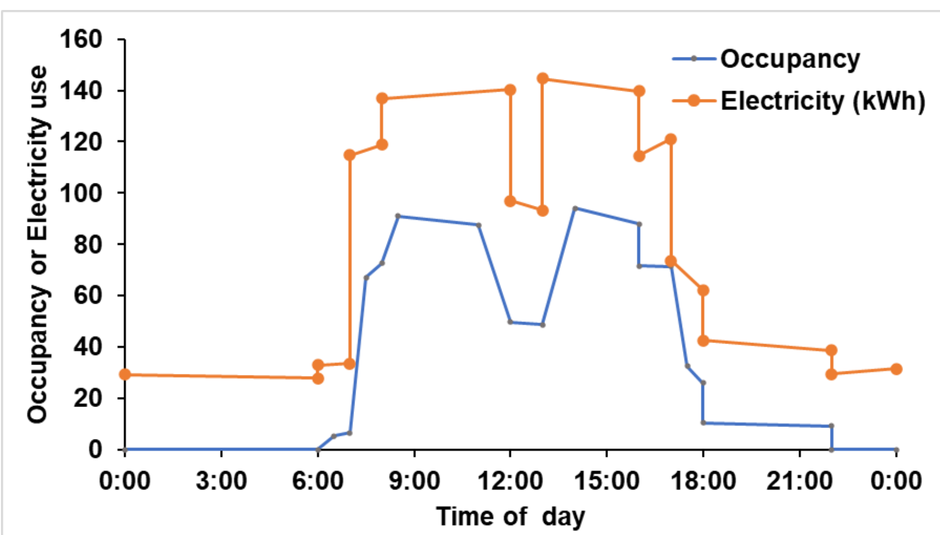


Figure 5.6 Electricity Use and Estimated Occupancy.

For the Intermediate level, we recommend that utility use profiles be used to estimate first occupant arrival and last departure (assuming buildings are periodically occupied). These times can be approximated as follows.

a. First arrival: first hour in the day when the energy use deviates significantly from the nighttime load.
b. Last departure: last hour in the day before the time when the energy use returns to the nighttime load.

For an example see Figure 5.6, where occupancy spans from approximately 6 AM to 10 PM.

5.2.4 Level 2: Performance Evaluation and Benchmarks. The fractional occupancy (AKA diversity profile) can be directly compared to benchmarks such as ASHRAE Standard 90.1, as discussed below. Many occupancy-related parameters require comparison to other buildings and norms for meaningful interpretation. We recommend two approaches: 1) comparison to ASHRAE standards and other recognized sources, or 2) comparison between like buildings in a portfolio. For example, the building's operating schedule and occupancy schedule can be compared to that of ASHRAE Standard 90.1 for a particular building type. Similarly, the measured occupant density can be compared to the nominal occupant densities, by building type, in ASHRAE Standard 62 (ASHRAE 2022). The context of standardized values should be considered, as they are often designed to be conservative or the upper expected limit.

a. **Occupant density**: Occupant density can be directly benchmarked against standardized values or other buildings within a portfolio or class of buildings. The Basic level provides standardized occupant densities by building type.
b. **Occupancy profile**: The estimated occupancy profiles can be compared to other buildings in the portfolio or standardized schedules such as ASHRAE Standard 90.1. As was the case for the Basic level, first arrivals and last departures can be extracted from the occupancy profiles.

The results of the occupant density/profile benchmarking may be used to identify operational inefficiencies (e.g., excessive ventilation or plug-in equipment), and may also be used for space planning. For example, a poorly utilized building may present opportunities for down-sizing, deferred new construction, or more strategic scheduling of occupants.

Benchmarking using first arrival and last departure can follow the approaches described in Level 1.

5.3 Level 3: Advanced Analysis

5.3.1 Level 3: Objective. The objective of the advanced level, Level 3, for occupant measurement is to form a deep and quantitative understanding of how occupants are using a building and how this compares to benchmarks. The advanced level covers both occupancy (i.e., occupant presence) and behavior. At the advanced level, after low-cost/low-effort opportunities have been exploited, increased accuracy and granularity of measurements necessitate a larger investment in time and equipment than the basic and intermediate levels. For example, if a portfolio of buildings is believed to be poorly utilized (low occupancy), the owner may seek to consolidate occupancy in fewer buildings and then sell one or more buildings. Normally the proceeds would greatly exceed the cost of monitoring occupancy. Or perhaps the building operator has a hypothesis that occupants are significantly misusing building systems (e.g., not turning on stovetop hoods, leaving windows open in winter, using thermostats erratically) and would like to understand the behavior better to try to address the root of the problem (e.g., chronic comfort problems, usability challenges).

A high-level mapping of measurement methods to metrics and performance evaluation/benchmarking is summarized in Figure 5.7.

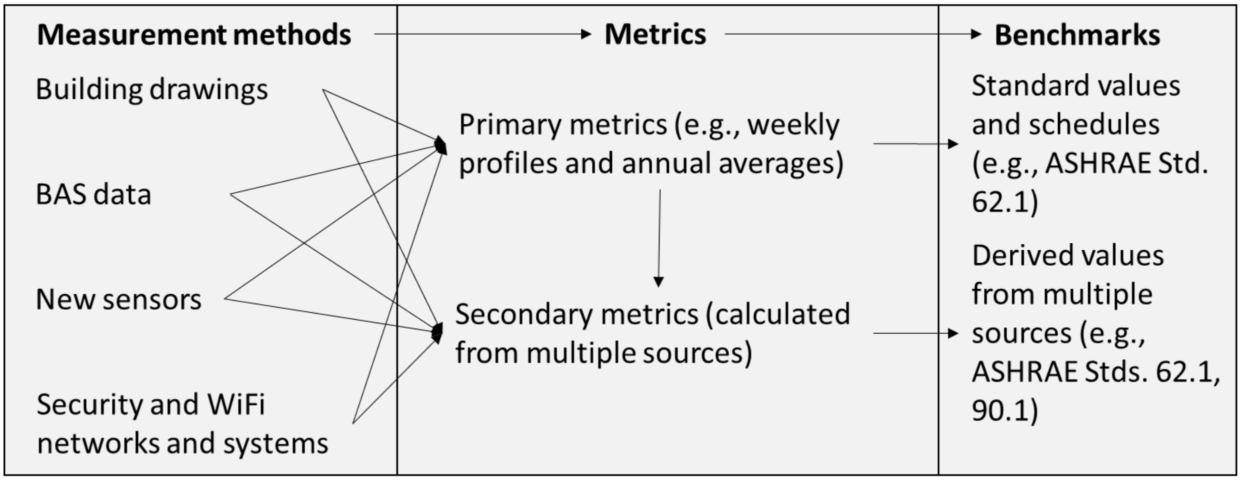


Figure 5.7 Summary of Level 3 Measurement, Metrics, and Benchmarks.

5.3.2 Level 3: Metrics. The advanced metrics are an extension of the previous two levels, but significantly more data-intensive, often covering a year or more of data for many datapoints (100s or 1000s). Here we focus on two types of metrics: primary and secondary. Primary metrics are those available directly from individual sensors (or sensor types) without significant post-processing; secondary metrics typically involve two or more measurands that are analyzed to reveal new insights.

5.3.2.1 Primary Metrics. The primary metrics may be as simple as a single annual average or count, but are often best represented by 24-hour average profiles (schedules), given the cyclical nature of activity in buildings. These may be further separated into days of the week, months, or seasons – particularly for buildings occupied only seasonally and for systems that are operated differently in different seasons (e.g., operable windows are more likely to be open in warmer months). The following list comprises key primary metrics. Additional example profiles were shown in the intermediate level.

a. Occupancy, occupant density, and occupancy
b. Plug load
c. Lighting
d. Operable windows/blinds
e. Thermostat setpoint

5.3.2.2 Secondary Metrics. The secondary metrics are derived from multiple primary metrics or other available data (e.g., metrics collected as part of the Basic and Intermediate levels or other measurement domains). There are numerous metrics that could be developed to better understand and benchmark occupancy and occupant behavior. These metrics should stem from the questions or concerns at hand. The scientific literature has focused in the past decade on developing probabilistic/stochastic models that predict how occupants behave as a function of one or more independent variables (e.g., time, indoor air temperature) (D'Oca et al. 2019). Such models can be used to identify the most significant predictors of behaviors and how they affect behavior. However, these advanced methods are beyond the scope of the current text. Here, the focus is on basic mathematical operations and metrics that have at least some data available for benchmarking. The following secondary metrics are addressed here, along with sample units.

a. Equipment energy per occupant (kWh/occupant-year): the annual plug-in equipment energy normalized by the number of unique occupants of a building. Alternatively, the denominator could be occupant-hours, which would yield the average equipment power (watts) associated with each occupant present. Regardless, this metric is an indicator of office equipment or appliance use and may identify opportunities for upgrading equipment or using energy efficiency modes (e.g., sleep mode for computers).
b. Ratio of unoccupied to occupied plug load (unitless): similar to the above metric, this metric is aimed at understanding potential energy waste for equipment that is only needed during occupancy. For

such equipment, the optimal value is 0, while values approaching or exceeding unity suggest significant wasted energy.

c. Lighting energy per occupant-hour (W/occupant-hour): the lighting energy divided by the number of occupant hours for a given period. The metric indicates the amount of light energy expended on each occupant and may indicate unnecessary light use (i.e., lights on in vacant spaces).
d. Fraction of windows open when heating or cooling is on (unitless): this unit provides an indication of wasted HVAC energy resulting from periods when the windows are open and a space is being conditioned.

There are many other potential secondary metrics that could be developed, based on other domains of measurement (e.g., whole building energy, water, clothing level, activity level, etc.) and occupancy. Readers are encouraged to explore data and develop useful and intuitive metrics that reveal new, actionable insights.

5.3.3 Level 3: Measurement Methods. At the advanced level, occupant measurement is focused on installing new equipment or advanced leveraging of existing resources (e.g., building automation system and security data). This level is aimed at maximizing accuracy, scope, and resolution, at the cost of substantial investment and effort. Methods are focused on direct or indirect measurement of occupants and systems with which occupants interact, including the following domains.

a. Occupancy
b. Plug-in equipment and appliances
c. Lighting
d. Operable windows/blinds/doors
e. Thermostats

There are other occupant-related measurands, such as water use, building-level energy use, and occupant clothing and activity level. These are excluded from this chapter and the reader is referred to relevant chapters in this document for details.

Table 5.11 and Table 5.12 summarize the most common technologies used to measure occupancy and occupant behavior. The following subsections then discuss the merits of different methods for implementation in buildings.

Table 5.11 Occupancy Sensor Technologies.

Technology (examples)	Description
Motion sensors (PIR, ultrasonic, break beam)	Sensors that send and receive signals to detect the presence or motion of objects (inferred occupancy) in a space and generally require line of sight between the sensor and occupant(s). These technologies are used to detect occupancy in a space, but not the number of occupants.
Vision sensors	Visible/non-visible (e.g., infrared) cameras used to capture an image and discern occupancy. Can be paired with computer vision to detect and count occupants, or even activities, using an embedded computer to protect image from being transmitted when it violates data security.
Radio frequency technologies	Sensor devices that measure signals (e.g., Bluetooth, RFID tags) being emitted from devices carried by people. This approach requires that occupants carry such devices (e.g., cellphones), but does not provide accurate knowledge about the number of devices per person.
Electromechanical sensors	Sensors that covert a mechanical force into an electrical signal to infer occupancy (e.g., piezoelectric sensors integrated into floor mats at building entrances)
Indirect occupancy measurement	Sensors that detect gasses or noises emitted by occupants. For example, carbon dioxide sensors are frequently used to estimate occupancy in the context of HVAC systems and demand-controlled ventilation.

Table 5.12 Occupant Behavior Sensor Technologies.

Technology	Explanation

Plug load meter/smart plug	Sensors integrated into electrical circuits (i.e., serving multiple receptacles) or at the receptacle-level (either integrated or plug-in) to measure current, voltage, power, and/or energy use over time
Lighting state sensor	Sensors used to directly or indirectly measure lighting state. Key methods include reading the building automation system (BAS) signal for lighting state, sensors to measure lighting level (and using calibration to recognize on/off state) and measuring power to lights/light circuits.
Window/blind/doors sensors	Contact sensors or potentiometers used to detect window/blind/door state (open/closed) or degree to which it is open/closed.
Thermostats/temperature sensors	In spaces where occupants have control over air temperature or HVAC state via a thermostat or other interface, interactions can be measured either directly via that interface or indirectly by measuring air temperature and inferring adjustments and settings.

5.3.3.1 Building Automation Systems. Depending on the age and type of building, the building automation system (BAS) may offer significant occupant-related data, with many of the above sensors integrated already. For example, occupant interfaces may include temperature and lighting control, while also measuring occupancy and CO_2. Advanced buildings may also have other occupancy sensors (e.g., ceiling or furniture mounted) and window/door state sensors (e.g., activate/deactivate HVAC). Similarly, some advanced buildings may have motorized window shades or operable windows that are integrated into the BAS.

The major advantages of leveraging BAS data are that the hardware investment has already been made, it is non-invasive (i.e., no need to enter spaces and install new equipment), and the data and communications infrastructure already exists. However, it is unlikely that the BAS senses all measurands of interest and integrating further sensors may be costly.

The presence of sensor hardware does not necessarily mean that data are readily available. In the BAS's existing configuration, sensor data may be used immediately to support control decisions or stored in limited controller-level memory (perhaps just 10 or 100 historical datapoints). Thus, longer term occupant-related measurement requires data archiving. An increasing number of products exist to continuously scan and store data from the BAS. These products include local and/or cloud storage as well as database software to query and visualize the data.

Another challenge of existing sensors (or even new sensors and supporting hardware) is maintenance (e.g., failure with age or from obstruction). Frequent (e.g., yearly) verification of sensor outputs is wise.

5.3.3.2 Installation of New Sensors. While it would be ideal if the BAS already incorporates sensors for the measurands of interest, this is often not the case – particularly for older buildings. Since measurements are usually needed for the long term, there are several approaches to integrate new sensors, as follows.

a. BAS-integrated sensors: BAS-grade sensors may be installed, thus leveraging existing power and data networks, though with some restrictions on product availability.
b. Sensors with wireless communication capability: packaged sensor systems with wireless communications can be used to send data to a hub or to the cloud (i.e., Internet-enabled/Internet of Things) for further analysis. This approach is likely easier to set up than the previous approach (no requirement to integrate it into the BAS), but may also be less resistant to disruptions.
c. Sensors with included memory: there are a wide variety of sensor products that store data, which requires periodic retrieval. While likely being the lowest cost, this option is the most labor-intensive in the long run. Ideally, such sensors can be plugged into wall receptacles for power, or are self-powered using embedded photovoltaic cells or other ambient energy sources. Otherwise, batteries, which have a finite life, can be used to power sensors and their communications/data storage equipment.

5.3.3.3 Other Sources of Data. There are numerous additional sources of occupant-related data that leverage existing building systems, as follows.

a. Security systems: There are a multitude of security systems that track occupancy state and count, and occupant identity, such as turnstiles and swipe-card systems and fingerprint systems. While these data can be sensitive and private, the building owner may provide permission for these data to be leveraged for occupant-related performance studies.

b. Camera networks: Similar to above, installed cameras for security or other purposes may be used to quantify occupancy. Computer vision algorithms may extract occupant characteristics (e.g., count, activity) from video feeds.
c. Wireless networks: Wireless networks can be used to detect WiFi-enabled devices (e.g., laptops, cellphones, tablets) as a proxy for occupancy. Commercial services are available that use advanced algorithms to improve accuracy by using the co-location of multiple devices.

5.3.4 Level 3: Performance Evaluation and Benchmarks. The primary occupant metrics can be directly compared to ASHRAE Standards 62 and 90 (ASHRAE, 2022, ANSI/ASHRAE/IES 2022) and Deru et al. (2011), or to other buildings in a portfolio (similar to the basic and intermediate levels, Levels 1 and 2). Note these references do not include typical or optimal window and blind positions; thus, these metrics must be evaluated for appropriateness in the local context. Primary metrics represented by scalar values can simply be compared to each other (e.g., measured value divided by reference value). Time series data could be compared in a similar way, or else standard parameters such as CV(RMSE) (coefficient of variance of the root mean squared error) could be applied. CV(RMSE) allows the difference between the measured and reference time series to be expressed with a single value.

The availability of published benchmarks for secondary metrics is limited, but some can be derived from the sources above. Alternatively, secondary metrics for similar buildings in a portfolio can be compared to each other to identify anomalies and opportunities for improved performance. A sample secondary metric benchmark calculation is illustrated below.

Example: Secondary metric benchmarking calculation

Equipment energy use per occupant requires the values for the total equipment load and the number of occupied hours. Reference values for both can be obtained from ASHRAE Standard 90.1 Appendix G data. Suppose we have a 10,000 square foot (929 m^2) office building. According to Appendix G, we have the following values.

a. Each nominal occupant is present for the equivalent of 2534 hours per year. Note that this is simply the integrated schedule (i.e., sum of partial occupants) and does not necessarily indicate individual occupants are present for this duration.
b. The occupant density is 275 square feet/occupant or 25.6 m^2/occupant.
c. Office equipment is on for the equivalent of 2,920 hours per year.
d. Equipment power density is 0.75 W/ft2 (8.1 W/m^2)

With the above data, the annual number of occupant hours is:

$$2{,}534\ \frac{h}{year} \times \frac{1}{275\,\frac{\text{SF}}{\text{occ}}} \times 10{,}000\ \text{SF} \approx 92{,}000\ \frac{\text{occ-hr}}{\text{year}}$$

The total building-wide office equipment energy use is:

$$2{,}920\,\frac{\text{h}}{\text{y}} \times \frac{0.75\text{W}}{\text{SF}} \times 10{,}000\ \text{SF} \approx 21{,}900{,}000\ \text{kWh}$$

Dividing equipment energy by occupancy, the final value for this metric is:

$$\frac{21{,}900{,}000\ \text{kWh/y}}{92{,}000\ \text{occ-h/y}} \approx 240\,\frac{\text{kWh}}{\text{occ-year}}$$

The above value represents a benchmark with which measured data can be compared. The context for which such standardized schedules are established is important to remember. In this case, it is a standardized approach for code compliance and typical, but not necessarily ambitious from an energy efficiency perspective. These values have remained largely unchanged for several decades, despite major evolutions in office equipment and occupancy.

One further step that could be taken with the above example is to separate the equipment energy use into occupied and unoccupied periods to identify waste and potential improvements. The same could be performed for lighting, noting the caveats of after-hours cleaning and safety/security lighting. A similar calculation approach can be taken to develop benchmarks for other secondary metrics.

6. ENERGY USE

6.0 General Introduction and Background

6.0.1 General Introduction: Scope of Each Level. This guideline details the methods for measuring and analyzing building energy use from the simplest to the most complex in three levels of effort: basic, diagnostic, and advanced. Users can determine the level of measurement that best fits the project needs, their level of expertise, the need for evaluation detail, the types of problems that may be encountered, and the available project budget.

Level 1 (Section 6.1) describes the **Basic Evaluation** procedures for measuring and analyzing building or facility energy use at the most basic level. It is recommended that every facility should perform these basic procedures before proceeding to the more complex procedures of Level 2 and 3.

Level 2 (Section 6.2) describes the **Diagnostic Measurement** procedures for measuring and analyzing building or facility energy use for diagnostic purposes for the whole building or different types of energy using systems. It is recommended that these procedures be applied after Level 1 and before using Level 3 procedures.

Level 3 (Section 6.3) describes the **Advanced Analysis** procedures for measuring and analyzing building or facility energy use using detailed measurement and analysis strategies. These procedures are meant to represent the most comprehensive procedures that have been publicly documented and/or published in publications such as ASHRAE journals.

This guideline provides measurement and analysis methods for whole-building or whole-facility energy use and for seven (7) types of energy using systems, including:

a. Chillers
b. Pumps
c. Fans
d. Boilers
e. Furnaces
f. Thermal Storage Systems
g. Lighting systems

Details about these methods can be found in Level 3 for individual energy systems.

6.0.2 Background. Reducing non-renewable energy use in buildings has become an important concern due to increasing energy costs and, more recently, efforts to reduce greenhouse gas emissions, including oxides of nitrogen (NO_X) in areas with high ozone concentrations, and carbon dioxide (CO_2) in all areas where fossil fuel combustion is used to provide electricity and in all natural gas utilities. Recently, governments are increasing their control of, and developing mandates for, reducing energy use in buildings and facilities, as well as providing their needed energy use from on-site or utility-scale renewable sources. As a result, many building owners have begun programs to reduce their facility's energy use, and, in some cases, to provide their building energy use from renewable energy sources. To accomplish this a building owner needs to measure and analyze their on-site building energy use, and then reduce their total energy use to meet the desired energy use levels, without compromising building services.

Developing standardized methods for the measurement of building energy use began in the late 1960s and early 1970s with multiple national efforts, including a method to weather-normalize residential heating energy use in single-family and multi-family buildings (Socolow 1978; Fels et al. 1986; Fels et al. 1996). In commercial buildings, numerous methods have been developed (USDOE 1985; Lyberg 1987; IEA 1990) for weather normalization, using monthly utility billing data (Eto 1988; SRC Systems 1996), daily and hourly methods (Haberl and Vajda 1988), and dynamic inverse models using resistance-capacitance (RC) networks (Sonderegger 1977). In the 1980s procedures and methodologies for developing baseline energy use in commercial buildings were published (USDOE 1985; Lyberg 1987; IEA 1990) and continued into the early 1990s (ASHRAE 1991; Haberl and Lopez 1992; Claridge et al. 1991).

During this period public and proprietary toolkits and software were developed that are useful in developing performance metrics for buildings, as well as for commercial HVAC systems and components.

These efforts include: The Princeton Scorekeeping Method (PRISM) (Fels 1986; Fels et al. 1995), which is useful for developing variable-based degree day models of daily average, monthly energy use data; linear and change-point linear models (Kissock 1993; Kissock et al. 2003), Fourier series models (Dhar et al. 1999), hybrid models using hourly and monthly energy use (Singh et al. 2013), dynamic models (Reddy 1989), inverse analysis tools for parameter estimation (Rabl 1988), and other inverse models (Fu et al. 2021; Zhang et al. 2015; Rouchier 2018; Thamilseran 1999). In addition, ASHRAE has developed toolkits for primary HVAC systems, including HVAC01, which are software programs for modeling primary HVAC systems such as boilers and chillers (ASHRAE 1999), and software for modeling secondary HVAC systems, including pumps, fans, cooling coils, and terminal boxes - HVAC02 (ASHRAE 1993).

ASHRAE research has also developed Monitoring and Verification (M&V) procedures for: in-situ measurement of chillers, pumps, and fans, RP-827 (Brandemuehl et al. 1996; Phelan 1997a, 1997b, 1997c); in-situ measurement of thermal storage systems, RP-1004; (Haberl et al. 2000a; Elleson et al. 2002; Reddy et al. 2002); a general purpose toolkit for calculating linear, change-point linear, and multiple-linear inverse building energy analysis models, RP-1050 (Kissock 1993; Kissock et al. 2001; Kissock et al. 2003; Haberl et al. 2003b); and a toolkit for calculating diversity factors for energy and cooling loads, RP-1093 (Abushakra et al. 2001; Claridge et al. 2003; Claridge et al. 2004; Abushakra et al. 2004; Haberl and Cho 2004).

In addition, a report by Oak Ridge National Laboratory in the later 1980s (MacDonald and Wasserman 1989) classified the diverse commercial building analysis methods into five categories: annual total energy and energy intensity comparisons, linear regression and component models, multiple linear regression, building energy simulation, and dynamic (inverse) thermal performance models.

The history of M&V protocols in the United States can be traced to independent efforts with states such as New Jersey, California, and Texas developing protocols that contained procedures for measuring the energy use savings and electric demand reductions from retrofits to existing buildings. These efforts culminated in the development of national protocols, including the U.S. Department of Energy (USDOE)'s 1996 North American Measurement and Verification Protocol (NEMVP) (USDOE 1996), which was accompanied by the USDOE's 1996 FEMP guidelines (FEMP 1996); and analysis methods developed in the Texas LoanSTAR program (Haberl et al. 2002; Liu et al. 2003; Haberl et al. 1998).

In 1997 the NEMVP was updated and republished as the International Performance Measurement and Verification Protocols (IPMVP) (USDOE 1997). The IPMVP was then expanded in 2001 into two volumes: Volume I covering Energy and Water Savings (USDOE 2001), and Volume II covering Indoor Environmental Quality (USDOE 2002). In 2003, Volume III of the IPMVP was published, which covers protocols for new construction (USDOE 2003), and Volume I of the IPMVP was updated beginning in 2007 (USDOE 2007). Current versions of the IPMVP can be found on the Efficiency Valuation Organization (EVO) website (EVO 2024).

In 2002 ASHRAE released Guideline 14-2002: Measurement of Energy and Demand Savings (ASHRAE 2002), which was revised in 2014 and 2023 to serve as the technical document for the IPMVP (ASHRAE 2014; ASHRAE 2023). In 2010 ASHRAE published Performance Measurement Protocols for Commercial Buildings (ASHRAE 2010), which were developed as part of ASHRAE Special Project 115, with contributions from the USGBC and CIBSE. These protocols were developed to provide advice to practitioners regarding the measurement methods for building energy use, water use, thermal comfort, indoor air quality, lighting/daylighting, and acoustics. For each type of measurement, three levels were provided: Level 1 Basic level for simple, low-cost measurement; Level 2 Intermediate level; and Level 3 Advanced, detailed analysis. In 2012 a supplementary guide Performance Measurement Protocols for Commercial Buildings: Best Practices Guide was published (ASHRAE 2012).

In 2013 the USDOE published Phase I of the Uniform Methods Project (USDOE 2017) for evaluating, measuring, and verifying savings for seven energy efficiency measures (i.e., Residential Lighting; HVAC, Unitary Commercial; Commercial Lighting; Residential Refrigerator Recycling, Residential Whole-House Retrofit, Commercial Lighting Controls, and HVAC Residential Boilers/Furnaces) and six cross-cutting protocols to supplement the measure-specific protocols by addressing common topics across all measures (Assessing Persistence and Other Evaluation Issues; Metering; Peak Demand and Time-Differentiated

Energy Savings; Sample Design; and Survey Design and Implementation for Estimating Gross Savings). This was followed by Phase II in 2014 that covered: Adjustable-Speed Drive Motors; Chillers; Commercial New Construction; Commercial HVAC Controls - Energy Management Systems/Direct Digital Control systems; Commercial Retro-commissioning; Compressed Air Systems; Data Center Efficiency; Estimating Net Savings: Methods and Practice; and Residential Behavioral Programs. In 2017 Phase III of the protocols was published, which included: Combined Heat and Power; and Strategic Energy Management (USDOE 2017).

In 2018 ASHRAE released Standard 211-2018, Standard for Commercial Building Energy Audits, to establish consistent practices for conducting and reporting energy audits for commercial buildings. In this standard, procedures for energy audits are provided in three levels. The standard provides a consistent methodology that minimizes the amount of analysis, and includes the following reporting requirements:

a. Level 1 procedure includes reviewing historical utility and onsite generation data, which consist of 12 consecutive months, aggregated for the whole-building, in accordance with ASHRAE Standard 105, Section 5.3. These procedures also include gathering facility site information, including: site address, building type and function, year constructed, dates of renovations, number of floors, number of occupants, building schedule, utility rates, meter locations, data availability, review of O&M procedures, interviews, space function analysis, and historical preservation status. Level 1 also includes identifying low-cost/no-cost energy efficiency measures, and potential capital improvements.
b. Level 2 audit includes
    1. Level 1 information, plus energy cost component breakdowns (i.e., electricity use, electric demand, other energy and demand costs).
    2. A facility site survey that includes a walkthrough using the forms provided in Standard 211-2018.
    3. A determination of key operating parameters (e.g., space heating set points, lighting levels, hot and chilled water setpoints, etc.).
    4. Determining operating schedules, equipment efficiencies, and a qualitative assessment of ducts, insulation, steam systems (if any), energy recovery, transformer efficiencies, etc.
    5. Conducting an end-use system breakdown, including: space heating, space cooling, service water heating, lighting, plug loads, cooking, and other end-uses.
    6. An analysis of end-use energy use, using an estimate of energy use, a building energy model, or submetering data.
    7. An assessment of distributed and renewable energy resource opportunities, which considers building orientation, shading, available roof area, thermal and electrical loads, and electric metering, resulting in an initial measures list.
    8. A calculation of potential energy savings by individual measures, including interactive effects, resulting in estimates of Energy Efficiency Measure costs .
c. Level 3 audit includes
    1. All procedures in Level 1 and Level 2
    2. Determination of recommended EEMs
    3. Cost and cost savings of recommended EEMs
    4. Life-cycle cost analysis (LCCA), including initial costs, financing costs, annual energy costs, escalation rates, discount rates, tax credits, periodic replacements, and estimates of recurring nonenergy costs (i.e., maintenance).
    5. Risk assessment that includes uncertainty and sensitivity of critical parameters.
    6. An analysis that illustrates best-case, worst-case impacts and resulting costs.

ASHRAE released Standard 105-2014, Standard Methods for Determining, Expressing and Comparing Building Energy Performance and Greenhouse Gas Emissions. This standard is intended to facilitate a comparison of design strategies and/or operation improvements as well as the development of building energy performance standards and reporting of greenhouse gas emissions associated with the design of new buildings and operation of existing buildings. It also provides a common basis for reporting building energy use, in terms of delivered energy, forms and expressions of energy performance, comparing design options, and comparing energy performance in terms of energy resources and greenhouse-gas emissions, both across buildings and for energy-efficiency measures within. Standard 105-2014 covers new buildings and existing buildings or portions thereof, the determination and expression of building energy use and the greenhouse gas emissions associated with that use; and techniques for the comparison of the energy performance and associated greenhouse gas emissions between buildings, alternative designs for the same new building, or improvements in the operation of existing buildings. However, it does not establish building energy or greenhouse gas emissions goals or limits, or present a method for certification of prediction methodology, such as computer program, or address embodied energy of building materials and systems, or incorporate transportation energy or associated greenhouse gas emission for building functions, including commuting, business travel and process transportation.

ASHRAE has also held three competitions to determine the most accurate inverse method for modeling and forecasting whole-building or whole-facility energy use. These competitions include descriptions of the methods used by the top scoring contestants: (Kreider and Haberl 1994a and 1994b; Haberl and Thamilseran 1996; Haberl and Thamilseran 1998; Miller et al. 2020).

6.0.3 Target Audience. The target audience for the energy use measurement and analysis methods depends on the use case (or task) being performed, including: benchmarking, energy audits, retrofits, retro-commissioning, new building commissioning, controls and operation, financial audits, community energy management, and building energy research.

For each of these use cases users will generate and use the data, including tenants/occupants, building owners/owner's representatives, architects, consulting engineers, facility managers, building auditors/raters, government agencies, legal counsel, energy service companies, utility providers, manufacturers/product suppliers, commissioning specialists, and researchers.

6.0.4 Energy Use Measurement Plan. All users of this Guideline will develop an energy use measurement plan, in which building or facility characteristics are documented to support the measurement objectives. These characteristics will then form the foundation of the energy use performance determinations for the Level 1, Level 2, or Level 3 analysis. The plan should include:

Building or Facility Information. Information about the building or facility needs to be collected and recorded prior to the measurement and analysis effort. The information needed is:

a. Building or facility type, function, or primary use.
b. Building or facility location (e.g., latitude and longitude if available, or building address).
c. Year of construction and major retrofits.
d. Building size (using gross conditioned floor area) based on exterior building dimensions (including exterior walls), which includes occupied and unoccupied conditioned spaces, but excludes unoccupied or un-conditioned spaces.
e. Number of above-grade and below-grade conditioned floors.
f. Total annual occupied hours.
g. Area of exterior lighting on the premises and type of exterior lighting control (e.g., photocell) that uses electricity recorded by the main meter.
h. EV charging stations that are included in the building meter.
i. General description of the type of heating/cooling system (e.g., chiller, boiler, VAV w/reheat, chilled-water/hot water from campus utilities, etc.), and description of any on-site renewable systems, rainwater harvesting systems, domestic hot water (DHW) or service hot water (SHW) systems, water recycling, etc.
j. Energy-consuming systems on the property that are recorded by the main meter but may not be directly associated with the building's operation (e.g., irrigation pumps, sanitary sewer lift stations, heated driveway systems, etc.).

For Level 3, additional details may be required, depending on the focus of the assessment.

Meter Description. A complete description of installed meters, including: electric meters, natural gas meters, and other meters, as well as meters that will be used in the performance measurement and analysis process, should be included. This description should include: the meter type, manufacturer, model and serial number of the meter, and information about meter calibration. Additional information about metering as needed, including how the meter is connected to the energy supply (i.e., main meter, sub-meter, tandem meters, etc.), meter placement (i.e., diameters of developed flow for flow meters), meter environment (i.e., inside the facility versus outside, etc.), and data acquisition capabilities.

Identification of Individuals to Perform the Following Tasks:

a. Supervise the performance plan and processes.
b. Take or accumulate the measurement data, and coincident weather data.
c. Perform the data analysis and comparisons.
d. Decide on what corrections or adjustments to make.
e. Be responsible for making the corrections or adjustments.
f. Be responsible for archiving and maintaining historical data records.
g. Publish the results to management, facility operators, and occupants.

6.0.5 Appendix. The informative appendix for Section 6 (i.e., Informative Appendix F Energy Use Applications) contains plots that show the application of the ASHRAE Inverse Model Toolkit (IMT) to analyze data from the former ASHRAE HQ building in Atlanta, GA (Figures F.1 to F.8). Figure F.9 shows the models contained in the ASHRAE IMT along with a table illustrating how the coefficients are formulated. Figure F.10 shows an example of a binned, pre-post retrofit analysis, and Figure F.11 shows an example of weekday/weekend weather-daytype plots.

6.1 Level 1: Basic Evaluation

6.1.1 Level 1: Objective. The objective for Level 1: Basic Evaluation is to report the annual energy use and peak electric demand of a whole building or whole facility and to compare it with the annual energy use and peak demand for the same building or facility in previous years, or with similar (peer) buildings in comparable seasons and climates.

6.1.2 Level 1: Metrics. For the Level 1, the annual energy use of a building or facility is calculated, and the annual average dry-bulb temperature, annual daily average dry-bulb temperature range, annual heating/cooling degree days, or climate zone are used in the analysis. Weather data from the weather station closest to the building location, obtained from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI), is used in the analysis (see Table 6.1).

Table 6.1 Level 1: Basic Evaluation Metrics and Methods

Metric	Required Data	Measurement Method	Information Source	Time Interval for Data
Energy Metrics				
• Annual whole-building energy use	• Electricity use • Natural gas use • Other energy use (propane, fuel oil, coal, wood, biomass, etc.)	• Monthly whole-building utility bills • Monthly sub-meter readings	• On-site whole-building utility meter • Building Automation System (BAS)	• Monthly
• Annual peak electric demand • Seasonal peak electric demand (cooling or heating season) • Other whole-building peak demand	• Peak hourly electric demand	• Monthly whole-building utility bills	• On-site whole-building utility meter • BAS	• Hourly peak for the billing year • Note interval data used for peak hourly demand (i.e., 5-minute, 15-minute, hourly, etc.)
• Annual electricity use for exterior lighting	• Electricity use for exterior lighting	• Sub-meter readings for exterior lighting • Calculated use of exterior lighting	• On-site electricity sub- meter for exterior lighting • BAS	• Monthly

• Annual electricity use for other special purposes	• Electricity use for other purposes	• Sub-meter readings for other purposes • Calculated use for other end-uses	• On-site electricity sub- meter for other end-uses • BAS	• Monthly
• Annual fuel use for other special purposes	• Natural gas use • Propane use • Fuel oil use • Other (coal, wood, biomass, etc.)	• Fuel sub-meter readings for other purposes • Calculated fuel use for other end-uses	• On-site fuel sub-meter for other end-uses • BAS	• Monthly
• Annual on-site renewable energy production	• Wind • Solar PV • Solar thermal • Hydroelectric • Other	• Whole-building/facility energy production	• On-site whole-building renewable energy meter • BAS	• Monthly
• Annual load factors	• Electric Load Factor (ELF) • Occupancy Load Factor (OLF)	• Whole-building utility bills • Whole-building occupancy information	• On-site whole-building utility meter • BAS • Occupant survey	• Monthly
Other Metrics				
• Weather data closest to building location	• Annual average dry-bulb temperature • Annual peak minimum and maximum dry-bulb temperature • Total annual heating degree days (HDD) at base 18°C (65°F) and cooling degree days (CDD) at base 10°C (50°F) • Climate zone for the location	• Annual average daily dry-bulb temperature corresponding to annual utility billing period • Annual peak minimum and maximum dry-bulb temperature • Annual HDD and CDD corresponding to annual utility billing dates	• Closest weather station (NCEI site) • BAS	• Daily average dry-bulb temperature for entire year • Daily average dry bulb temp range • Annual heating and cooling degree days calculated from daily average temperatures
• Conditioned area of building/facility	• Conditioned area (heated & cooled, heated only, partially heated, heated and mech. ventilated, etc.)	• Extract conditioned area from building plans • Determine status from plans, and HVAC system info • Identify if partial heating/cooling exists	• Architectural plans • Building footprint from satellite images times number of floors • Conditioned area from walk-thru • Conditioned area from local tax office	

6.1.3 Level 1: Measurement Methods. At the Level 1: Basic Evaluation, all energy-using systems that have meters, energy use data, and other relevant information are measured and recorded as noted in Table 6.1. These include the following:

Annual whole-building energy use for electricity, natural gas, and other energy sources (i.e., propane, fuel oil, etc.) can be obtained from twelve (12) consecutive monthly whole-building or whole-facility utility bills. This data can include coincident monthly sub-meter readings of selected sub-systems (if available). Monthly use data may also be obtained from the Building Automation System (BAS) meters if such data accurately represents whole-building utility meters.

Annual peak electric demand, Seasonal peak electric demand for whole-building/facility can be obtained from the twelve (12) consecutive monthly peak hourly electric demand readings for the building or facility. In the absence of such data from monthly utility bills, monthly peak electric hourly readings can also be obtained from the BAS. The twelve monthly peak demand readings are first sorted into two seasonal peaks (i.e., cooling or heating) using coincident, monthly peak dry-bulb temperature readings (i.e., peak minimum and maximum temperatures for the month corresponding to the billing period) from a nearby weather data source or from the BAS for each billing period. Hourly interval readings calculated from sub-hourly readings should be noted.

Annual electricity use for exterior lighting (i.e., parking or security lighting). Record annual electricity use for exterior lighting using sub-metered data. If the annual electricity used for exterior lighting is not separately measured and this use is part of the whole-building or whole-meter electricity use, calculate the use using a fixture count times the electric power draw per fixture times annual operating hours, and note the method of lighting control (i.e., timeclock, photocell, etc.).

Annual electricity use for other special purposes (i.e., well-water pumps, fountains, sanitary sewer lift pumps, heated driveways, Electric Vehicle (EV) charging stations, etc.). Record annual electricity use using sub-metered data. If the electricity used for other special purposes is not separately measured and the energy use is part of the whole-building or whole-meter electricity use, calculate the electricity use using spot measurements, which is then multiplied by annual operating hours, and note the method of control (i.e., water level sensors, on/off, etc.).

Annual fuel use for other special purposes (i.e., gas-fired radiant heaters in parking garages, gas-fired heated sidewalks or driveways, natural gas emergency generators, etc.). Record annual fuel use for special purposes using sub-metered data or the amount of fuels (i.e., dry weight of wood, coal, etc.). If the measured fuel energy used for other special purposes is not separately measured and the energy use is part of the whole-building or whole-meter energy use, calculate the energy use for other special purposes using spot measurements, which is then multiplied by annual operating hours, and note the method of control (i.e., thermostat, on/off, etc.).

Annual on-site renewable energy production. Measure and record annual on-site renewable energy production, including: on-site wind electricity production, solar PV electricity production, solar thermal energy production, biomass thermal production using dry weight conversion, and hydroelectric production. If on-site renewable energy production is not metered, calculate the renewable energy production using spot measurements. The method of calculation should be noted.

Annual load factors. Data for calculating annual load factors should be gathered for the building/facility. Such load factors include Electric Load Factor (ELF) and Occupancy Load Factor (OLF) gathered from monthly utility billing or BAS data. If occupant data are not available, calculations can be performed using scheduled building/facility operation information (i.e., operating hours). The annual ELF and OLF are calculated as:

a. Annual ELF = [total annual electricity use (kWh/yr)] / [peak electric demand (kW) x number of hours per year (i.e., usually 8,760) (hr/yr)]
b. Annual OLF = [total annual occupied hours (hr/yr)] / [number of hours per year (i.e., usually 8,760) (hr/yr)]

Weather data closest to building location. Annual average ambient dry-bulb temperature is calculated as the average of 365 daily average temperatures corresponding to the annual billing period. For mid-month to mid-month energy use readings, mid-month to mid-month daily average dry-bulb temperature readings are required that correspond to the billing period. Annual average daily ambient dry-bulb temperatures can also be obtained from continuous hourly measurements, if available. The annual average daily temperature range can be calculated from daily minimum-maximum dry bulb temperature data (NCEI 2024). The climate zone for the building location can be obtained from ASHRAE Standard 169-2020 (ASHRAE 2020).

Conditioned area of building/facility can be obtained from architectural plans or from a site visit if plans do not exist. For buildings with a uniform floor layout from the first floor to the top floor, the conditioned area can be determined from a measurement of the footprint of the building obtained from current satellite images times the number of floors (including conditioned basements). Adjustments will need to be made for atriums, voids (i.e., missing spaces or floors in the multistory footprint, unconditioned floors, etc.), or multistory interior spaces. Note the conditioned area should correspond to the conditioned area during the utility billing period.

6.1.4 Level 1: Performance Evaluation and Benchmarks. Level 1 performance evaluation and benchmarks include comparing energy use and demand with previous use from the same facility, comparing energy use and demand with similar facilities in comparable climates, and comparing energy use with benchmark databases (Table 6.2).

Table 6.2 Level 1: Basic Energy Performance Evaluation and Benchmarks

Type of Evaluation	Required Metric (From Table 6.1)	Benchmark	Evaluation Reference
• Compare current annual energy use to previous year's annual energy use for the same building or facility	• Annual whole-building energy use • Weather data closest to building location	• Annual energy use for the same building/facility in previous years (Note the difference in HDD and CDD between previous year and current year)	• MacDonald & Wasserman 1989 • Haberl et al. 2002 • ASHRAE 2002, 2014, and 2023
• Compare annual peak electric demand to previous peak electric demand • Compare heating and cooling season peak electric demand	• Annual peak electric demand • Seasonal peak electric demand (cooling or heating season) • Other whole-building peak demand	• Annual peak electric demand for the same building/facility in previous years • Seasonal peak electric demand for the same building/facility in previous years	• Haberl & Komor 1989, 1990a, and 1990b
• Compare current annual energy use to similar buildings/facilities or national databases	• Annual whole-building energy use • Weather data closest to building location	• Annual energy use of similar buildings/facilities in similar climates • EUI database for similar buildings/facilities in similar climates	• USEPA 2020 • USEIA 2022 • LBNL n.d. • USDOE n.d -a. • ASHRAE 2022 and 2024
• Compare annual Electric Load Factors (ELF) with Occupancy Load Factors (OLF)	• Annual load factors • Weather data closest to building location	• Comparison of current ELF against OLF • Annual ELF/OLF for the same building/facility in previous years • ELF/OLF database for similar buildings/facilities in similar climates	• Haberl & Komor 1989 and 1990b • ASHRAE 1995
• Compare annual electricity use for exterior lighting	• Electricity used for exterior lighting	• Annual electricity use for exterior lighting for same building/facility in previous years. • Annual electricity use for exterior lighting of similar	• USDOE 2011

		buildings/facilities in similar climates.	
• Compare annual electricity use for other special purposes	• Electricity used for other special purposes	• Annual electricity use for other purposes for same building/facility in previous years. • Annual electricity use for other purposes in previous years.	• USDOE 2011
• Compare annual fuel use for other special purposes	• Fuel used for other special purposes	• Annual fuel used for other purposes.	• USDOE 2011
• Compare annual on-site renewable energy production	• Energy generated by on-site renewable energy systems.	• Annual on-site energy generation for same building/facility in previous years. • Annual on-site energy production of similar buildings/facilities in similar climates.	• USEPA 2014

Compare annual energy use to previous year's annual energy use for the same building or facility. Compare annual, whole-building energy use to the previous year's annual energy use. Also, compare heating degree days (HDD) and cooling degree days (CDD) for the current year to the previous year. (If the difference in HDD and CDD for this year versus previous year is greater than 10%, make note of the difference in HDD and CDD in the Level 1 analysis.) The annual average ambient dry-bulb temperature for the year corresponding to the utility data can be obtained from the closest National Weather Service (NWS) stations (NCEI 2024) or from the BAS.

Compare annual peak electric demand to previous peak electric demand. Using monthly data from utility bills or from the BAS, compare annual peak electric demand to the previous year's peak electric demand. Make note of the time interval used for the peak readings (i.e., 15-minute, 30-minute, 60-minute, etc.). To determine heating or cooling season peak demand, use NCEI monthly, min/max data (i.e., peak minimum and maximum temperature for each month corresponding to billing period) to determine heating and cooling seasons.

Compare annual energy use to similar buildings/facilities or national databases. Compare current annual energy use to similar buildings/facilities or national database(s) in similar climates using annual energy use calculated from monthly utility billing data or the BAS. Use current HDD and CDD data to determine similar climates.

The annual whole-building/facility energy use is most easily compared by calculating an annual building, site, and primary Energy Use Intensity (EUI) in $MJ/m^2{\cdot}yr$ or $kWh/m^2{\cdot}yr$ ($kBtu/ft^2{\cdot}yr$), which uses the conditioned area at the time of the evaluation. ASHRAE Standard 105-2021 outlines methods for determining the annual primary energy use of a building based on its annual site energy use (ASHRAE 2021). It is important for users to choose a consistent metric that matches the chosen database to accurately compare their building's energy performance with national or regional databases.

In addition, a whole-building/facility peak electric demand (kW) can be calculated and compared where the peak electric demand in kW/m^2 (kW/ft^2) can be calculated and compared to the peak electric demand for similar buildings in similar climates. (Use coincident, measured HDD and CDD to determine similar climates). The interval used for recording the peak demand should be hourly. If only sub-hourly demand is available, then one year of sub-hourly demand records should be obtained, and hourly demand are subsequently calculated.

Comparisons to the EUI or peak electric demand either for the same building/facility from a previous period, or to similar buildings in similar climates (i.e., similar HDD, CDD), or to a benchmark database must consider any changes in the building/facility use that may impact the whole-building/facility energy use or demand.

Examples of national databases include:

a. Energy Star Portfolio Manager (USEPA 2020). Energy Star Portfolio Manager was developed as a joint program of the U.S. Environmental Protection Agency (USEPA) and the USDOE. The USEPA/USDOE Energy Star Portfolio Manager is an interactive tool that serves as a resource management tool that enables benchmarking of the energy use of any type of building against a national database.
b. Commercial Building Energy Consumption Survey (CBECS) (USEIA 2022). CBECS was developed by the U.S. Energy Information Administration (USEIA). CBECS is the only nationally representative source of statistical information on energy-related characteristics, consumption, and expenditures for the nation's 5.6 million commercial buildings totaling 87 billion square feet.
c. LBNL Building Performance Database (BPD) (LBNL n.d.). The LBNL Building Performance Database (BPD) is the nation's largest dataset of information about the energy-related characteristics of commercial and residential buildings. The BPD combines, cleanses and anonymizes data collected by federal, state and local governments, utilities, energy efficiency programs, building owners, and private companies, and makes it available to the public. The BPD website allows users to explore the data across real estate sectors and regions, and to compare physical and operational data.
d. USDOE Buildings Energy Data Book (USDOE n.d. -a). The USDOE Buildings Energy Data Book is a statistical compendium prepared and published by the Pacific Northwest National Laboratory (PNNL) with support from the USDOE's Office of Energy Efficiency and Renewable Energy (EERE). The 2010 Buildings Energy Data Book provides an accurate set of comprehensive buildings-related data for consistent use throughout DOE programs. It is a compendium of data and does not provide original data.
e. ASHRAE Standard 90.1-2022 (ASHRAE 2022). ASHRAE Standard 90.1 provides the minimum requirements for energy-efficient design of most commercial buildings, except low-rise residential buildings. It contains the minimum energy-efficient requirements for the design and construction of new buildings and their systems, new portions of buildings and their systems, and new systems and equipment in existing buildings, as well as criteria for determining compliance with these requirements. Standard 90.1 also contains design data EUIs for energy and lighting systems.
f. ASHRAE Standard 100-2024. ASHRAE Standard 100 provides normative primary energy EUI target tables in addition to primary energy EUI calculation options (ASHRAE 2024). Such EUI targets are intended for use by authorities having jurisdiction to permit compliance using either the site energy target or primary energy target selected by the authority having jurisdiction.

Compare annual Electric Load Factors (ELF) to Occupancy Load Factors (OLF). Compare annual ELF with OLF for the corresponding evaluation period, and evaluate them against ELF/OLF indices from the previous year or nationally-published databases for similar buildings/facilities in similar climates (HDD or CDD). A high annual ELF indicates constant electricity use, while a low annual ELF indicates a high electric demand and low average electricity use. A mismatch between the annual ELF and OLF indices for a building or facility may indicate electrical equipment left running during unoccupied periods.

Compare annual electricity use for exterior lighting. Comparisons of the annual electricity used for exterior lighting can include comparisons to annual electricity use for exterior lighting with the same building during previous periods, or it can include comparisons of annual electricity used for exterior lighting to similar buildings/facilities in similar climates, such as those included in the USDOE (2011) report.

Compare annual electricity use for other special purposes. Comparisons of the annual electricity used for special purposes can include comparisons to annual electricity use for special purposes with the same building during previous periods, or it can include comparisons of annual electricity used for special purposes to similar buildings/facilities in similar climates, such as those included in the USDOE (2011) report.

Compare annual fuel use for other special purposes. Comparisons of the annual fuel used for other, special purposes can include comparisons to annual fuel used for other purposes with the same building during previous periods, or it can include comparisons of annual fuel used for other special purposes to similar buildings/facilities in similar climates, such as those included in the USDOE (2011) report.

Compare annual on-site renewable energy production. Comparisons of annual on-site renewable energy production can include comparisons to annual on-site renewable energy production from same building during previous periods, or it can include comparisons of annual on-site renewable energy production for similar buildings/facilities in similar climates, such as those included in the USDOE (2011) report.

6.2 Level 2: Diagnostic Measurement

6.2.1 Level 2: Objective. The objective for Level 2: Diagnostic Measurement is to measure the monthly energy use of a whole-building/facility to provide monthly, daily-average use that can be weather-normalized using billing period average, ambient dry-bulb temperature or other measures for the whole-building or whole-facility energy use. This gives greater insight into energy saving opportunities at a whole-building or whole-facility level and allows for a more accurate analysis of energy costs and paybacks for reducing the whole-building/facility energy use compared to Level 1.

6.2.2 Level 2: Metrics. For the Level 2, monthly energy use and coincident daily average dry-bulb temperatures are needed, corresponding to the monthly billing period (see Table 6.3). A Level 2 analysis should also be preceded by a Level 1 analysis.

Table 6.3 Level 2: Diagnostic Measurement Metrics and Methods.

Metric	Required Data	Measurement Method	Information Source	Time Interval for Data
Energy Metrics				
• Monthly whole-building energy use	• Electricity use • Natural gas use • Other energy use (propane, fuel oil, coal, wood, biomass, etc.)	• Monthly whole-building utility bills • Monthly sub-meter readings	• On-site whole-building utility meter • Building Automation System (BAS)	• Monthly
• Monthly peak electric demand	• Peak hourly electric demand	• Monthly whole-building utility bills	• On-site whole-building utility meter • BAS	• Hourly peak for the billing period • Note interval data used for peak hourly demand (i.e., 5-minute, 15-minute, hourly, etc.)
• Monthly electricity use for exterior lighting	• Electricity use for exterior lighting	• Sub-meter readings for exterior lighting • Calculated use of exterior lighting	• On-site electricity sub-meter for exterior lighting • BAS	• Monthly
• Monthly electricity use for other special purposes	• Electricity use for other purposes	• Sub-meter readings for other purposes • Calculated use for other end-uses	• On-site electricity sub-meter for other end-uses • BAS	• Monthly
• Monthly fuel use for other special purposes	• Natural gas use • Propane use • Fuel oil use • Other (coal, wood, biomass, etc.)	• Sub-meter fuel readings for other purposes • Calculated fuel use for other end-uses •	• On-site fuel sub-meter for other end-uses • BAS	• Monthly

• Monthly on-site renewable energy production	• Wind • Solar PV • Solar thermal • Hydroelectric • Other	• Whole-building/facility energy production	• On-site whole-building renewable energy meter • BAS	• Monthly
• Monthly load factors	• Electric Load Factor (ELF) • Occupancy Load Factor (OLF)	• Monthly whole-building utility bills • Monthly whole-building occupancy information	• On-site whole-building utility meter • BAS • Occupant sensors • Occupant survey	• Monthly
Other Metrics				
• Monthly weather data closest to building location	• Monthly daily average ambient temperature • Maximum daily average ambient temperature of the billing month	• Monthly daily average ambient temperature for the monthly billing period, calculated from hourly dry-bulb temperature • Maximum daily average ambient temperature of the billing month	• On-site or closest weather station (NCEI site) • BAS	• Daily average ambient temperature calculated from hourly dry-bulb temperature readings

6.2.3 Level 2: Measurement Methods. At the Level 2: Diagnostic Measurement, in a similar fashion to Level 1, energy-using systems that have meters, energy use data, and other relevant information are measured and recorded as noted in Table 6.3. These include the following:

Monthly whole-building energy use for electricity, natural gas, and other energy sources (i.e., propane, fuel oil, wood, biomass, coal, etc.). Obtain monthly whole-building energy use either from on-site whole-building utility meters or from the BAS. Include the reading dates of the monthly utility bills so that the coincident average ambient temperature for the billing period can be calculated. This is important because the date of the monthly energy use reading may occur at irregular calendar intervals and needs normalization for the billing period.

Monthly peak electric demand for whole building/facility. Obtain and record monthly peak hourly electric demand for whole building/facility If the time interval is not hourly, then note the time interval of the reading, for example 5-minute, 15-minute or 30-minute.

Monthly electricity use for exterior lighting (i.e., parking or security lighting). Obtain and record monthly electricity use for exterior lighting. If the monthly electricity used for exterior lighting is not separately metered, and the exterior lighting electricity use is part of the whole-building or whole-meter electricity use, calculate the electricity use using a fixture count times the electric power draw per fixture times monthly operating hours, and note the method of lighting control (i.e., time clock, photocell, etc.).

Monthly electricity use for other special purposes (i.e., well-water pumps, fountains, sanitary sewer lift pumps, EV charging stations, etc.). Obtain and record monthly electricity use for other purposes using sub-metered data. If the measured, monthly electricity used for other special purposes is not separately measured and the electricity use is part of the whole-building or whole-meter electricity use, then calculate this electricity use using spot measurements, which is then multiplied by monthly operating hours, and note the method of control (i.e., water level sensors, on/off, etc.).

Monthly fuel use for other special purposes (i.e., gas-fired radiant heaters in parking garages, gas-fired heated sidewalks or driveways, natural gas emergency generators, etc.). Obtain and record monthly fuel use for other purposes using sub-metered data. If the measured fuel energy used for other special purposes is not separately measured and the energy use is part of the whole-building or whole-facility energy use, calculate the energy use using spot measurements, which is then multiplied by monthly operating hours, and note the method of control (i.e., thermostat, on/off, etc.).

Monthly on-site renewable energy production. Obtain and record monthly on-site renewable energy production for electricity-producing systems or for thermal systems. If monthly metered on-site renewable energy use is not available, calculate the renewable energy production using spot measurements. The method of calculation should be noted.

Monthly load factors. Calculate the monthly ELF and OLF, defined as:

a. Monthly ELF = [total monthly electricity use (kWh/month)] / [peak electric demand (kW) for the month x number of hours per month (hr/month)]
b. Monthly OLF = [total monthly occupied hours (hr/month)] / [number of hours per month (hr/month)]

Monthly weather data closest to building location. Calculate the daily average temperature for the monthly billing period, which may contain temperatures from two adjacent months, from hourly dry-bulb temperature obtained from the nearby NCEI weather station or BAS. The maximum daily average temperature of the billing months can then be determined and used for monthly peak electric demand analysis.

6.2.4 Level 2: Performance Evaluation and Benchmarks. Level 2 performance evaluation and benchmarks should begin with a Level 1 analysis of the annual energy assessment to help identify if the building or portions of the building or facility are over-consuming or experiencing high peak electric demand levels. Level 2 then proceeds with a monthly energy use and demand analysis, which uses monthly daily average ambient temperatures to develop an analysis that is normalized for differences in the length of the billing period and ambient conditions (Table 6.4).

Table 6.4 Level 2: Diagnostic Energy Performance Evaluation and Benchmarks.

Type of Evaluation	Required Metric (From Table 6.3)	Benchmark	Evaluation Reference
• Evaluate monthly energy use using a normalized, change-point linear analysis	• Monthly whole-building energy use • Monthly weather data (i.e., monthly daily average ambient temperature) closest to building location	• Normalized parameters of whole-building energy use IMT models from previous years or from similar buildings/facilities in similar climates	• Kissock et al. 2003 • Haberl et al. 2003 • Paulus et al. 2015
• Evaluate hourly peak electric demand for each month using a normalized, change-point linear analysis	• Monthly peak electric demand • Monthly weather data (i.e., maximum daily average ambient temperature of the billing month) closest to building location	• Normalized parameters of whole-building peak demand IMT models from previous years or from similar buildings/facilities in similar climates	• Kissock et al. 2003 • Haberl, et al. 2003 • Paulus et al. 2015 • ASHRAE 2023
• Evaluate monthly ELF and OLF	• Monthly load factors	• ELF and OLF from previous years or from similar buildings/facilities in similar climates	• Haberl & Komor 1989 and 1990b

Evaluate monthly energy use using a normalized, change-point linear analysis. For facilities that are in operation continuously over a 12-month period, evaluate 12 monthly energy use readings using linear, change-point linear, or variable-based degree day regression models provided by the ASHRAE Inverse Modeling Toolkit (IMT) (Kissock et al. 2003; Haberl et al. 1998 and 2003). Model selection should utilize procedures outlined in Paulus et al. (2015).

For facilities that have a strong seasonal component (e.g., K-12 schools, recreational sites, convention centers), monthly utility data should first be grouped by use (e.g., school year, non-school year or summer-vacation period) prior to the application of the change-point linear models or variable-based degree day models from the IMT. Models for both periods will need to be developed for comparisons (Haberl et al 1998). The analysis of buildings needing more than two groups of models may need to utilize a Level 3 analysis that uses daily or hourly data.

Evaluate hourly peak electric demand for each month using a normalized, change-point linear analysis. For facilities that are in operation continuously over a 12-month period, evaluate 12 monthly peak electric demand readings using linear or change-point linear regression models provided by the ASHRAE IMT (Kissock et al. 2003; Haberl et al. 2003) and procedures provided by ASHRAE Guideline 14-2023 (ASHRAE 2023). The Appendix D3 of Guideline 14-2023 provides guidelines on calculating weather-dependent whole-building peak demand models, which can be used to model peak kW against maximum daily average temperature for the billing month.

For facilities that have a strong seasonal component (e.g., K-12 schools, recreational sites, convention centers), monthly peak demand data should first be grouped by use (e.g., school year, non-school year or summer-vacation period) prior to the application of the procedure outlined in ASHRAE Guideline 14-2023. Peak demand models for both periods will need to be developed for comparisons, including details of any grouping selection. The analysis of buildings needing more than two groups of models may need to utilize a Level 3 analysis that uses daily or hourly data.

Evaluate monthly ELF and OLF. Compare the twelve months of ELF and OLF for the same building during previous years to determine if there is a mismatch between the ELF and OLF, indicating opportunities for reducing monthly peak electric demand. Compare ELF and OLF with similar buildings in similar climate zones determined by HDD and CDD to determine if an opportunity exists for reducing monthly peak demand.

6.3 Level 3: Advanced Analysis

6.3.1 Level 3: Objective. The objective for Level 3: Advanced Analysis is to measure the daily or hourly energy use of a whole-building/facility, end-use energy use, or component energy use to provide daily or hourly data for analysis using selected procedures. Level 3 offers greater insight into energy savings opportunities for more accurate analysis of energy costs and paybacks compared to Level 1 and Level 2. In addition, when hourly data are combined with coincident hourly weather data from a nearby weather station, greater insight into hourly weather dependence can be provided.

6.3.2 Level 3: Metrics. For the Level 3, daily/hourly energy use and coincident daily/hourly weather data from a nearby weather station are needed (see Table 6.5). A Level 3 analysis should also be preceded by a Level 1 and Level 2 analysis.

In Level 3, daily, hourly, or sub-hourly whole-building/end-use interval energy use data is collected from utility meters, Energy Management Systems (EMS), BAS, or specially installed sensors/data logging systems. In certain cases, short-term energy monitoring using portable data logging systems or monitoring equipment, coupled with coincident weather data, has proven to be useful. Additionally, for selected system components with constant use profiles, instantaneous power measurements using portable data logging systems and coincident hourly weather data, have shown to be useful in characterizing the energy use of such equipment.

Table 6.5 Level 3: Advanced Analysis Whole-Building Measurement Metrics and Methods.

Metric	Required Data	Measurement Method	Information Source	Time Interval for Data
Energy Metrics				
• Daily/Hourly whole-building or component-level energy use	• Electricity use • Natural gas use • Other energy use (propane, fuel oil,	• Daily/Hourly whole-building/facility or component-level energy data	• On-site whole-building energy meter	• Daily/Hourly

	coal, wood, biomass, etc.)		• Building Automation System (BAS)	
• Hourly peak electric demand	• Peak hourly electric demand	• Hourly whole-building/facility electricity data	• On-site whole-building electricity meter • BAS	• Hourly peak • Note interval data used for peak hourly demand (i.e., 5-minute, 15-minute, hourly, etc.)
• Daily/Hourly electricity use for exterior lighting	• Electricity use for exterior lighting	• Daily/Hourly sub-meter readings for exterior lighting • Calculated hourly use of exterior lighting	• On-site electricity sub-meter for exterior lighting • BAS	• Daily/Hourly
• Daily/Hourly electricity use for other special purposes	• Electricity use for other purposes	• Daily/Hourly sub-meter readings for other purposes • Component-level hourly readings • Calculated hourly use for other end-uses	• On-site electricity sub-meter for other end-uses • BAS	• Daily/Hourly
• Daily/Hourly fuel use for other special purposes	• Natural gas use • Propane use • Fuel oil use • Other (coal, wood, biomass, etc.)	• Daily/Hourly fuel sub-meter readings for other purposes • Calculated hourly fuel use for other end-uses	• On-site fuel sub-meter for other end-uses • BAS	• Daily/Hourly
• Daily/Hourly on-site renewable energy production	• Wind • Solar PV • Solar thermal • Hydroelectric • Other	• Daily/Hourly whole-building/facility energy production •	• On-site whole-building renewable energy meter • BAS	• Daily/Hourly
• Daily load factors	• Electric Load Factor (ELF) • Occupancy Load Factor (OLF)	• Daily/Hourly whole-building energy data • Daily/Hourly whole-building occupancy information	• On-site whole-building energy meter • BAS • Occupant sensors • Occupant survey	• Daily/Hourly
Other Metrics				
• Daily/Hourly weather data closest to building location	• Dry bulb temp • Wet bulb temp, dewpoint temp, or relative humidity • Wind Speed • Solar radiation (global horizontal)	• Daily/Hourly weather data	• On-site or closest weather station (NCEI site) • Local weather station • BAS	• Daily/Hourly

6.3.3 Level 3: Measurement Methods. At the Level 3: Advanced Analysis, in a similar fashion to Level 2, energy-using systems that have meters, energy use data, and other relevant information are measured and recorded as noted in Table 6.5. Prior to applying Level 3, Levels 1 and 2 analysis should be conducted. These data include the following:

Daily/Hourly whole-building or component-level energy use for electricity, natural gas, and other energy sources (i.e., propane, fuel oil, wood, biomass, coal, etc.). Obtain whole-building energy use either from on-site whole-building utility meters or from the BAS.

Hourly peak electric demand for whole building/facility. Obtain and record hourly peak electric demand for whole building/facility. If the time interval is not hourly then note the time interval of the reading, for example: 5-minute, 15-minute, or 30-minute.

Daily/Hourly electricity use for exterior lighting (i.e., parking or security lighting). Obtain and record daily/hourly electricity use for exterior lighting. If the daily/hourly electricity used for exterior lighting is not separately metered, and the exterior lighting electricity use is part of the whole-building or whole-meter electricity use calculate the electricity use using a fixture count times the electric power draw per fixture times daily/hourly operating hours, and note the method of lighting control (i.e., time clock, photocell, etc.).

Daily/Hourly electricity use for other special purposes (i.e., well-water pumps, fountains, sanitary sewer lift pumps, EV charging stations, etc.). Obtain and record daily/hourly electricity use for other purposes using sub-metered data. If the daily/hourly electricity used for other special purposes is not separately measured and the electricity use is part of the whole-building or whole-meter electricity use, then calculate this electricity use using spot measurements, which is then multiplied by monthly operating hours, and note the method of control (i.e., water level sensors, on/off, etc.).

Daily/Hourly fuel use for other purposes (i.e., gas-fired radiant heaters in parking garages, gas-fired heated sidewalks or driveways, natural gas emergency generators, etc.). Obtain and record daily/hourly fuel use for other purposes using sub-metered data. If the measured fuel energy used for other special purposes is not separately measured and the energy use is part of the whole-building or whole-facility energy use, calculate the energy use using spot measurements, which is then multiplied by daily/hourly operating hours, and note the method of control (i.e., thermostat, on/off, etc.).

Daily/Hourly On-site renewable energy production. Obtain and record daily/hourly on-site renewable energy production for electricity-producing systems or for thermal systems. If daily/hourly metered on-site renewable energy use is not available, calculate the renewable energy production using spot measurements. The method of calculation should be noted.

Daily load factors. Calculate the daily ELF and OLF, defined as:

a. Daily ELF = [total daily electricity use (kWh/day)] / [peak electric demand (kW) for the day x number of hours per day (hr/day)]
b. Daily OLF = [total daily occupied hours (hr/day)] / [number of hours per day (hr/day)]

Daily/Hourly weather data closest to building location. Calculate the daily average temperature from hourly dry-bulb temperature obtained from the nearby NCEI weather station or BAS. The maximum hourly temperature of the day can be also determined and used for peak electric demand analysis.

6.3.4 Level 3: Performance Evaluation and Benchmarks. Level 3 performance evaluation and benchmarks should begin with Level 1 and Level 2 analyses of the annual and monthly energy assessment to help identify if the building or portions of the building or facility are over-consuming or experiencing high peak electric demand levels. Level 3 then proceeds with a daily/hourly energy use and demand analysis, which uses daily/hourly ambient temperatures to develop an analysis that is normalized for differences in ambient conditions. The Level 3 analysis includes evaluating and benchmarking whole-building energy performance (Table 6.6 and Section 6.3.4.1) and component-level energy performance (Table 6.7 and Section 6.3.4.2).

Table 6.6 Level 3: Advanced Whole-Building Energy Performance Evaluation and Benchmarks.

Type of Evaluation	Required Metric (From Table 6.5)	Benchmark	Evaluation Reference
• Evaluate daily energy use using a change-point linear analysis	• Daily whole-building energy use	• Normalized parameters of daily whole-building energy use IMT models	• Kissock et al. 2003 • Haberl et al. 2003 • Haberl et al. 1998

	• Daily weather data (i.e., daily hourly average ambient temperature) closest to building location	from previous years or from similar buildings/facilities in similar climates	• Paulus et al. 2015
• Evaluate hourly energy use using an inverse bin method	• Hourly whole-building energy use • Hourly weather data (i.e., hourly ambient temperature) closest to building location	• Analysis from previous years or from similar buildings/facilities in similar climates	• Haberl & Abbas 1998a and 1998b • Thamilseran 1999
• Evaluate hourly energy use using a weather-daytype procedure	• Hourly whole-building energy use • Hourly weather data (i.e., hourly ambient temperature) closest to building location	• Analysis from previous years or from similar buildings/facilities in similar climates	• Bou Saada & Haberl 1995 • Hadley 1993
• Evaluate hourly peak electric demand for weekdays or weekends using the ASHRAE's Diversity Factor Toolkit	• Hourly peak electric demand	• Analysis from previous years or from similar buildings/facilities in similar climates	• Claridge et al. 2003 • Claridge et al. 2004 • Abushakra et al. 2004 • Paulus et al. 2015 • Abushakra et al. 2001
• Evaluate daily ELF and OLF	• Daily load factors	• ELF and OLF from previous years or from similar buildings/facilities in similar climates	• Haberl & Komor 1989, 1990a, and 1990b
• Evaluate whole-building energy use using calibrated simulation	• Hourly whole-building energy use • Hourly weather data closest to building location	• Analysis from similar buildings/facilities in similar climates • Analysis from buildings in dissimilar climates by substituting weather files • USDOE Reference Buildings	• ASHRAE 2023 • Reddy 2006 • Clarke et al. 1993 • Coakley 2014 • Haberl & Bou-Saada 1998 • Song & Haberl 2008

Table 6.7 Level 3: Advanced Component-Level Energy Performance Evaluation and Benchmarks.

Type of Evaluation	Required Metric (From Table 6.5)	Benchmark	Evaluation Reference
• Evaluate in-situ performance of chillers	• Hourly component-level energy use (i.e., chiller's electricity use, chiller's cooling production)	• Energy use of respective components in previous years or of similar equipment • Design performance	• Brandemuehl et al. 1996 • Phelan et al. 1997a and 1997b
• Evaluate in-situ performance of pumps	• Hourly component-level energy use (i.e., pump's electricity use)	• Energy use of respective components in previous years or of similar equipment • Design performance	• Brandemuehl et al. 1996 • Phelan et al. 1997a and 1997c
• Evaluate in-situ performance of fans	• Hourly component- level energy use (i.e., fan's electricity use)	• Energy use of respective components in previous years or of similar equipment	• Brandemuehl et al. 1996 • Phelan et al. 1997a and 1997c

		• Design performance	
• Evaluate in-situ performance of non-reheat boilers/furnaces	• Hourly component- level energy use (i.e., boilers' or furnaces' energy use)	• Energy use of respective components in previous years or of similar equipment • Design performance	• ASHRAE 2023 • Chernick 1985
• Evaluate in-situ performance of lighting systems	• Hourly component- level energy use (i.e., lighting systems' electricity use)	• Energy use of respective components in previous years or of similar equipment • Design performance	• ASHRAE 2023
• Evaluate in-situ performance of thermal storage systems	• Hourly whole-building energy use (i.e., whole-building electricity use, cooling plant electricity use, building/chiller thermal cooling load, TES thermal load) • Hourly weather data (i.e., hourly ambient temperature) closest to building location	• Energy use of respective components in previous years or of similar equipment • Design performance	• Reddy et al. 2002 • Elleson et al. 2002

6.3.4.1 Whole-Building Energy Performance. The Level 3 whole-building energy performance evaluation and benchmarks, as noted in Table 6.6, include the following:

Evaluate daily energy use using a change-point linear analysis. Evaluate the daily whole-building or whole-facility weather-dependent energy use using linear, change-point linear, or variable-based degree-day regression models provided by the ASHRAE IMT (Kissock et al. 2003; Haberl et al. 2003; Haberl et al. 1998). Model selection should use procedures outlined in Paulus et al. (2015). Compare the results to previous energy use from the same building or to the energy use of similar buildings in similar climate zones, determined by HDD or CDD.

Evaluate hourly energy use using an inverse bin method. Evaluate the hourly whole-building or whole-facility energy use using the inverse bin method. In this analysis, one year of hourly, whole-building energy use is sorted into outdoor temperature bins (e.g., 2.8°C (5°F) bins, 5.6°C (10°F), etc.). Each bin is then analyzed statistically using a quartile analysis to determine the median value for each bin as well as the statistical variation. The median values represent the average energy use for each ambient temperature bin (See Informative Appendix F4). Retrofit savings can then be determined by comparing the pre-retrofit energy use in each bin to the post-retrofit energy use in the corresponding bin.

Evaluate hourly energy use using a weather-daytype procedure. Evaluate the hourly whole-building or whole-facility energy use using a weather-daytype procedure (Hadley 1993; Bou-Saada and Haberl 1995). In this analysis one year of hourly, whole-building energy use is categorized into defined outdoor temperature ranges, referred to weather-daytypes (e.g., less than 7°C (45°F), 7°C (45°F) to 24°C (75°F), and greater than 24°C (75°F)). Each group is then analyzed statistically using a quartile analysis to determine the median value and statistical variation for each hour of the day by day-type (i.e., weekday, weekend). (See Informative Appendix F4) Compare weather-daytypes with previous use for the same building, use weather-daytypes for pre-retrofit and post-retrofit analyses, or compare with similar buildings in similar climates determined by annual HDD and CDD.

Evaluate hourly peak electric demand for weekdays or weekends using the ASHRAE's Diversity Factor Toolkit. ASHRAE's Diversity Factor Toolkit (RP-1093) can evaluate hourly peak demand for annual, monthly, or seasonal periods (e.g., heating or cooling). RP-1093 yields peak or 90th percentile values for each hour of the day, representing peak usage. These values can be displayed for all seven days of the week or separately for weekday and weekends. Peak values can be compared to previous usage or to similar building in similar climates as defined by CDD or HDD.

Evaluate daily ELF and OLF. Evaluate daily ELF and OLF using hourly electricity use and hourly occupancy data. Compare daily ELF and OLF profiles for the same building during previous years, or with similar buildings in similar climates as determined by HDD and CDD. Determine if there is a mismatch between the ELF and OLF indicating opportunities for reducing electric demand.

Evaluate whole-building energy use using calibrated simulation. Evaluate whole-building energy performance using calibrated, whole-building simulation. This approach uses an hourly computer simulation of the building or facility's energy use. Such a model is created from building plans, specifications, and on-site inspections of the building, including: building materials, construction, operational practices, occupancy loads, installed equipment, schedules, etc. The simulated energy use of the building is then calibrated against actual measured hourly energy consumption data, requiring the use of on-site hourly weather data that is coincident with the energy measurements. Depending on the evaluation purpose, the simulated energy use from the calibrated simulation can be compared with similar facilities in similar climates or at different locations by substituting weather files. Additionally, the simulated annual energy use can be compared to USDOE Reference Buildings (USDOE n.d. -b), or to similar buildings with varying energy code requirements.

6.3.4.2 Component-Level Energy Performance. The Level 3 component-level energy performance evaluation and benchmarks, as noted in Table 6.7, include the following:

Evaluate in-situ performance of chillers. Evaluate the in-situ performance of a chiller(s) using measurements of the chiller's electricity use and cooling production, following the methods defined by ASHRAE RP-827 (Brandemuehl et al. 1996; Phelan et al. 1997a, 1997b, and 1997c). These include: 1) single point test with manufacturer's data; 2) imposed load test for simple model; 3) imposed load test for temperature dependent model; 4) short-term monitoring test for simple model; and 5) short-term monitoring test for temperature-dependent model.

Evaluate in-situ performance of pumps. Evaluate the in-situ performance of a pump(s) using measurements of the pump's electricity use, fluid flow, and head pressure, following the methods defined by ASHRAE RP-827. These include: 1) single-point test (constant speed/constant volume); 2) single-point test with manufacturer's pump curve (constant speed/variable volume); 3) multiple-point test with imposed loads at pump (constant speed/variable volume); 4) multiple-point test with imposed loads at zones (constant speed/variable volume and variable speed/variable volume); 5) multiple-point test through short-term monitoring (variable speed/variable volume); and 6) no-flow test for pump characteristics (all types).

Evaluate in-situ performance of fans. Evaluate the in-situ performance of a fan(s), following the methods developed by RP-827. These include: 1) single-point test (constant volume); 2) single-point test with manufacturer's data (variable volume without fan control); 3) multiple-point test with imposed loads at fan (variable volume without fan control); 4) multiple-point test with imposed loads at zone (variable volume without fan control, variable volume with fan control); and 5) multiple-point through short-term monitoring (variable volume without fan control, variable volume with fan control).

Evaluate in-situ performance of non-reheat boilers/furnaces. ASHRAE Guideline 14-2023 describes three techniques for in-situ boiler performance evaluation (Chernick 1985) and discusses the advantages and applications of each. These include: the self-referent method, comparative method, and absolute method. 1) In the self-reference method, each unit's performance is determined by a self-reference standard based on the unit's past performance. This method is easy to apply, but it does not usually produce fair and even-handed results. It is stricter for those units with good performance histories than for those with poor past performance. 2) The comparative method is based on comparative analyses, which use data from other similar boilers. 3) The absolute method uses an absolute measure of proper performance, which is then compared with its design performance. ASHRAE Guideline 14-2023 also describes other methods based on the first and second laws of thermodynamics, including the entropy method and the exergy method.

Evaluate in-situ performance of lighting systems. ASHRAE Guideline 14-2023 provides six methods for evaluating lighting systems, including: 1) before/after measured lighting power levels and stipulated diversity profiles (no thermal interaction); 2) before/after measured lighting power levels and sampled before/after diversity profiles (no thermal interaction); 3) baseline measured lighting power levels with sampled diversity profiles and post-retrofit power levels with continuous diversity profile measurements (no thermal interaction); 4) baseline measured lighting power levels with baseline sampled diversity profiles and post-retrofit continuous sub-metered lighting (no thermal interaction); 5) method 1, 2, or 3 with measured thermal effect (calculated thermal interaction); and 6) before/after sub-metered lighting and thermal measurements (measured thermal interaction).

Evaluate in-situ performance of thermal storage systems. ASHRAE RP-1004 developed and tested an in-situ method for measuring the performance of a thermal storage system. The developed method includes: 1) obtain facility data and perform a data quality analysis, including: utility bills, facility electricity use, cooling plant electricity use, cooling plant load, outdoor dry-bulb temp, separate metering of chillers and pumps, and separation of data into periods of Thermal Energy Storage (TES) charging or discharging; 2) verify schedules and operating strategies of TES; 3) obtain one year of data for TES (or at least cooling season data); 4) develop models of TES such as demand model, energy use model, or baseline model; and 5) calculate energy use and demand using the developed models.

7. WATER USE

7.0 Introduction. This guideline details the measurement methods and reduction strategies for water use, from simple to complex, in three logical levels of effort. The user can determine what measurement and use reduction strategy to utilize that best fits their level of expertise and the level of detail needed to evaluate the problems in their facility, within the available budget.

Level 1 (Section 7.1) describes the **Basic Evaluation** Procedures for measuring water usage at the most basic level. Every facility should perform these basic procedures before going on to the more complex procedures of level 2 and 3.

Level 2 (Section 7.2) describes the **Diagnostic Measurement** Procedures for measuring and calculating water usage for different types of water using systems.

Level 3 (Section 7.3) describes the **Advanced Analysis** Procedures for measuring and modeling water usage over time to analyze water use reduction strategies.

7.0.1 General Introduction and Background. Reducing potable water use and the amount of waste stream flows is becoming very important to municipalities the world over, due to our increasing shortage of quality, potable water supplies. Political will is increasing in the area of control and mandates for water conservation. Building owners and operators should begin to reduce their facilities water use, to do this you first must actively measure your water use, and then take action to reduce total water use. In the past the very low cost of potable water has led some designers and building operators to ignore the cost of water and only concentrate on the higher expense of energy, but this is changing due to the increasing cost of water and the severe drought in the western U.S. limiting water supply.

Water use reduction strategy is not a one-time fix that provides the desired improvement, but rather an ongoing process that continuously measures, repairs, and adjusts water systems to maintain persistent low water usage. It is the nature of water distribution systems to deteriorate over time, causing leaks and changes to flows and pressures, which directly affect the quantity of water used.

Potable water conservation is directly coupled to energy conservation and carbon reduction due to the amount of embodied energy in supplying potable water. Water requires a great deal of energy for water treatment and pumping. Wastewater also has a significant amount of embodied energy required to transport and treat wastewater.

Detailed historical water use records and benchmark records are not readily available for most types of commercial buildings or for different types of buildings in different climates. A few local, small group studies have been published that may shed light on possible water baseline amounts, but no large study exists in the public domain that indicates a consensus regarding water use. Therefore, the best approach is to use water conservation techniques and then measure and verify actual use reduction over time. This data could then be accumulated by national organizations to begin recording historical water use by building type and location. Unfortunately, at this time a national water use baseline or benchmark database, detailed enough to be generally meaningful, does not exist. However, some groups or associations do provide assistance and procedures for managing water use in buildings. There are also design guides that provide direction to the design engineer on system design for low water consumption. Some of these guides are listed in Informative Appendix G1.

Types of water systems considered in this guideline include:

a. Sanitary Plumbing fixtures
b. Water Softeners & Filters
c. Domestic Water Supply
d. Domestic Hot Water Systems
e. Landscape Irrigation
f. Facility Cleaning Water Use
g. HVAC Cooling Towers
h. Steam Boilers
i. Kitchen Sinks & Cooking Appliances
j. Swimming Pools & Fountains
k. Process Water Use

Approaches to water use reduction include:

a. Repairing leaks
b. Use of low-flow plumbing fixtures
c. Reducing or limiting total building water pressure
d. Reducing domestic hot water load and usage
e. Reducing building cooling loads and improved cooling tower water management
f. Reducing building heating loads and improved boiler water management
g. Improving management of process water
h. Improving management of irrigation systems
i. Utilizing rain harvesting systems
j. Utilizing gray water systems

7.1 Level 1: Basic Evaluation

7.1.1 Level 1: Objective. The objective of this level of investigation is to measure the water use in your facility and to compare it to past water use and to available baselines for water use in similar buildings (See Informative Appendix G2). Without the knowledge of past water use, improvements cannot be evaluated as to the benefit of the results. The objective is to provide continuous improvements in water use reduction over time; if a system is not established to do this, persistent water use reduction will not be achieved.

7.1.2 Level 1: Metrics. In order to investigate the basic water use of a facility it is recommended that a measurement plan be developed and continuously implemented. The range of measurement methods to meet various information requirements is shown in Table 7.1.

Table 7.1 Level 1: Basic Water Use Measurements.

Type of information	Water Source	Measurement Methods	Information Source	Time interval
• Annual whole-building water use (Gallons).	• Utility water • On site well	• Whole-building utility bills • Sub-meter readings	• On-site utility meter • Building Automation System (BAS)	• Monthly
• Annual landscape irrigation water use (Gallons).	• Utility water • On site well • Reclaimed water	• Sub-meter readings • Calculated use	• Landscape utility meter • Building Automation System (BAS)	• Monthly

• Annual water use for other purposes (Gallons).	• Utility water	• Sub-meter readings • Calculated use	• On-site sub- meter for other use • Building Automation System (BAS)	• Monthly
• Annual on-site reclaimed water use (Gallons)	• Rain water collection • Condensate collection • Gray water systems	• Sub-meter readings • Calculated use	• On-site sub-meters • Building Automation System (BAS)	• Monthly
• Annual Load Factors	• Occupancy Load Factor (OLF)	• Whole-building occupancy information	• Occupant survey • Occupant measurement system	• Monthly

7.1.2.1 Water Use Measurement Plan. The following building characteristics should be documented in the water measurement plan to provide the basis for all water performance determinations and water reduction strategies:

a. Basic Facility Information: Basic information about the facility needs to be collected and recorded to use during the measurement and comparison process:
   1. Building type, function, or primary use
   2. Building size gross floor area: the sum of the floor areas of all spaces within the building, with no deductions for floor penetrations other than atria. Gross floor area is measured from the exterior faces of exterior walls or from the centerline of walls separating buildings, but it excludes covered walkways, open roofed-over areas, porches and similar spaces, pipe trenches, exterior terraces or steps, roof overhangs,
   3. parking garages, surface parking, and similar features. Number of floors included in the occupied area
   4. Estimated average number of annual occupants by gender
   5. Total annual occupied hours
   6. Cooling tower system type and size (Tons). Total capacity of all cooling towers required for base load (excluding backup or redundant cooling tower capacity)
   7. Steam boiler size (Watts, HP or Btu/h). Total capacity of all steam boilers required for base load (excluding backup or redundant boiler capacity)
   8. Location of facility (climate zone)
   9. Design water use of toilets and lavatory fixtures
   10. Design water use of on-site kitchens, food service preparation equipment, and showers (e.g., gymnasiums or dormitories), (average Liters/day [LPD] or gallons/day [GPD])
   11. Water softener size and average water hardness, cycle times and flow rates
   12. Reverse Osmosis or Deionized water systems size and standard rejection rates
   13. Descriptions of any special water uses such as kitchens, pools or fountains
   14. Process water use quantity (average LPD or GPD)

b. Landscape Water Use: The following landscape data needs to be collected to provide the basis for all water reduction strategies and calculations.
   1. Total landscaped area. Site areas that have no landscaping, such as parking lots, gravel areas or non-irrigated natural areas, should not be included in the landscape area. Distinguish between areas of native and non-native plants.
   2. Irrigation type. If landscape areas are irrigated, which type is used: drip, sprinklers or flooded
   3. Climatic zone parameters that determine estimated annual water use

c. A specific water reduction goal over time. This may be a percentage saved per year or a specific quantity over time.

d. A description of the end uses to be a part of the water reduction plan, such as building sanitary water use, landscape water use, kitchen water use, process water use, cleaning water use, etc.
e. A description of existing water meters and what meters will be used in the performance improvement process, including meter calibration information or documentation.
f. Identification of who will perform the following:
    1. Supervise the Water Use Measurement Plan and Processes
    2. Take and accumulate water use measurement data
    3. Perform the data analysis and comparisons to benchmark the data
    4. Decide on what corrections or adjustment to make
    5. Be responsible for making the corrections or adjustments
    6. Publish the results to management, operators and occupants

7.1.2.2 Measurements. At the basic level all water using systems that have meters or use data are measured. These include the following:

a. Whole building water meter utility bill use data. Record current period rate of use in liters/m^2 or (gal/ft^2) and total to-date rate of use in liters/occupant or (gal/occupant).
b. Landscape water meter utility bill or landscape water submeter use data. Record current period rate of use in liters/m^2 or (gal/ft^2) and total to-date rate of use in liters/m^2 or (gal/ft^2)
c. Record submeter water use for current period and total to-date water use for water submeters for specific uses:
    1. Kitchen water use. Record liter/meal or gal/meal served
    2. HVAC cooling tower water use. Record water use per measurement period
    3. Process water use. Record water use per production metric
    4. Pool or Fountain water use. Record water use per measurement period

7.1.3 Level 1: Measurement Methods

7.1.3.1 Utility Bill Usage Data. It is suggested that monthly readings are preferred to obtain more accuracy in the use over time. This data can be obtained from monthly utility water bills or can be taken directly from the water meter manually, or automatically by the BAS. Verify that the utility bills list actual water used and not water units. Some utilities use 748 gallons per metered unit. This data can be obtained from the utility or from your meter manufacturer.

Utility water meters are normally positive displacement meters with either dial readouts which give data in several available units such as 1, 5, 10, 50, 100, 250, 500, liters or m^3 or (1, 10, 100 or 1000 gallons) per digit or may be digital meters with standard readouts. Most large municipalities have implemented automatic meter transmitters that allow data collection by electronic transmission, which lowers their costs but does not change the monthly read interval. In the near future smart meters will allow real time data collection at any interval, which will make performance evaluation to any time interval very easy.

7.1.3.2 Water Submeters. If taking manual or local readings, verify what units the meter readout is calibrated in. This data must be obtained from the meter manufacturer. This also applies if the data is recorded by the BAS system through the meter pulse which may be a single unit or higher multiple units per pulse.

Water Submeters may be manually read or may be connected to a BAS or SCADA system for remote monitoring. For manual meters the measurement interval is normally monthly to match utility main meter data. If the meter is automated, then the interval can be programmed to either hourly, daily, weekly or monthly as desired.

7.1.3.3 Data Normalization. If using monthly data this data needs to be normalized for the number of days in the month billing cycle. Unfortunately, most utilities do not use standard days for each billing period but use actual days between meter readings which may vary by more than 8 days per month. Normalizing this data allows direct comparison with prior year, monthly or daily comparable data.

For better accuracy the data should be normalized by the total number of occupants for each measurement period, since they contribute directly to the amount of water used.

7.1.4 Level 1: Performance Evaluation and Benchmarks. The range of water use benchmarks to meet various information requirements is shown in Table 7.2.

Table 7.2 Level 1: Water Performance Evaluation and Benchmarks.

Type of information	Water Source	Measurement Methods	Benchmarks	Time interval
• Annual whole-building water use (Gallons).	• Utility water • On site well	• Whole-building utility bills • Sub-meter readings	• Previous period measurements • Energy Star Portfolio Manager • ASHRAE 90.1 Prototype Building Models	• Monthly • Annually
• Annual landscape irrigation water usage (Gallons).	• Utility water • On site well • Reclaimed water	• Sub-meter readings • Calculated use	• Previous period measurements	• Monthly • Annually
• Annual water use for other purposes (Gallons).	• Utility water	• Sub-meter readings • Calculated use	• Previous period measurements	• Monthly • Annually
• Annual on-site reclaimed water use (Gallons)	• Rain water collection • Condensate collection • Gray water systems	• Sub-meter readings • Calculated use	• Previous period measurements	• Monthly • Annually

7.1.4.1 Comparing Measured Data. The basic evaluation process is to take measurements on a monthly basis, record them and compare them to the past month's use and to the previous year's measurement for that period, and the period to date.

7.1.4.2 Comparing to Baseline or Benchmark Databases. Once past use is established, use Energy Star Portfolio Manager or other national databases to rate the existing facility water use to water use of similar facilities in similar climates. Record this rating for future reference when comparing future results.

7.1.5 Performance Improvement Evaluation. A walk-through of the building should be conducted to identify wateruse issues. Any observed water use issues such as pipe leaks, leaks from plumbing fixtures or leaks and overflowing of landscape irrigation systems should be noted.

7.1.5.1 Water Pressure. Lower the building supply water pressure to the lowest level possible that still allows the top-most fixture to operate adequately, normally from 35 to 45 PSI at the highest fixture. Higher pressure causes fixtures to use more water than intended.

7.1.5.2 Eliminate Water Leakage. The first and most important method is done by eliminating any observed water pipe leaks, leaking plumbing fixtures or leaking or overflowing landscape watering systems.

7.1.5.3 Upgrading Plumbing Fixtures. The second method is to improve the water use efficiency of existing plumbing fixtures by upgrading the fixture or adding water restrictors at the fixture.

7.1.5.4 Lower Landscape Irrigation Water Use. Reduce the amount of water used for landscaping by eliminating all leaks and overwatering of plants.

7.1.5.5 Once Corrections are made, Reevaluate Performance. Once any changes are made each correction is tested to verify the correction actually improved the operation of the system and lowered water use (see Figure 7.1). To evaluate the results of the changes for the whole building, perform the following procedure:

a. Re-measure Water Use Performance: This can be done by using the next utility bill or by taking manual meter readings. If taking manual readings make sure the time duration sampling periods are the same as previous sampling periods.
b. Compare new Results to Past Results: Using the new period measurements compare this time period to the past year during the same time period to determine if the adjustments or corrections have made a difference in water use characteristics. Be aware that variances in the number of building occupants

or schedules will change water use due to increased use of plumbing facilities and increased load on HVAC systems. If it is desired to normalize present use for these variances, use the Diagnostic Measurement level procedures (Level 2) of this chapter, which include procedures for water use calculations and normalization.

c. Report Results: It is important that building operators and occupants be made aware of how successful the recent water reduction efforts have been. The actions of building occupants and operators will have a large effect on water use.

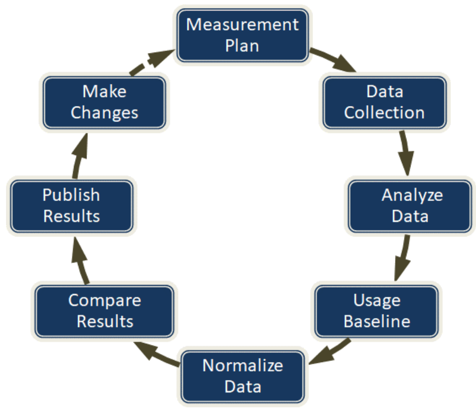


Figure 7.1 Water Performance Improvement Process (ASHRAE 2012).

7.2 Level 2: Diagnostic Measurement

7.2.1 Level 2: Objective. The objective of this level is to determine detailed diagnostic analysis and related calculations and measurements for each type of water using system to provide a more granular view of water use. This will allow insight to more water saving corrections and allow the analysis of costs and paybacks on an individual correction basis.

7.2.2 Level 2: Metrics.

Measurement Metrics. To determine the detailed water use of water using equipment and systems, the following analytic metrics in Table 7.3 are used in isolation to determine predicted water usage.

Table 7.3 Level 2: Water Use Systems Metrics

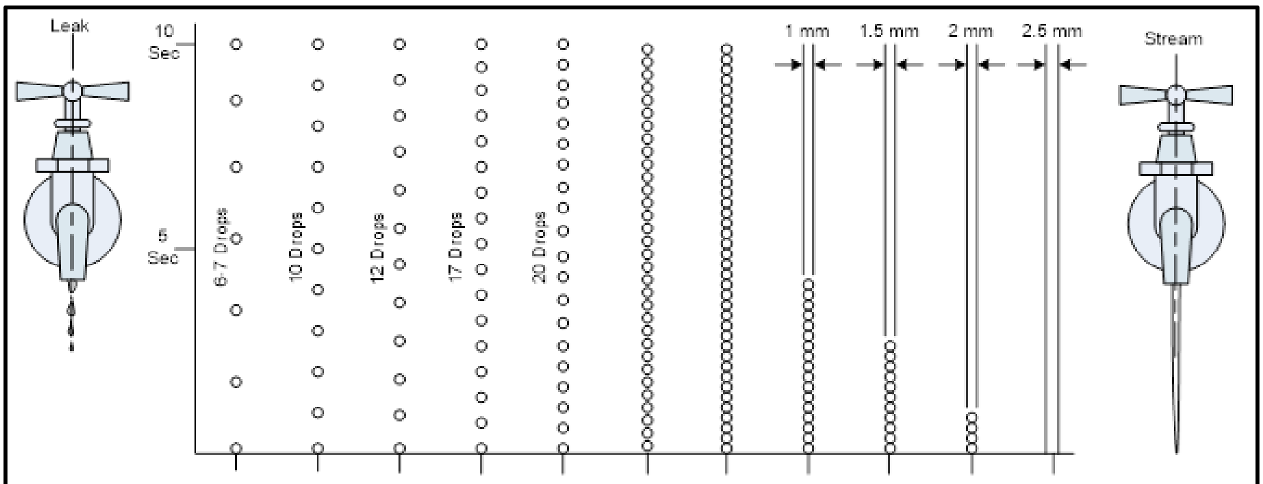
Type of information	Water Source	Measurement Methods	Water Usage Data Source	Variables	Time interval[1]
• Water Leaks	• Utility water	• Observation • Sub-meter readings	• Analysis	• Water Pressure	• Hourly • Daily • Monthly
• Building Equipment or System water use	• Utility water • On site well	• Whole-building utility bills • Sub-meter readings	• Calculation	• Pressure • Occupancy • System Load • Water TDS • Schedule	• Hourly • Daily • Monthly
• landscape irrigation	• Utility water • On site well • Reclaimed water	• Sub-meter readings • Calculated use	• Calculation	• Water Pressure • Area • Vegetation Type • Weather • Schedule	• Monthly

• Exterior pools & Fountains	• Utility water • On site well • Reclaimed water	• Sub-meter readings • Calculated use	• Calculation	• Weather • Surface Area	• Monthly

1. Time interval must be the same as the measurement source data interval or multiple of the measurement source. For hourly or daily data, the water meter data collection must be daily, or hourly and totaled to daily values.

Analytic Metrics. The calculations for this section are intended to be used to determine the water use for each system in isolation; for whole building water use modeling see Advanced Level 3, section 7.3. For each of the following systems, water use can be calculated based on facility and occupant information.

7.2.2.1 Water Leaks. Water leaks from pipes and fixture faucets can be estimated by using Figure 7.2. Counting the number of drops over a 10 second time period or the width of the continuous stream determines the total amount of flow over time, as shown in the columns in the Table 7.4 based on the size of the opening and the pressure in the pipe. See Informative Appendix G3.1 for leak water use example calculations.



0.5	0.7	0.9	1.3	1.8	3.0	4.0	9.0	18.0	25.0	36.0	Liter/Hour
12.0	16.8	21.6	31.2	43.2	72.0	96.0	216.0	432.0	600.0	864.0	Liter/Day
4.4	6.1	7.9	11.4	15.8	26.3	35.0	78.8	157.7	219.0	315.4	m^3/Year
0.1	0.2	0.2	0.3	0.5	0.8	1.1	2.4	4.8	6.6	9.5	Gallons/Hour
3	4	6	8	11	19	25	57	114	159	228	Gallons/Day
1,157	1,620	2,083	3,009	4,166	6,943	9,258	20,830	41,659	57,860	83,318	Gallons/Year

Figure 7.2 Water Losses Due to Leaks in Fixtures (Association of German Engineers 2015).

Table 7.4 Water Losses at 5 Bar Pressure Due to Pipe Leaks (Association of German Engineers 2015[a,b]).

Opening Size			GPM	Gallons /Day	Gallons /Year	Liters /Sec	Liters /Hour	m^3 /Day	m^3 /Year
Inch	16^{th} Inch	mm							
0.0197	0.3152	0.5	0.079	114	41,655	0.005	18	0.43	158
0.0394	0.6304	1.0	0.254	365	133,295	0.016	58	1.38	505
0.0591	0.9456	1.5	0.476	685	249,928	0.030	108	2.59	946
0.0787	1.2592	2.0	0.840	1,210	441,539	0.053	191	4.58	1,671
0.0984	1.5744	2.5	1.347	1,940	708,128	0.085	306	7.34	2,681
0.1181	1.8896	3.0	2.156	3,104	1,133,005	0.136	490	11.75	4,289
0.1378	2.2048	3.5	2.980	4,291	1,566,213	0.188	677	16.24	5,929
0.1548	2.4768	4.0	3.915	5,638	2,057,737	0.247	889	21.34	7,789
0.1771	2.8336	4.5	4.818	6,939	2,532,599	0.304	1,094	26.27	9,587
0.1968	3.1488	5.0	5.896	8,491	3,099,101	0.372	1,339	32.14	11,731

0.2165	3.4640	5.5	6.879	9,906	3,615,618	0.434	1,562	37.50	13,687
0.2362	3.7792	6.0	7.925	11,412	4,165,459	0.500	1,800	43.20	15,768
0.2590	4.1440	6.5	8.987	12,941	4,723,630	0.567	2,041	48.99	17,881
0.2756	4.4096	7.0	10.398	14,973	5,465,082	0.656	2,362	56.68	20,688

a. Association of German Engineers VDI 3807 Part 3 Table 21

b. Correction factors for different pressures

0.5 Bar 7.3 psi 26%	1 Bar 14.5 psi 45%	2 Bar 29.0 psi 63%	3 Bar 43.5 psi 77%
4 Bar 58.0 psi 77%	5 Bar 72.5 psi 100%	6 Bar 87.0 psi 108%	7 Bar 101 psi 118%
8 Bar 116 psi 125%	9 Bar 130 psi 132.5%	10 Bar 145 psi 140%	

7.2.2.2 Plumbing Fixtures Water Use. Allowable flows for plumbing fixtures in the United States are regulated by the US DOE and individual states. The current DOE standard is DOE/EE-0264 1992 with updates through 2000. European plumbing fixture water use is based on a voluntary recommended labeling program by the EU, but many countries have their own water use standard. Predicted water use for plumbing fixtures can be estimated using the formulas for each type of fixture shown below and using the water use quantities from Tables 7.5 and 7.6. See Informative Appendix G3.2 for plumbing fixture water use example calculation.

a. Water Closets: Water closets are rated in volume per flush and the number of flushes a day by male and female occupants. To find the predicted water use multiply number of occupants by the use factor, times the flow per fixture efficiency as shown in Tables.
   Liters (or Gallons) per day = Number of Occupants x Average Usage per day x Flow
b. Urinals: Urinals are rated in volume per flush and the number of flushes a day by male occupants. To find the predicted water use multiply number of occupants by the use factor, times the flow per fixture efficiency.
   Liters (or Gallons) per day = Number of Occupants x Average Usage per day x Flow
c. Sinks & Lavatories: Sink and lavatory flows vary depending upon the type of fixture trim and the water supply pressure. The flow ratings indicated in Tables 7.5 and 7.6 are based on standard system pressure from 2 to 5 Bar (29 PSI to 74 PSI). Pressures outside this range may change the amount of flow and affect the performance of the fixture. Note that the tables also indicate flow ratings for both cold and hot water for fixtures that have both cold and tempered water. To find the predicted water use multiply number of occupants by the use factor, times the flow per fixture efficiency. Note that average length of time per use is listed. If faucets are set for longer or shorter duration, flow must be adjusted by an equal percentage to the on time.
   Liters (or Gallons) per day = Number of Occupants x Average Usage per day x Flow
d. Showers: Shower flows vary depending on the type of fixture trim and the water supply pressure. The flow ratings indicated in Tables 7.5 and 7.6 are based on standard system pressure from 2 to 5 Bar (29 PSI to 74 PSI). Pressures outside this range may change the amount of flow and affect the performance of the fixture. To find the predicted water use, multiply number of occupants by the use factor, times the flow per fixture efficiency. Note average length of time per use is listed; if shower is set for longer or shorter duration flow must be adjusted by an equal percentage to the on time.
   Liters (or Gallons) per day = Number of Occupants x Average Usage per day x Flow
e. Bathtubs: Bathtub water use depends on the size of the tub and how much water is utilized per use. Tables utilize a 40% fill for water calculations.
   Liters (or Gallons) per day = Fixture Water Use x Number of Uses per day
f. Trap Primers: Water trap primer flows, both electrical and mechanical types, are based on the recommended drip setting of the primer. To find the predicted water use multiply the number of trap primers times the volume per day flow factor. Note that this flow is based on one drop every 8 seconds time period. Trap primers not set to this standard will use more or less water; use Figure 7.2 to adjust the flow to match the drip time of the primer. To find the predicted water use, multiply the number of trap primers by the daily amount of flow.
   Liters (or Gallons) per day = Number of primers x Flow per day

g. Clothes Washers (Residential Type): Residential type clothes washer water use can be predicted by multiplying the total number of occupants times the usage per day times the flow per fixture efficiency type. If the actual number of wash cycles is known then those values should be used. For commercial clothes washers use actual unit flow information.
   Liters (or Gallons) per day = Number of Occupants x Average Use per day x Flow
h. Dishwashers (Residential Type): Residential type dishwashers use can be predicted by multiplying the total number of occupants times the use per day times the flow per fixture efficiency. If the actual number of wash cycles is known then those values should be used. For commercial dish washers, use actual unit flow information.
   Liters (or Gallons) per day = Number of Occupants x Average Use per day x Flow
i. Clean up: Cleaning water use for plumbing fixtures can be predicted by multiplying the total number of fixtures, times the cleaning volume, times the number of times the fixture is cleaned per day.
   Liters (or Gallons) per day = Number of fixtures x Flow x Times cleaned per day
j. Keys to Accuracy for Calculating Flow: Plumbing fixture flows determined by codes are grossly over stated for actual operation and lower flows are almost always indicated by field measurements. The key to making accurate determination of actual average fixture water flow is to accurately predict the number of uses and to know the normal water flow per fixture type per use.
   1. Water Closets: For tank type water closets, measure the amount of water in the tank that is used by each flush. For flush valve water closets, measure the flow of the fixture over the valve time cycle. This can be done with a special water closet flow meter that is installed in the inlet of the trap or by estimating the equivalent gallons per flush.
   2. Urinals: Urinal flow is measured the same as a water closet with a flush valve
   3. Sinks: For manual sink faucets you need to measure flow of the faucet at full flow and then estimate the average time per use. For auto faucets measure the flow over the auto faucets time cycle. This can be done by capturing the water into a measurable container for one minute or for the total time of the cycle.
   4. Showers: For showers you can measure the flow of the shower head by capturing the water into a measurable container for one minute and then multiplying that times the average use time.
   5. Trap Primers: For trap primers use Figure 7.2 to determine the flow rates of the drip pattern
   6. Clothes Washers: Determine the flow of each wash cycle from the washer manufactures literature.
   7. Dishwashers: Determine the flow of each wash cycle from the washer manufactures literature.
   8. Clean Up: Flow for hoses used for cleaning can be determined from Table 7.15.
k. Use Factor: The values shown in the following tables are based on code and reasonable average uses but tend to be on the maximum side. To more closely match actual use, a use factor of between 75% to 80% may be applied. This factor can be calibrated by comparing actual use to predicted use over time.

Table 7.5 SI Plumbing Fixture Water Use[a].

Item	Water Use				Usage								
	High Flow	Standard	Low Flow	Unit	Male Use	Female Use	Male Visitor Use	Female Visitor Use	Units	Cleaning	Units	Time (Minutes)	Units
Symbol	HF	MF	LF		M	F	MV	FV		C		T	
Sanitation													
Water Closet Tank Type	13.0	6.0	3.5	lpf	1.0	3.0	0.1	0.5	fpdpp	1.0	fpd		
Water Closet Dual Flush Tank Type (Low Flush)	6.5	4.5	3.0	lpf	1.0	2.0	0.1	0.3	fpdpp	1.0	fpd		
Water Closet Flush Valve	13.0	6.0	3.5	lpf	1.0	3.0	0.1	0.5	fpdpp	1.0	fpd		
Water Closet Flush Valve Dual Flush Type (Low Flush)	6.5	4.5	3.0	lpf	1.0	2.0	0.1	0.5	fpdpp	1.0	fpd		
Urinal	6.0	4.0	1.0	lpf	2.0		0.4		fpdpp	1.0	fpd		
Waterless Urinal	0.0	0.0	0.0	lpf	2.0		0.4		fpdpp	1.0	fpd		
Lavatory Faucet (Cold Water Only)	15.1	13.0	6.0	lm	3.0	3.0	0.5	0.5	upd	1.9	lpd	0.15	mpu
Lavatory Faucet (Tempered CW Component)	7.6	6.5	3.0	lm	3.0	3.0	0.5	0.5	upd	1.9	lpd	0.15	mpu
Lavatory Faucet Automatic (Cold Water Only)	2.3	2.0	0.9	lpv	3.0	3.0	0.5	0.5	upd	1.9	lpd	0.15	mpu
Lavatory Faucet Automatic (Tempered CW Component)	1.1	1.0	0.5	lpv	3.0	3.0	0.5	0.5	upd	1.9	lpd	0.15	mpu
Sink Faucet (Cold Water Only)	15.1	13.0	6.0	lm	1.0	1.0			upd	1.9	lpd	0.25	mpu
Sink Faucet (Tempered CW Component)	7.6	6.5	3.0	lm	1.0	1.0			upd	1.9	lpd	0.25	mpu
Shower (Cold Water Only)	15.1	13.0	6.0	lm	0.1	0.1			upd	1.9	lpd	5.00	mpu
Shower (Tempered CW Component)	7.6	6.5	3.0	lm	0.1	0.1			upd	1.9	lpd	5.00	mpu
Bathtub (Tempered CW Component)	50.0	40.0	31.0	lpu									
Trap Primer	12.1	12.1	12.1	lpd									
Hot Water													
Lavatory Faucet (Hot Water Only)	15.1	13.0	6.0	lm	3.0	3.0	0.5	0.5	upd	1.9	lpd	0.15	mpu
Lavatory Faucet (Tempered HW Component)	7.6	6.5	3.0	lm	3.0	3.0	0.5	0.5	upd	1.9	lpd	0.15	mpu
Lavatory Faucet Automatic (Tempered HW Component)	1.1	1.0	0.5	lpv	3.0	3.0	0.5	0.5	upd	1.9	lpd	0.15	mpu
Sink Faucet (HW Only)	15.1	13.0	6.0	lm	1.0	1.0			upd	1.9	lpd	0.25	mpu
Sink Faucet (Tempered HW Component)	7.6	6.5	3.0	lm	1.0	1.0			upd	1.9	lpd	0.25	mpu
Shower (Tempered HW Component)	7.6	6.5	3.0	lm	0.1	0.1			upd	1.9	lpd	5.00	mpu
Bathtub (Tempered HW Component)	50.0	40.0	31.0	lpu									
Clothes Washer (Residential)	100.0	50.0	60.0	lpu	1.0	1.0			upd				
Dishwasher (Residential)	40.0	30.0	20.0	lpu	0.2	0.2			upd				

a. Data taken from Europeanwaterlabel.eu

Table 7.6 (IP) Plumbing Fixture Water Use[a].

Item	Water Use				Usage								
	Std After 1990	EPA Act 1997	Low Post 2000	Unit	Male Use	Female Use	Male Visitor Use	Female Visitor Use	Units	Cleaning	Units	Time (Minutes)	Units
Symbol	**S**	**L**	**VL**		**M**	**F**	**MV**	**FV**		**C**		**T**	
Sanitation													
Water Closet Tank Type	3.5	1.6	1.28	gpf	1	3	0.1	0.5	fpdpp	1	fpd		
Water Closet Dual Flush Tank Type (Low Flush)	1.6	1.1	0.8	gpf	1	2	0.1	0.3	fpdpp	1	fpd		
Water Closet Flush Valve	3.5	1.6	1.28	gpf	1	3	0.1	0.5	fpdpp	1	fpd		
Water Closet Flush Valve Dual Flush Type (Low Flush)	1.6	1.1	0.8	gpf	1	2	0.1	0.5	fpdpp	1	fpd		
Urinal	1.5	1	0	gpf	2		0.4		fpdpp	1	fpd		
Urinal High Efficiency (HEU)	1	1	0.5	gpf	2		0.4		fpdpp	1	fpd		
Lavatory Faucet (Cold Water Only)	4	2.5	0.5	gpm	3	3	0.5	0.5	upd	0.5	gpd	0.15	mpu
Lavatory Faucet (Tempered[b] CW Component)	2	1.25	0.25	gpm	3	3	0.5	0.5	upd	0.5	gpd	0.15	mpu
Lavatory Faucet Automatic (Cold Water Only)	1	0.25	0.25	gpv	3	3	0.5	0.5	upd	0.5	gpd	0.15	mpu
Lavatory Faucet Automatic (Tempered CW Component)	0.5	0.13	0.13	gpv	3	3	0.5	0.5	upd	0.5	gpd	0.15	mpu
Sink Faucet (Cold Water Only)	2.5	1	1	gpm	1	1			upd	0.5	gpd	0.25	mpu
Sink Faucet (Tempered[b])	1.25	0.5	0.5	gpm	1	1			upd	0.5	gpd	0.25	mpu
Shower (Cold Water Only)	1.5	2.5	1.5	gpm	0.1	0.1			upd	0.5	gpd	5	mpu
Shower (Tempered[b])	1.75	1.25	0.75	gpm	0.1	0.1			upd	0.5	gpd	5	mpu
bathtub (Tempered[b] CW Component)	15	12	9	gpu									
Trap Primer	3.2	3.2	3.2	gpd									
Hot Water													
Lavatory Faucet (Hot Water Only)	4	2.5	0.5	gpm	3	3	0.5	0.5	upd	0.5	gpd	0.15	mpu
Lavatory Faucet (Tempered HW Component)	2	1.25	0.25	gpm	3	3	0.5	0.5	upd	0.5	gpd	0.15	mpu
Lavatory Faucet Automatic (Tempered HW Component)	0.5	0.13	0.13	gpv	3	3	0.5	0.5	upd	0.5	gpd	0.15	mpu
Sink Faucet (HW Only)	2.5	1	1	gpm	1	1			upd	0.5	gpd	0.25	mpu
Sink Faucet (Tempered HW Component)	1.25	0.5	0.5	gpm	1	1			upd	0.5	gpd	0.25	mpu
Shower (Tempered[b] HW Component)	1.75	1.25	0.75	gpm	0.1	0.1			upd	0.5	gpd	5	mpu
Bathtub (Tempered[b] HW Component)	15	12	9	gpu									
Clothes Washer (Residential)	50	45	25	gpu	1	1			upd				
Dishwasher (Residential)	13	13	6	gpu	0.2	0.2			upd				

a. U.S. Department of Energy DOE/EE-0264 1992 and ANSI/ASME A112.19.2 3

b. Tempered water calculated as 50% HW to 50% CW

7.2.2.3 Cooling Tower Water Use (Delta Cooling Towers, 2021). Cooling towers use a large quantity of water to cool condenser loads. The amount of water used depends on the total amount of heat, the temperature of the fluid and the ambient dry-bulb and wet-bulb air temperatures. To calculate the predicted water use, from the total HVAC load, determine the average condenser water flow rate or the average chiller cooling load in Wh or Btu/h and average differential temperature between the inlet and outlet water. Use the specified design for cooling basin cycles of concentration or use actual chemical service records to determine average cycles of concentration. Use the following formulas to determine water use:

a. SI Units

1. **Average annual Condenser water load (Q)**, not needed if average condenser flow is known
2. **Average Condenser Flow (C)**, if not known C = (Average Chilled Water Load in Wh/((T1 – T2) x 1152.1599),
   where 1152.1599 is the constant for standard water properties at 32.2°C, for density and specific heat at ambient conditions of 35°C. Rule of thumb for HVAC applications.
3. **Evaporation Loss (E)** m^3/h = 0.0015179 x C x (T1 – T2),
   where C = Condenser flow m^3/h,
   T1 – T2 = inlet water temperature minus outlet water temperature ^oC,
   0.0015179 is the evaporation constant (rule of thumb for 35^{o}C water). Evaporation rate varies based on the enthalpy of vaporization, which is dictated by the temperature of the water and the dry-bulb and wet-bulb temperatures of the air.
4. **Drift Loss (D)** = 0.02% of condenser water flow (rule of thumb)
   Drift loss is entrained water in the tower discharge vapor. Drift loss in cooling tower is a function of drift eliminator design and wind velocities.
5. **Cycles of Concentration (COC)**. COC is best described as the ratio of chloride content in circulation water and in makeup water. Cycle of concentration for normal water treatment is 3-4 cycles. When using standard water treatment chemistry where cycles of concentration are below 3 the quantity of blowdown water is increased; when cycles are over 4, scaling of the tower and piping may occur.
6. **Blowdown (BD)** = (E – (COC – 1) x D) / (COC – 1)
   Blowdown is a portion of circulating water that is discharged in order to lower solids concentration due to evaporation of the condenser water. The requirement of blowdown is related to the cycles of concentration (COC).
7. **Total cooling water makeup m^3/h (MU)** = evaporation loss (E) + drift loss (D) + blowdown (BD).
8. **Annual Cooling Tower Water Use m^3** = MU x annual operating hours

b. (IP Units)

1. **Average annual Condenser water load (Q)**, not needed if average condenser flow is known
2. **Average Condenser Flow (C)**, if not known = (Average Chilled Water Load Btu/hr/ (500 x ΔT)) x 1.3,
   where 500 is the constant for standard water properties at 60°F, density is 8.33 lbs. per gallon for water with a specific heat of 1 Btu/lb-°F and 1.3 is the heat of compression factor (rule of thumb).
3. **Evaporation Loss (E)** GPM = 0.00085 x C x (T1 – T2),
   where C = Condenser flow GPM,
   T1 – T2 = inlet water temperature minus outlet water temperature ^oF,
   0.00085 is evaporation constant (rule of thumb for 85^o to 95^o water). Evaporation rate varies based upon the enthalpy of vaporization which is dictated by the temperature of the water and the dry-bulb and wet-bulb temperatures of the air.
4. **Drift Loss (D)** = 0.02% of condenser water flow (rule of thumb).
   Drift loss is entrained water in the tower discharge vapor. Drift loss in a cooling tower is a function of drift eliminator design and wind velocities.

5. **Cycles of Concentration (COC)**. COC is best described as the ratio of chloride content in circulation water and in makeup water. Cycle of concentration for normal water treatment is 3-4 cycles. When using standard water treatment chemistry where cycles of concentration are below 3 the quantity of blowdown water is increased; when cycles are over 4, scaling of the tower and piping may occur.
6. **Blowdown (BD)** = (E – (COC – 1) x D) / (COC – 1)
   Blowdown is a portion of circulating water that is discharged to lower solids concentration due to evaporation of the condenser water. The requirement of blowdown is related to the cycles of concentration (COC).
7. **Total cooling water makeup GPM (MU)** = evaporation loss (E) + drift loss (D) + blowdown (BD).
8. **Annual Cooling Tower Water Use Gallons** = MU x annual operating hours x 60

Key to Accuracy for Calculating Flow: An accurate cooling tower flow calculation depends on the average system load or condenser flow (Table 7.7). This amount needs to be the average over the measurement period of time. If using the system load, this number can be obtained from either the integrated heat gain or the energy model. Normal measurement time periods are days, months or annual, if using a model then you can use hourly, as long as you adjust the calculation for hourly ambient conditions.

See Informative Appendix G3.3 for cooling tower water use example calculations.

Table 7.7 Maximum Cooling Tower Water Use at Full Load[a]

Chiller KW	Chiller Tons	COC Cycles of Concentration											
		1.5		2		2.5		3		3.5		4	
		m^3/h	GPM	m^3/h	GPM	m^3/h	GPM	m^3/h	GPM	m^3/h	GPM	m^3/h	GPM
352	100	76	337	56	245	49	214	45	199	43	190	42	184
703	200	236	1,040	153	673	125	551	111	490	103	453	97	428
1,055	300	480	2,111	292	1,285	229	1,010	198	872	179	789	167	734
1,407	400	806	3,550	473	2,081	361	1,591	306	1,346	272	1,200	250	1,102
1,758	500	1,216	5,355	695	3,060	521	2,295	434	1,913	382	1,683	348	1,530
2,110	600	1,710	7,528	959	4,223	709	3,121	584	2,570	509	2,240	459	2,020
2,462	700	2,287	10,067	1,265	5,569	924	4,070	754	3,320	652	2,870	584	2,570
2,814	800	2,947	12,974	1,612	7,099	1,168	5,141	945	4,162	812	3,574	723	3,182
3,165	900	3,691	16,249	2,002	8,813	1,439	6,334	1,157	5,095	988	4,351	876	3,856
3,517	1,000	4,518	19,890	2,433	10,710	1,738	7,650	1,390	6,120	1,182	5,202	1,043	4,590

a. Tabulated values are only appropriate for systems where the evaporation rate is greater than cycles -1. For systems with less evaporation rate than cycles-1 use BD = ((E+(COC-1) X D)/(COC-1).

7.2.2.4 Steam Boiler Water Use (Armstrong International, Inc. 2015). Steam boiler water use is caused by any of the following:

a. Steam heat exchangers that do not return steam to the boiler but discharge all condensate to plumbing drains
b. Steam injected into products or food
c. Steam injected into air for humidification
d. Flash Steam from atmospheric receivers and condensate tanks
e. Flash Steam from trap and pipe leaks
f. Boiler blowdown required to regulate the Total Dissolved Solids (TDS) of the boiler

To calculate the amount of water used by a steam system, first calculate the percentage of condensate return from the steam loads. Once the percentage of return is estimated the boiler blowdown and the flash steam water losses are calculated which, are added to the amount of water not returned through the condensate system. The following data needs to be known or estimated to calculate the blowdown and flash steam water losses:

a. Estimate of the percentage of condensate return: Total all steam rates for loads that do not return condensate to the boiler system, such as loads that inject the steam into the air or products or discharge condensate into plumbing drain systems. Convert the pounds per hour steam rate into percentage of total steam rate.

b. Calculation of the blowdown water loss: Using the following formula, calculate the boiler blowdown loss:

$$B = \frac{S \; x \; m}{b - m}$$

S = Average Steam Rate
B = Boiler Water Maximum TDS
M = Makeup Water TDS
R = Fraction of condensate return

c. Calculation of the amount of flash steam water loss: Flash steam occurs any time live steam is discharged into an atmospheric tank for condensate return or into a flash tank for discharge into a sewer system; both losses are calculated the same. Using the following formula (Tables 7.8 and 7.9), calculate all flash steam losses:

SI Units

Table 7.8 Partial SI Steam Table.

Gauge P	Temp	SH Liquid	LH of Evap.	Volume
kPa	**^{0}C**	**kJ/kg**	**kJ/kg**	**m^3/kg**
0.0	101.3	419.1	2,257	1.67
28.6	107.1	449.2	2,238	1.33
118.7	123.3	517.6	2,193	0.81
178.7	131.2	551.4	2,170	0.65
448.7	155.5	655.8	2,096	0.34
698.7	170.4	720.9	2,047	0.24
848.7	177.7	752.8	2,021	0.20

$$FS = \left(\frac{SH - SL}{H}\right) x \; 220.462$$

(IP Units)

Table 7.9 Partial IP Steam Table.

Gauge P	Temp	SH Liquid	LH of Evap.	Volume
PSI	**^{0}F**	**Btu/lb**	**Btu/lb**	**ft^3/lb.**
0	212.0	180.0	970.0	26.8
5	227.0	195.0	960.0	20.1
14	248.0	216.0	947.0	14.3
24	265.0	233.0	934.0	10.8
65	312.0	282.0	901.0	5.5
100	338.0	309.0	880.0	3.9
125	353.0	325.0	868.0	3.2

$$FS = \left(\frac{SH - SL}{H}\right) x \; 100$$

d. Calculation of total makeup water to the steam system: To obtain the total makeup water for the steam system, add the non-return condensate amount to the blowdown and flash steam loss.

$$Make\ Up = Non - Return\ Steam + Blowdown + Flash\ Loss$$

e. Key to Accuracy for Calculating Flow.
   1. The first measurement that affects accurate steam boiler flow calculations is an accurate average steam flow rate. This amount needs to be the average over the measurement period. If

using the system load this number can be obtained from either the integrated heat gain or an energy model. Normal measurement time periods are days, months or annual, if using a model then you can use hourly as long as you adjust the calculation for hourly ambient conditions.

2. The second measurement that greatly affects the accuracy of the boiler water use is the average amount of steam condensate returned to the boiler. This can be measured by using a flow meter on the condensate return line back to the boiler or receiver. If no flow meter exists it can be determined by recording the condensate pump run time over the measurement period and multiplying it by the pump flow rate.

See Informative Appendix G3.4 for steam system water use example calculations.

7.2.2.5 Landscape Water Use (USGBC LEED-NC, 2005). Landscape irrigation is the second largest water use in most buildings. Irrigation systems are prone to using more water than needed due to constant changes to the system, system leaks and landscapers not properly adjusting emitter flow to that required for the vegetation. To calculate the predicted water flow for a landscape system, use the following process:

a. Obtain Evapotranspiration Rate (ETO) from local meteorological sources and determine vegetation type and the species factor, density factor and the microclimate factor. ETO is typically expressed in units of inches of water evaporated per month. An ETO calculator by zip code can be found at: http://www.rainmaster.com/historicET.aspx. This gives ETO values by month.
   The species factor is separated into low, medium, and high water use as a function of plant species, whereas the plant species density factor accounts for shading of the planting area. A low-density factor is where trees and plantings shade 60% of the ground, an average density factor is where trees and plantings shade 90-100% of the ground, and high density is where a tree canopy fully shades plantings.
   The microclimate factor accounts for areas that allow sun or wind to increase the evaporation rate of the soil. High microclimate factors are parking lots, west sides of buildings, west and south side of slopes, meridians and areas exposed to wind tunnel effects. Low microclimate factors include shaded areas, areas protected from the wind, north sides of buildings, courtyards, areas shaded by building overhangs and north sides of slopes.
   1. Step 1. Determine Reference Evapotranspiration Rate (ETL)
      $ET_L = ET_O \times K_L$, using the landscape factors from Table 7.10, and
      $K_L = K_S \times K_D \times K_{MC}$

Table 7.10 Landscape Factors[a].

	Species Factor (K_S)			Density Factor (K_D)			Microclimate Factor (K_{MC})		
Vegetation Type	**Low**	**Avg.**	**High**	**Low**	**Avg.**	**High**	**Low**	**Avg.**	**High**
Trees	0.2	0.5	0.9	0.5	1.0	1.3	0.5	1.0	1.4
Shrubs	0.2	0.5	0.7	0.5	1.0	1.1	0.5	1.0	1.3
Groundcovers	0.2	0.5	0.7	0.5	1.0	1.1	0.5	1.0	1.2
Mixed trees, shrubs & groundcover	0.2	0.5	0.9	0.6	1.1	1.3	0.5	1.0	1.4
Turfgrass	0.6	0.7	0.8	0.6	1.0	1.0	0.8	1.0	1.2

a. USGBC LEED-NC v2.2 2005

K Factor Definitions for Table 7.10

K_S = 0 for native species (no irrigation)
K_S = Low. For adaptative species. Low watering.
K_S = Average. For adaptative species. High watering.
K_S = High. For invasive species.
K_D = Low. If leaf shading is less than 60% ground coverage
K_D = Average. If leaf shading is greater than 60% but less than 90% ground coverage
K_D = High. If leaf shading is 100% ground coverage

K_{MC} = Low. Areas protected from wind and sun, such as court yards and north shaded areas
K_{MC} = Average. Areas only partially protected from wind and sun.
K_{MC} = High. Areas exposed to wind and sun, such as parking lots, west and south exposures, and areas with wind tunnel effects.

2. **SI Units**
Step 2. Calculate water use in Liters by using the irrigation type factors from Table 7.11:
$K_L = K_S \times K_D \times K_{MC}$
TWA= Area x (ET_L/IE) x CE x ETO where area is expressed in m^2 and ET_L is in CM.
TPWA= (TWA x 12) – Reuse Water
where TWA is irrigation water use and TPWA is potable water use.

Table 7.11 SI Irrigation Type.

Type	IE	CE Dry Climate	CE Wet Climate
Sprinkler	0.099	0.25	0.5
Drip Irrigation	0.1425	0.25	0.5

(IP Units)
Step 2. Calculate water use in Gallons by using the irrigation type factors from Table 7.12:
$K_L = K_S \times K_D \times K_{MC}$
TWA= Area x (ET_L/IE) x CE x ETO where area is expressed in ft^2 and ET_L is in inches.
TPWA= (TWA x 12) – Reuse Water
where TWA is irrigation water use and TPWA is potable water use.

Table 7.12 IP Irrigation Type.

Type	IE	CE Dry Climate	CE Wet Climate
Sprinkler	0.625	0.25	0.5
Drip Irrigation	0.9	0.25	0.5

b. Keys to accuracy for calculating flow. Average flows for landscape irrigation systems are obtained by running each zone for one minute and determining flow from the landscape water meter. If the system does not have a flow meter you can use a temporary ultrasonic flow meter to obtain the base rate. System flow is then determined by multiplying each zones flow by the operating time of each zone cycle.

See Informative Appendix G3.5 for landscaping water use example calculation.

7.2.2.6 Water Softener Water Use. Salt based water softeners use a salt brine to backflush a resin bed to charge the bed with a negative sodium ion. During normal use with water flowing over the resin, any dissolved magnesium and calcium minerals that naturally have a positive charge will be held by the resin before releasing a sodium ion to the water. Once the hardness minerals have been removed, the water is naturally softened. Backflush water is piped to the drain lines and is considered wasted and not used by the system. The calculations below assume the softener system is a flow-based control cycle and not a time-based cycle where the softener keeps track of the total flow of water processed before entering a backwash cycle.

Table 7.13 Water Hardness Scale.

Classification	Grains/Gallon	mg/l & ppm
Soft	< 1	< 17.1
Slightly Hard	1 - 3.5	17.1 - 60
Moderately Hard	3.5 - 7	60 - 120
Hard	7 - 10	120 - 180
Very Hard	> 10	> 180

a. To calculate the amount of backflush water discharged by a salt-based water softener the following data is needed:
   1. Average water flow during occupancy
   2. Hours of occupancy
   3. Hardness of incoming domestic water (ppm)
   4. Amount of iron in the domestic water (ppm)
   5. Total Hardness = ppm of water + 3 x Iron Content ppm
   6. Cubic feet of resin of the softener system
b. From data above calculate total grains of hardness captured
   1. Convert the ppm to grains by dividing total ppm / 17.1 = grains
   2. Find grains of hardness per liter or gallon of water (Table 7.13)
   3. Find capacity of softener resin in liters or gallons of water before regeneration
   4. Convert resin bed to grains capacity 1 liter = 1,130 grains or (1 CU FT = 32,000 grains)
c. Key to Accuracy for Calculating Flow. The most important flow is the average flow during hours of occupancy for the time period of measurement. Normally the time period is one day of occupancy. Since plumbing water use is sporadic, using shorter time periods is problematic. Water hardness is easily measured using a Total Dissolved Solids (TDS) meter.

See Informative Appendix G3.6 for water softener water use example calculation.

7.2.2.7 Reverse Osmosis Water Purification System Water Use. Reverse Osmosis (RO) filter systems are used to purify water making brackish water near pure water. RO systems are grouped into two groups as Point-of-Use (POU) and Point-of-Entry (POE) systems. POU systems are small capacity residential type systems and POE are larger, pressurized systems that can produce larger quantities of water at higher efficiencies. All RO systems have a waste stream that flushes the impurities from the RO membrane to maintain the system removal efficiency. Traditionally this waste stream has been at ±20% efficiency, meaning the system has 4 times the wastewater for every unit of pure water generated.

a. POU systems are pressurized by the incoming water supply and include several water filters ahead of the RO membrane and normally a finishing filter after the RO membrane. Efficiency of the system is based on the design of the unit and selection of filters. POU systems are traditionally ±20% efficient but some manufactures are listing efficiencies up to ±50%.
b. POE systems use pressure pumps to boost the incoming water well above city water pressures to improve the efficiency of the RO membrane and filters. POE systems are normally in the 40 - 50% efficiency range but some manufactures are listing efficiencies up to 75%.
c. To calculate total wastewater, use from an RO system, determine the total incoming average flow to the system from a submeter and use the following formula; efficiency is obtained from manufactures literature:
   FW = Average waste water flow
   FT = Average Incoming water flow
   FP = Average process water flow
   E = Efficiency Fraction
   $$FW = FT - (FT\ x\ \ E)$$
d. To calculate total wastewater use using the average pure water output, the formula becomes:
   $$FW = \left(\frac{FP}{E}\right) - FP$$
e. Key to Accuracy for Calculating Flow. The most important factor to determine flow for RO units is the end use flow, which is sporadic. The easiest method is to use a flow meter on the incoming water supply over the period of measurement.

See Informative Appendix G3.7 for RO water use example calculation.

7.2.2.8 Swimming Pools and Fountains Water Use (Christopher Wanamaker 2011). Outdoor swimming pools and fountains all lose water to evaporation, which varies depending on the temperature of the water, air temperature and the water's vapor pressure. Pools also lose water due to human activities of splashing, which is not considered here.

The following equation was developed by Warren Stiver and Dennis Mackay of the Chemical Engineering Department at the University of Toronto. It can be used to estimate evaporation from the surface of a pool of liquid that is at or near ambient temperature.

SI Units

$$E = \frac{PAW}{T - 5.346}$$

E = Evaporation Rate (liters/day)
A = Pool Surface Area (m^2)
W = Wind Speed Above Pool (Kph)
P = Water's Vapor Pressure (mm of HG) at Ambient Temp (Table 7.14)
T = Temperature (°C)

(IP Units)

$$E = \frac{PAW}{T + 459.67}$$

E = Evaporation Rate (gallons/day)
A = Pool Surface Area (ft^2)
W = Wind Speed Above Pool (mph)
P = Water's Vapor Pressure (mm of HG) at Ambient Temp (Table 7.14)
T = Temperature (°F)

Table 7.14 Vapor Pressure of Water at Atmospheric Pressure.

Temperature		Vapor Pressure	Vapor Pressure
°C	°F	psia	mm HG
4.44	40	0.122	6.309
10.00	50	0.178	9.205
15.60	60	0.256	13.239
21.10	70	0.363	18.773
26.70	80	0.506	26.168
37.80	100	0.949	49.077

Key to Accuracy for Calculating Flow. The most important number is the ambient temperature which sets the water vapor pressure. The second important item is the average wind speed for the measurement period.

See Informative Appendix G3.8 for swimming pool or fountain water use example calculation.

7.2.2.9 Water Used for Area Cleaning (Green Line Industrial Hose Catalog, 2024, p 191). Water used for cleaning surface areas or equipment can be calculated from standard hose flows. Table 7.15 indicates maximum flow from a 30m (100') length hose with no fittings or restrictors and no sharp bends. Multiply these values times the number of minutes the hose is in use to determine total flow.

Key to Accuracy for Calculating Flow. The most important item for calculating flow from hoses is the water pressure. Water pressure can be measured using a pressure gauge on the outlet of the hose. To obtain total water use, average use time is estimated based on observation.

See Informative Appendix G3.9 for area cleaning water use example calculation.

Table 7.15 Hose Flow.

Liters/min Flow for 30 meters of Hose at 15% pressure drop		GPM Flow for 100' of Hose at 15% pressure drop	
Inlet P	Inside Diameter in Millimeters	Inlet P	Inside Diameter in Inches

KPA	12	15	19	25	31	38	PSI	1/2	5/8	3/4	1	1 1/4	1 1/2
137.9	15	30	45	98	178	288	**20**	4	8	12	26	47	76
206.8	19	34	57	121	220	356	**30**	5	9	15	32	58	94
275.8	23	42	68	144	257	416	**40**	6	11	18	38	68	110
344.7	26	45	76	163	291	469	**50**	7	12	20	43	77	124
413.6	30	53	83	178	322	519	**60**	8	14	22	47	85	137
517.5	34	57	95	201	360	583	**75**	9	15	25	53	95	154
689.5	38	68	110	235	424	681	**100**	10	18	29	62	112	180

7.2.3 Level 2: Measurement Methods.

7.2.3.1 Using Water Meters. Measuring water use is easy if submeters are installed where you want to have accurate water use data (see Fig. 7.3). Unfortunately, submeters are not normally installed on many uses besides the incoming water line to a building, so you must find other means of determining the water use for other than total facility water use. There are several methods of determining water use without installing permeant submeters, such as installing temporary submeters or calculating water use for the individual water using system.

Water meters should be of the positive displacement type so low or no-flow will not affect the accuracy of the readings. These positive displacement meters record water use as pulses with each pulse representing 1, 5, 10, 50, 100, 250, 500, liters or m^3 or (1, 10, 100 or 1000 gallons) per digit depending on how the meter head is programmed. Since the meter is reading total use to date, it makes it simple for EMS systems to keep track of use. It is important to note that these meters do not record instantaneous flow, only total use over time. For instantaneous flow use a flow meter that records instantaneous flow in the pipe, not total use over time. Instantaneous meters are not useful in EMS systems for measuring potable water flow since the EMS must calculate total use over time even when there is no flow in the pipe.

For temporary meters you can use portable ultrasonic clamp-on meters that are very accurate and easy to install since they are strapped to the bare pipe and measure the flow through the pipe wall. These meters normally work on all types of pipe and can be used on a range of pipe sizes.

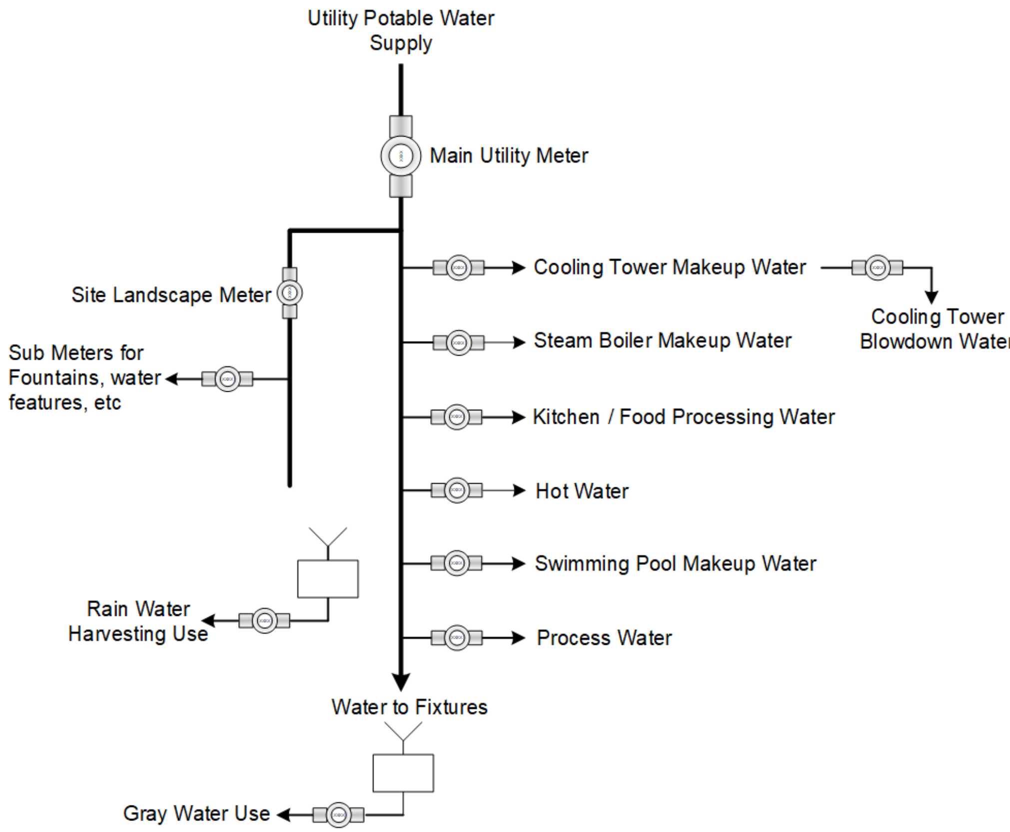


Figure 7.3 Typical Water Meter Locations (ASHRAE 2010).

7.2.3.2 Obtaining Flow Rates without Meters. Flow rates from individual fixtures or pieces of equipment can be estimated using one of the following methods; see the Key measurements paragraph for each system water using calculation in Section 7.3.2.1:

a. Measure flow over time by draining the flow into a measurable container.
b. Manage uses so only one use is operable at one time so the main water meter or other upstream meter can be used to measure the desired flow.
c. Use special plumbing fixture flow meter hand tools, manufactured to approximate water flow in a specific type of plumbing fixture, such as a WC P-trap flow meter.
d. Estimate stream flow for a unit of time by comparing it to known stream flows at similar pressures.
e. Use pump curves and pressure data to determine flow from pumps.
f. Use manufacturer's data for water flows at anticipated pressures.

7.2.4 Level 2: Performance Evaluation and Benchmarks. (See Section 7.3.4)

7.3 Level 3: Advanced Analysis. Level 3 water use analysis for new buildings without historic water use data should use the calculation methods outlined in Level 2 for each water use system.

Level 3 water use analysis for existing buildings is largely based on modeling. To assist in water use reduction, it is important to improve the measurement of water use and to improve the accuracy of modeling water use. In the past there has been little effort to model building water use due to the lack of focus on water and the lack of detailed studies of water use by facility type. Most water use studies have only addressed municipal aggregate use, without regard to use in specific building types.

One study published in 2014 (Kim and Haberl 2014) demonstrated how a three parameter multi variable regression (MVR) cooling model, using outdoor temperature and precipitation, provided accurate results above the threshold R2 value of 0.8, as specified in the (ASHRAE 2010). This study calculated the water use for a building with a water-cooled HVAC system, whereas a building with an air-cooled HVAC system would be significantly different. This demonstrates the need for more studies showing the effectiveness of water use models for different types of buildings with different water using systems.

7.3.1 Level 3: Objective. The objective of this level is to determine analytic procedures for the determination of whole building water use over time. These procedures and calculations are intended to model water use based on varying conditions that affect building water systems. These calculations or models can be used to validate a facility's design for lower water use and should be used to validate the actual water use, as compared to design. Using a calibrated model, in conjunction with the water use tracking system detailed in Level 1, will facilitate lower water use.

7.3.2 Level 3: Metrics.

Modeling Metrics (ASHRAE 2014). The modeling calculations for existing building water use apply the calculation methodology documented in ASHRAE Guideline 14, Measurement of Energy, Demand and Water Savings, Appendix D4. These models can be average-based spreadsheet models or regression statistical models using the variables shown in Table 7.16.

Table 7.16 Level 3: Water Use Systems Analysis.

Type of information	Water Source	Measurement Methods[b]	Water Usage Data Source	Independent Factors	Dependent Variables	Time interval[a]
• Building Equipment or System with **water cooled** HVAC systems water use	• Utility water • On site well	• Whole-building utility bills • Main meter readings • Sub-meter readings	• Measured Data • Calculation	• Building area • Quantity of Plumbing Fixtures	• Water Pressure • Cooling Load • CT Cycles of concentration • Schedule • No. Occupants	• Hourly • Daily • Monthly
• Building Equipment or Systems with **air cooled** HVAC systems water use	• Utility water • On site well	• Whole-building utility bills • Main meter readings • Sub-meter readings	• Measured Data • Calculation	• Building area • Quantity of Plumbing Fixtures	• Water Pressure • Schedule • No. Occupants	• Daily • Monthly
• Building Equipment for Steam Systems water use	• Utility water • On site well	• Sub-meter readings • Calculated use	• Measured Data • Calculation	• Building area • Equipment size	• % condensate return • Steam Load • Schedule	• Hourly • Daily • Monthly
• landscape irrigation water usage	• Utility water • On site well • Reclaimed water	• Sub-meter readings • Calculated use	• Measured Data • Calculation	• Irrigation Area • Vegetation Type • Wind Exposure Area	• Water Pressure • Weather[c] • Schedule	• Daily • Monthly
• Pools & Fountains	• Utility water • On site well	• Sub-meter readings • Calculated use	• Measured Data • Calculation	• Surface Area	• Evaporation rate • Temperature	• Daily • Monthly

a. Time interval must be the same as the measurement source data interval or multiple of the measurement source. For hourly or daily data, the water meter data must be daily or hourly and totaled to daily values.

b. Measurement Methods for existing buildings are as shown; for new buildings calculations based upon design specifications must be used for the model base load.

c. For landscape irrigation using weather as a dependent variable the system must use control systems that vary flow or schedule based on weather conditions.

Typical Regression formulas used for water analysis include:

a. Temperature-dependent 3-P cooling change point model
   $\boldsymbol{W} = X_{CP} + RS\ x\ (T - T_{CP})^{+}$
b. Temperature-dependent 3-P cooling change point model with precipitation
   $\boldsymbol{W} = Y_{CP} + RS\ x\ (T - T_{CP})^{+} + X_2\ x\ P$
c. Statistical indicators
   $$\boldsymbol{R^2} = 1 - \left|\frac{\sum(y_i - \bar{y}_i)^2}{\sum(y_i - \bar{y})^2}\right|$$
   R^2 is used to quantify goodness-of-fit of the model between 0.8 to 1
   $$\boldsymbol{CV - RMSE} = 100\ x\ \frac{\left|\sum(y_i - \bar{y}_i)^2 /\ (n - p)\right|^{1/2}}{\bar{y}}$$
   CV-RMSE is used to quantify how data is scattered around the mean
   where:
   W = monthly water use
   Y_{CP} = base load
   T = monthly ambient temperature
   T_{CP} = change point temperature
   X_2 = coefficient for precipitation
   P = precipitation or number of rainy days
   RS = coefficient of determination
   CV-RMSE = coefficient of variation of the root mean square
   $\bar{y}_i$ = regression model predicted use
   $\bar{y}$ = arithmetic mean of the measured use
   n = number of observations
   p = number of parameters in the regression model

7.3.2.1 Modeling Water Use in the Building. Modeling water use normally is based on daily or monthly data, since water use and billing data are normally obtained on a monthly basis. Calculations are normally done on an average daily basis which may be aggregated from hourly calculation. Using hourly data will indicate base load when night time loads are low.

To improve calculation accuracy, it is recommended to include all the key dependent variables that directly affect water use in the building. Table 7.16 indicates the dependent variables to be used in an algorithm to calculate water use. The following indicates how these variables are used for each type of water using system:

a. Water-Cooled systems or evaporative coolers are directly dependent on ambient temperature and humidity. (COC, Cooling tower cycles of concentration are normally assumed to be constant and the same for both pre and post retrofit. If COC are not well maintained and drop below 2.5, the excessive water use can be very large.) Using these variables in an MVR regression calculation should provide accurate use data. These systems will have a very small base load that is not directly coupled to the ambient, which should result in a very low calculation error.
b. Steam heating systems are directly dependent on ambient temperature but will have a higher base load than a heating system not coupled to the ambient, such as steam used for sterilization, cooking or pre-heating the steam distribution system.
c. Air-Cooled Cooling and Heating Systems do not have any water use so they should not be included in water use calculations.
d. Building plumbing fixture water use and other internal water use, such as kitchens, water softeners and drinking fountains are directly coupled to the average number of occupants and not to weather. The challenge is obtaining accurate occupant data. Methods of occupant data, from least accurate to

more accurate, are: average design counts, average counts from building managers or records, access control systems, and people counting systems.

e. Other indoor water uses, such as general cleaning or indoor fountain evaporation, are normally neglected unless the water use is large.

The calculations above can be combined into one Multi Variable Regression (MVR) model but it is recommended that separate regression models be applied for weather-dependent and occupant-dependent calculations, and then adding the results for improved accuracy.

7.3.2.2 Modeling Water Use Outside the Building. Modeling water use normally is based on daily or monthly data since water use and billing data are normally obtained on a monthly basis. Calculations are normally done on an average daily basis, which may be aggregated from hourly calculations. Using hourly data will indicate base load when night time use is low.

Modeling exterior water use may include irrigation and evaporation from pools and fountains, and may also include infeed from water harvesting systems.

a. Site irrigation can directly depend on ambient temperature and precipitation, if the irrigation system is either manually operated or is controlled by a smart irrigation controller that adjusts flows or is schedule based on temperature and precipitation. If irrigation systems are controlled by a fixed time schedule controller they will not be coupled to the ambient. Using temperature and precipitation variables in an MVR regression calculation should provide accurate use data.
b. Swimming pool and fountain water use is directly dependent on ambient temperature and the evapotranspiration rate. Using these variables in an MVR regression calculation should provide accurate use data

Once all component calculations are complete, add all component use amounts into one monthly table for comparison of actual to predicted amounts.

7.3.3 Level 3: Measurement Methods. Water use measurements normally are based on whole building, utility water billing data or submeter data, which are then used to calibrate water use models to predict future water use. For new buildings basic design assumptions establish a base water use that is then used in regression models to predict water use over time.

7.3.3.1 Building Water Use Measurements. The following characteristics should be documented to provide the basis for all water performance determinations and water reduction strategies:

a. Building type, function, or primary use.
b. Building gross floor area: the sum of the floor areas of all spaces within the building, with no deductions for floor penetrations other than atria. Gross floor area is measured from the exterior faces of exterior walls or from the centerline of walls separating buildings, but it excludes covered walkways, open roofed-over areas, porches and similar spaces, pipe trenches, exterior terraces or steps, roof overhangs, parking garages, surface parking, and similar features.
c. Estimated average number of full time equivalent annual occupants by gender. (Note, if the gender count is not known, use average total occupants and estimate the count between genders)
d. Total annual occupied hours.
e. Cooling tower system type and size (tons); total capacity of all cooling towers required for base load (excluding backup or redundant cooling tower capacity).
f. Steam boiler size kJ/h or KW or (hp or Btu/h); total capacity of all steam boilers required for base load (excluding backup or redundant boiler capacity).
g. Makeup water requirements for boilers, cooling towers, and chilled water loops
h. Location of facility (climate zone).
i. Design water use of all plumbing fixtures, including toilets, urinals, showers, sinks and lavatory fixtures.
j. Design water use of kitchens, food service preparation equipment, and showers (e.g., gymnasiums or dormitories) average L/d or (gal/day)
k. Water softener or RO/DI system size, cycle times, flow rates and average hardness of the supply water. (Average L/d or gpd)
l. Exterior pools and fountains surface area and exposure to wind.

m. Water reclaim systems that are used to replace potable water with anticipated annual flows.

7.3.3.2 Landscape Water Use Measurements. The following landscape data should be collected to provide the basis for irrigation water calculations and reduction strategies:

a. Total area of landscaping. Site areas that have no landscaping, such as parking lots, gravel areas, or non-irrigated natural areas, should not be included in this value.
b. Measurement should distinguish between type of species factor, density factor and microclimate factor:
    1. Species Factors
        i. K_S = 0 for native species (no irrigation)
        ii. K_S = Low. For adaptative species. Low watering.
        iii. K_S = Average. For adaptative species. High watering.
        iv. K_S = High. For invasive species.
    2. Density Factors
        i. K_D = Low. If leaf shading is less than 60% ground coverage
        ii. K_D = Average. If leaf shading is greater than 60% but less than 90% ground coverage
        iii. K_D = High. If leaf shading is 100% ground coverage
    3. Microclimate Factors
        i. K_{MC} = Low. Areas protected from wind and sun, such as court yards and north shaded areas
        ii. K_{MC} = Average. Areas only partially protected from wind and sun.
        iii. K_{MC} = High. Areas exposed to wind and sun, such as parking lot planting areas, west and south exposures, and areas with wind tunnel effects.
c. Irrigation type. Where landscape areas are irrigated, determine the system type used (drip, sprinklers, or flooded) and their flow rates.
d. Climatic zone characteristics that determine estimated annual water evapotranspiration.

7.3.4 Level 3: Performance Evaluation and Benchmarks

7.3.4.1 Water Use Performance Evaluation. Because water use in commercial buildings is not well documented, other than some aggregate studies of water use over large sectors, benchmarks cannot be used as an accurate starting point of building water use. Normally maximum building water use is calculated based on the water using systems in the design, and applying system use factors laid out in this guideline, as well as other system load factors. New building water use is calculated using the following:

a. Water Use inside the Building:
    1. Plumbing fixture water use based on quantity and fixture type.
        i. Dependent variables
            (a) Number of occupants per day (If variable)
            (b) Water Pressure
            (c) Occupancy Schedule
    2. HVAC system water use for water-cooled systems.
        i. Dependent variables
            (a) Cooling Load
            (b) Cooling tower TDS or cycles of concentration
            (c) Occupancy Schedule
            (d) Weather data
    3. HVAC system water use for air-cooled systems.
        i. Dependent variables
            (a) Cooling Load
            (b) Occupancy Schedule
            (c) Weather data
    4. HVAC system water use for steam heating systems.
        i. Dependent variables
            (a) Steam Load
            (b) Occupancy Schedule

        (c) Weather data
5. Kitchen water use based on size and type of kitchen.
    i. Dependent variables
        (a) Plates of food served daily.
        (b) Occupancy Schedule
6. Process water use based on process average water flow.
    i. Dependent variables
        (a) Process Operating Schedule

b. Water Use Outside the Building:
    1. Landscape Irrigation based on area of irrigation, vegetation and type of vegetation.
        i. Dependent Variables
            (a) Amount of Precipitation (For precipitation to affect irrigation water amounts the control system must be capable of adjusting flows or time of flows when precipitation is detected, or the flows must be adjusted manually)
            (b) Weather data (For weather to affect irrigation water amounts the control system must be capable of adjusting flows or time of flows when temperature changes are detected, or flows must be adjusted manually)
    2. Outdoor large pools and fountains water use based on surface area.
        i. Dependent Variables
            (a) Evaporation rate
            (b) Amount of Precipitation
            (c) Temperature of the water
            (d) Wind speed if exposed to wind

7.3.4.2 Water Use Benchmarks. Existing water use data bases, used as benchmarks, are not very helpful for determining water use in facilities because they do not take into account the differences between facility types and their water using characteristics. These benchmarks normally segregate facilities by type, and sometimes by size, but do not list the characteristics that affect water use. For instance, they lump both water-cooled and air-cooled facilities in the same data, and assume that all facilities of the same kind have the same number of occupants per building area; both of these characteristics drastically change the amount of water used, independent of its type or size. For future benchmarks to be useful for calculating building water use they need to segregate the data as follows:

a. For Buildings Benchmarks
    1. Building Type
    2. Building Size
    3. Climate Zone
    4. HVAC System Type (Air Cooled / Water Cooled)
    5. Occupants / by space type
    6. Food service (No food service kitchen / With food service Kitchen)
b. For Landscape benchmarks
    1. Landscape Type
    2. Landscape Area
    3. Climate Zone

8. THERMAL COMFORT

8.0 General Introduction and Background

8.0.1 Introduction and Scope. The heating and cooling of buildings significantly contributes to global energy consumption and carbon emissions. It is the largest component of energy consumption in buildings, accounting for 20% of total national energy use in the United States. However, this large expenditure of energy does not always produce a comfortable environment for occupants. Office workers report thermal comfort to be a major source of dissatisfaction with their buildings (Huizenga et al. 2006; Graham et al. 2021), with a significant proportion of them, around 20%, uncomfortable at a given time (Li et al. 2019).

Buildings are typically operated with minimal feedback about the thermal comfort they are providing. Occupant feedback, when collected, is gathered primarily via complaint logs or informal communications. Zone temperatures are measured at thermostats and return air ducts, but are rarely evaluated. Finally, there are few benchmarks or standard procedures that an operator can draw on for assessing a building's thermal comfort performance.

This state of thermal comfort assessment might seem surprising, as the physiological and psychological bases for thermal comfort have been studied for over a century. One explanation might be that these studies were largely controlled laboratory experiments that, though useful at discovering the causal mechanisms of comfort, did not represent real building environments or their diverse occupancies. Recently, large-scale surveys of occupant satisfaction with IEQ have created databases that allow a surveyed building's comfort performance to be evaluated and benchmarked (Foldvary et al. 2018; Karmann et al. 2018). Both laboratory- and field-study approaches to quantifying thermal comfort are reflected throughout this chapter.

The objective of future building design should be to improve occupants' comfort while at the same time reducing the energy used for their indoor environmental conditioning. This is possible through combinations of improved building design and construction, HVAC systems, controls, and operating procedures. The key finding in recent years has been that without providing occupants with the means to adjust their local (personal) environment, the great interpersonal differences in occupants' thermal comfort requirements will assure that a large percentage of them will be dissatisfied. High-performing designs in the future need to provide personal 'adaptive' or 'control' opportunities. This need is greatest in centrally controlled environments like large office buildings; residential and smaller-scale buildings usually provide more personal adaptive opportunities via greater access to operable windows and the thermostat (Zhai et al. 2019).

In addition to providing personal control features, future buildings should increase comfort-performance feedback – the sensing of physical indoor environmental data, collection of occupant responses, and evaluation of their thermal comfort performance against standardized benchmarks. Interpreted feedback should come from a range of audiences – the building's operators, owners, tenants, occupants – so that each can respond appropriately. Physical measurements should be more continuous, obtained with sensor systems installed in the building. Solicited occupant responses should be obtained at intervals not greater than a year, and opportunities for unsolicited feedback (e.g., via a desktop comfort reporting icon) should be continuously available to occupants.

8.0.2 Background. There is not a widely established thermal comfort consultancy as there is for lighting/daylighting, acoustics, and IAQ. Thermal comfort typically has been addressed by HVAC technicians setting the thermostats according to simple comfort rules (sometimes a fixed value year round) or in response to occupant complaints. Occasionally thermal comfort performance is addressed by design engineers, usually in the context of fixing a problem. Their design tools, typically design-day analyses for sizing or annual hourly simulations for energy prediction, tend to focus on temperature, relative humidity, and air supply volume, overlooking other thermal elements that strongly affect comfort. Air speeds in the occupied space and the radiant fields coming from windows or other heated and cooled surfaces are often insufficiently considered.

ASHRAE Standard 55 embodies the underlying criteria and models for establishing acceptable levels of comfort at a point in time. It has been regarded as a standard for designing buildings and their systems. Design consists of sizing equipment to keep designer-selected representative occupants within the Standard's comfort requirements, typically during selected extreme weather events.

Standard 55 has been augmented in recent years to establish a basis for field evaluations of thermal comfort in existing buildings. Methods for both occupant surveys and field measurements are addressed and standardized, see ASHRAE Standard 55-2023 Section 7 and Informative Appendix L. Many of the additions were informed by the preparation of the first two versions of the ASHRAE Performance

Measurement Protocols for Commercial Buildings (2010 and 2012). So Standard 55-2023 embodies most of the measurement protocols described here.

The basic ASHRAE Standard 55 thermal comfort requirements are summarized in the first two thermal comfort sections below (Section 8.1 Level 1: Basic Evaluation and Section 8.2 Level 2: Diagnostic Measurement). However, satisfying those requirements does not necessarily result in a system that is energy-efficient or even comfortable. To optimize thermal comfort performance, one must take advantage of all the thermal elements available in the indoor environment, as well as the behavioral responses of the occupants to their thermal environment. Such elements have recently been incorporated into Standard 55 based on recent thermal comfort research and are described in the subsections that follow.

In the thermal comfort context, Advanced Analysis (Section 8.3 Level 3: Advanced Analysis) is used to eliminate errors and unnecessary traditional practices that limit optimal performance, and to implement the best feasible design and operation solutions. In some cases, this may mean employing new technologies that overcome the limitations imposed by existing systems. The main strategies can be categorized as follows:

a. Manage occupant environment in more spatial detail, related to the scale and location of the occupants themselves, and to the perception of comfort and discomfort on local parts of the body.
b. Provide local thermal comfort control options, including air movement cooling and radiant heating.
c. Allow occupants to seasonally adapt by giving them greater access to thermostat and supply air temperature setpoints.
d. Reduce excessive minimum supply air volumes and velocities.
e. Control direct sunlight in work areas.
f. Control humidity independently of supply air temperature.

These strategies, each of which has the ability to both improve thermal comfort and reduce HVAC energy, are described in the following subsections. Informative Appendix H provides a detailed explanation of how these strategies can be used for energy-efficient building design and control.

8.0.3 Target Audience. The primary audience for this guideline includes facility managers, building operators, HVAC contractors, design engineers, commissioning authorities, green building and wellness raters, and appropriately qualified consultants. While the contents are tailored for these professionals, the guideline is also understandable to building owners, tenants, government officials, decision makers, and individuals with little technical backgrounds. The following sections are intended to facilitate effective commissioning for thermal comfort.

8.0.4 Thermal Comfort Measurement Plan. Approaches to measuring and evaluating thermal comfort depend on the intended application. The list of possible evaluation applications is extensive. They take place over varying time periods, from short term (ST) to long term (LT).

a. Real-time operation of a building using comfort metrics (ST)
b. Evaluating HVAC system performance (ST, LT)
c. Building management decisions regarding upgrades, continuous commissioning, and rating the performance of operators and service providers (LT)
d. Real-estate portfolio management: rating building quality and value (LT, ST)
e. Validating compliance with LEED existing-buildings requirements (ST, LT)
f. Validating compliance with requirements of codes – energy, hospital, etc. (ST)

These ST and LT applications are detailed in Table 8.1 (ASHRAE Standard 55-2023, Table L-1), outlining comfort evaluation approaches appropriate for the applications.

Table 8.1 Comfort Evaluation Approaches for Various Applications.

	Nature of Application	
	Short-Term	**Long-Term**
Occupant Surveys	Right-Now/Point-in-Time Survey (must survey relevant times and population):	Occupant Satisfaction Survey: • Survey scores give % dissatisfied directly. (“dissatisfaction” may be interpreted to start either below -1, or below 0).

	• Binning (TSENS scores) leads to % comfort exceedance during period of survey. (ASHRAE Standard 55-2023) • Needs coincident temperature to extrapolate to full range of conditions. (Used for research, problem diagnostics)	• Time period of interest can be specified to survey takers. (Used for building management, commissioning, rating operators and real estate value, compliance with green building rating systems)
Environmental Measurements	Spot Measurements, Temporary (Mobile) Sensors (must select a relevant time to measure): • Use measurements to determine PMV (ASHRAE Standard 55-2023, Section 5.3.2) • Use measurements to determine compliance with adaptive model (ASHRAE Standard 55-2023, Section 5.4) (Used for real-time operation, testing and validating system performance)	Logging Sensors over Period of Interest, or Trend Data from Permanently Installed (BAS) Sensors: • Exceedance hours: sum of hours over PMV or adaptive model limits. • Binned exceedances may be weighted by their severity. • Instances of excessive rate-of-temperature change or of local thermal discomfort can be counted. (Used for evaluating system and operator performance over time)

8.1 Level 1: Basic Evaluation

8.1.1 Level 1: Objective. The Level 1: basic thermal comfort evaluation is used to evaluate a building's comfort performance and identify deficiencies that require correction or further examination. The specific objectives are as follows:

a. Determine the occupants' satisfaction with the building's thermal environment, as experienced over a minimum of a few months' time.
b. Rate the building's satisfaction levels against benchmarks in a database of previously measured peer buildings.
c. Document thermal-comfort-related building characteristics in a format compatible with nationwide databases used for benchmarking building performance.
d. Identify problems with thermal comfort and obtain clues to their causes using occupant responses to diagnostic questions.
e. Take spot measurements of the thermal environment in cases where problems have been identified, for use in devising solutions to the problems.

8.1.2 Level 1: Metrics

8.1.2.1 Subjective Measurements. For the Level 1: basic thermal comfort evaluation, the primary measurement is the occupant survey. Such surveys determine occupants' satisfaction with the temperature and its impact on their ability to function effectively in the activities supported by the building. Occupants' experiences change somewhat from season to season and in response to daily HVAC loads and other activities, but their responses to the typical occupant survey integrate their perceptions ranging back more than three months, so two seasons are usually reflected in the responses.

Sample satisfaction survey questions used for the Level 1: basic thermal comfort evaluation include the following:

a. How satisfied are you with the temperature[3]?
b. Overall, does the temperature in your space enhance or interfere with your ability to perform at your best?

If an occupant expresses some level of dissatisfaction with the temperature in his or her workspace, the satisfaction survey asks a second level of questions to diagnose the source of the dissatisfaction. The following example questions help identify the nature of the problem and the features of the building and its operation that contribute to that problem.

[3] The term 'temperature' is used broadly in surveys to represent the combination of environmental factors that affect thermal comfort.

a. In warm/hot weather, is the temperature often too hot or too cold?
b. In cold/cool weather, is the temperature often too hot or too cold?
c. At what time of the day and/or week is this a problem?
d. Is it a Monday morning or weekend problem?
e. Are direct sunlight or hot/cold surrounding surfaces causing discomfort?
f. Is your area hotter/colder than other areas?
g. Does the heating/cooling system respond quickly enough to the environment?
h. Is the thermostat inaccessible or controlled by other people?

By comparing the first- and second-level responses to a database of previous survey results (e.g., the CBE survey database, (Zagreus et al. 2004)), one can benchmark (see Section 8.1.4) a building's thermal comfort performance and determine if there is enough of a problem to require additional action.

Note that in practice, thermally related health questions (such as asking about 'sick-building syndrome' symptoms such as itchy throat, headaches, etc.) are rarely included in occupant surveys. Building management is typically concerned that their presence might initiate discontent and risk of liability claims (see Section 9: Indoor Air Quality).

8.1.2.2 Physical Measurements. Some physical measurements of the thermal environment may be taken, in situations where problems have been identified in the survey and where spot measurements might help devise solutions to the problems. For flexibility, Basic measurements are done with handheld or tripod-mounted instrumentation with immediate readout. The most common measurements and the instruments used to take them are listed below.

a. **Air temperature and humidity**. Digital psychrometers are now common, measuring both air temperature and humidity. In use, the air temperature sensing element must be shielded within a reflective or insulated enclosure to minimize its radiation exchange with the surroundings.
b. **Surface temperatures**. Infrared spot meters or infrared thermal cameras are commonly used.
c. **Air speed**. A handheld anemometer is used. Airflow direction may be visualized with smoke or a suspended feather.

Table 8-2 specifies the requirements for measurement range and accuracy.

Table 8.2 Instrumentation Measurement Range and Accuracy (Adopted from ASHRAE Standard 55-2023, Table 7-1).

Quantity	Measurement Range	Accuracy
Air temperature	10°C to 40°C (50°F to 104°F)	±0.2°C (0.4°F)
Mean radiant temperature	10°C to 40°C (50°F to 104°F)	±1°C (2°F)
Plane radiant temperature	0°C to 50°C (32°F to 122°F)	±0.5°C (1°F)
Surface temperature	0°C to 50°C (32°F to 122°F)	±1°C (2°F)
Humidity, relative	25% to 95% rh	±5% rh
Air speed	0.05 to 2 m/s (10 to 400 fpm)	±0.05 m/s (±10 fpm)
Directional radiation	-35 W/m^2 to +35 W/m^2 (-11 Btu/ h·ft^2 to +11 Btu/ h·ft^2)	±5 W/m^2 (±1.6 Btu/h·ft^2)

8.1.3 Level 1: Measurement Methods

8.1.3.1 Collect Building Data. Basic information about the facility needs to be collected and recorded for the Basic Evaluation level. For thermal comfort, the following are needed:

a. List of the occupied spaces
b. Human activity (room use) in each space
c. Description of HVAC zones as related to building functions
d. Type of HVAC equipment supplying each space
e. Location of rooms within the building (outside wall, floor for multistory buildings, adjacent room uses, etc.)
f. Floor area (ft^2 or m^2)
g. Number of floors

h. Section depth from fenestration—perimeter/core; wings north, east, south and west

8.1.3.2 Review Building Maintenance Log. If a building maintenance log exists that includes occupant thermal comfort issues (e.g., hot/cold complaints), it should be reviewed for those issues. Building zones where problems are occurring should be noted and compared to zones without problems; this will identify areas for focus during the building walk-through. The frequency and nature of the issues give a sense of the nature of the problems. Are there conflicting requirements for different occupants within any given zone? This might indicate individuals' physiological or thermal perceptions that need attention. Any unresolved issues should be noted for follow-up.

Service issue logs are not equivalent to surveys in measuring performance or in comparing against benchmarks. They reflect only that subset of the population who are dissatisfied, have judged that their situation warrants informing facilities personnel, and expect that corrective action will be taken.

8.1.3.3 Conduct Occupant Satisfaction Survey. Occupant surveys can be conducted via web-based, paper-based, and interview-based approaches. The web-based surveys have become a popular option over the years as they can significantly reduce the administration cost and speed up the data collection and analysis process. All surveys should strive for a representative sample size and a high response rate across the occupied space in the building. A 40% response rate to a web-based survey of all occupants is considered sufficient to identify and diagnose problems, and to obtain a measure of the occupancy's satisfaction with a building's performance.

The occupant survey administered at this level is a satisfaction survey, which is used to evaluate thermal comfort response of the building occupants over a certain span of time. Because the survey results encompass a larger time frame, the survey can be administered every six months, or be repeated in heating and/or cooling seasons. In a new building, the first thermal satisfaction survey may be performed approximately six months after occupancy, late enough to avoid assessing the effects of putting the building into commission but early enough to help identify and solve long-term building problems that have escaped detection in the commissioning process.

8.1.3.4 Conduct Walk-Through. The purpose of a walk-through is to inspect the facility for indicators of building thermal comfort performance (by room or major zone). Physical measurements may be taken during the observational walk-through. Instruments used might include a handheld infrared spot meter for measuring surface temperatures (refer to Level 2 measurements for details) and supply air temperatures, and a temperature and humidity meter. Performance indicators may be visual clues of building failures (e.g., malfunctioning thermostats) or evidence of occupants having taken action to modify their environment. Take photographs of such modifications and document the problems they are addressing. Ask occupants for details concerning why and under what time or climate conditions they took these actions. Some example observational questions and/or issues specific to thermal comfort are summarized in the following list.

a. Positions of shades and blinds under known solar conditions: Shades are often lowered for a purpose and not returned after the condition passes, negating daylight harvesting opportunities for long periods of time. (Take photos.)
b. Glazing attachments: Look for cardboard or foil taped to window glass.
c. HVAC system tampering: Are personal radiant heaters or desk fans in wide use? Are vents or diffusers taped over? Have thermostats been tampered with?
d. Are occupancy sensors taped over? (Take photos.)
e. Is there any indication that office equipment is causing thermal problems?
f. Have the service issue logs indicated thermal problems in this area?

Other considerations include: Does the HVAC control system allow trend-logging of zone temperature readings or setpoints? Is it readily available and does anyone use it? Too often this essential performance measurement tool is inaccessible to normal users or requires a software upgrade from the control manufacturer.

8.1.4 Level 1: Performance Evaluation and Benchmarks

8.1.4.1 Evaluation Based on Survey Responses (Long-Term). In an occupant satisfaction survey, a building's thermal comfort can be evaluated using a seven-point thermal satisfaction scale with the following categories: “very satisfied,” “satisfied,” “slightly satisfied,” “neutral,” “slightly dissatisfied,” “dissatisfied,” and “very dissatisfied.” The evaluation process includes:

a. Thermal Satisfaction Criteria for Passing
    1. Count responses rated +1 (“slightly satisfied”) to +3 (“very satisfied”).
b. Branching Dissatisfaction Questions
    1. Count responses and tally by category to identify and correct problems. Dissatisfaction may be interpreted to start either below -1 (“slightly dissatisfied”), or below 0. (“neutral”).

8.1.4.2 Benchmarking Survey Results

a. To Past Performance: If previous occupant surveys exist, compare the current survey data to that of the previous survey. In addition to comparisons of the quantitative survey results, comparisons of previous field observations against current observations should be made. Any degradation in occupant satisfaction or changes of the physical layout should be noted for follow-up. The diagnostic questions will offer insight into the nature of the dissatisfaction.
b. To Baseline Databases: Satisfaction and other survey metrics are ideally evaluated against a database of identical or similar questions from earlier surveys.

One example of a database for long-term satisfaction results is from the CBE survey (See Informative Appendix E), which has over twenty years accumulated benchmarking scores for office buildings and other building types. The satisfaction results obtained from an occupant survey are the ‘bottom line’ for thermal comfort performance evaluation since they directly represent occupants’ long-term opinions about the building’s comfort. In many cases this should be sufficient for thermal comfort appraisal in buildings.

Results are tabulated according to mean scores for occupant satisfaction. The comparison can be against all buildings and also against a filtered set of buildings of similar type or characteristic. Filtering for peers is accomplished as follows: the IEQ questions can be subdivided for office buildings, schools, retail locations (answered by employees, usually not customers), hospitals (answered by nurses and staff, not patients), and laboratories.

Benchmarking performance is visualized using graphics such as those that show cumulative distributions of the building’s survey responses or histograms with standard deviation bars; examples are given in the example report in Informative Appendix E. Such graphics are automatically generated by the survey.

8.1.4.3 Evaluation Based on Field Observations. Although the occupant satisfaction scores are the primary quantitative metric for performance evaluation, field observations can also give a semiquantitative measure. If walk-through field observations exist from peer buildings, note any indication of trending, particularly any increase in comments or in observed issues, both in terms of frequency and intensity.

8.2 Level 2: Diagnostic Measurement

8.2.1 Level 2: Objective. At the Level 2: Diagnostic Measurement, subjective and physical measurements are taken to diagnose the causes and extent of performance problems identified during Basic Evaluation. Measurements are usually only needed in the areas having problems. Specific objectives are:

a. Take spot and time-series measurements to facilitate different types of fault detection and performance analysis.
b. Conduct point-in-time (short-term) surveys to evaluate the building’s day-to-day comfort performance through occupant feedback and further diagnose issues identified in the general occupant satisfaction survey during the Level 1 Basic Evaluation Process.
c. Compare measured data to ASHRAE Standard 55-2023 requirements to quantify compliance with the standard and identify any problems in system operation.

8.2.2 Level 2: Metrics. There are two main approaches to evaluating thermal comfort in operating buildings. One is to directly determine occupant thermal sensations through the evaluation of occupant surveys. The other is to use thermal comfort models to estimate sensations of the occupants from measured environmental variables. Surveys and physical measurements can be used separately or in combination for the purpose of problem diagnosis and corrections. (These measures are the ones listed as ‘short-term’ in Table 8.1.)

8.2.2.1 Subjective Measurements. Short-term (aka “point-in-time” or “right-now”) surveys are used to evaluate thermal perception of occupants at a single point in time. This is different from the occupant satisfaction survey used in the Basic Evaluation, which aims to provide a broad-brush assessment of environmental quality over a longer time period. The short-term survey should be conducted under various thermal conditions and building operating modes representative of occupants' day-to-day exposure.

The short-term surveys typically include the following questions.

a. Thermal satisfaction questions ask the direct question “Is the environment thermally satisfactory right now?” with a continuous or seven-point scale ending with the choices “very unsatisfactory” and “very satisfactory.”
b. Thermal sensation questions ask occupants to rate their sensation on the ASHRAE seven-point thermal sensation scale subdivided as follows: cold, cool, slightly cool, neutral, slightly warm, warm, hot.
c. Sometimes temperature preference and air-movement preference questions are used to ask occupants’ preferred state for temperature (cooler/no change/warmer) and air movement (less air movement/no change/more air movement).

8.2.2.2 Benchmarking Survey Results. The most prominent database archiving short term (real-time) thermal comfort study results is the ASHRAE Global Thermal Comfort Database II (https://cbe-berkeley.shinyapps.io/comfortdatabase/). It has mainly been used in thermal comfort research. The database is publicly available and provides tools for filtering and visualizing survey results for different building types, climates, and locations.

8.2.2.3 Predicting Point-in-Time Thermal Satisfaction from Environmental Models. Environment measurements can be used to predict occupant comfort through comfort models. Two comfort models included in the Standard 55 are Predicted Mean Vote (PMV) and Adaptive. PMV is a heat balance model of the human body and the environment, while the Adaptive Model is an empirical model of adaptive human responses to environments offering operable window control. Some “mixed-mode” buildings include a combination of both comfort model types. In ASHRAE Standard 55, the PMV model is combined with the Standard Effective Temperature (SET) model to better account for the cooling effect of sweat evaporation on thermal perception.

The PMV and Adaptive models are specific to mechanically conditioned and naturally ventilated buildings, respectively. Table 8.3 lists environment measurements needed to predict thermal comfort by space type.

Table 8.3 Environment Measurements by Space Type.

Space type	Measurements
Mechanically conditioned spaces	• Occupant metabolic rate (met) and clothing (clo) observations • Air temperature and humidity • Mean radiant temperature, unless it can be otherwise demonstrated that, within the space, is within 1°C (2°F) of air temperature at the occupant’s location. • Air speed, unless it can be otherwise demonstrated that, within the space, average air speed Va meets the requirements of ASHRAE Standard 55-2023, Section 5.3.4
Occupant-controlled naturally conditioned spaces	• Indoor air temperature and mean radiant temperature • Outdoor air temperature

The two personal parameters, activity level and clothing, can also be estimated for the occupants of the space if physical measurement is not feasible. Estimation methods are presented in Informative Appendices F and G in ASHRAE Standard 55-2023. If the occupants are not yet present, such as during design and commissioning, one may use clothing and activity values agreed upon by owners and designers as appropriate for the building’s function.

8.2.3 Level 2: Measurement Methods.

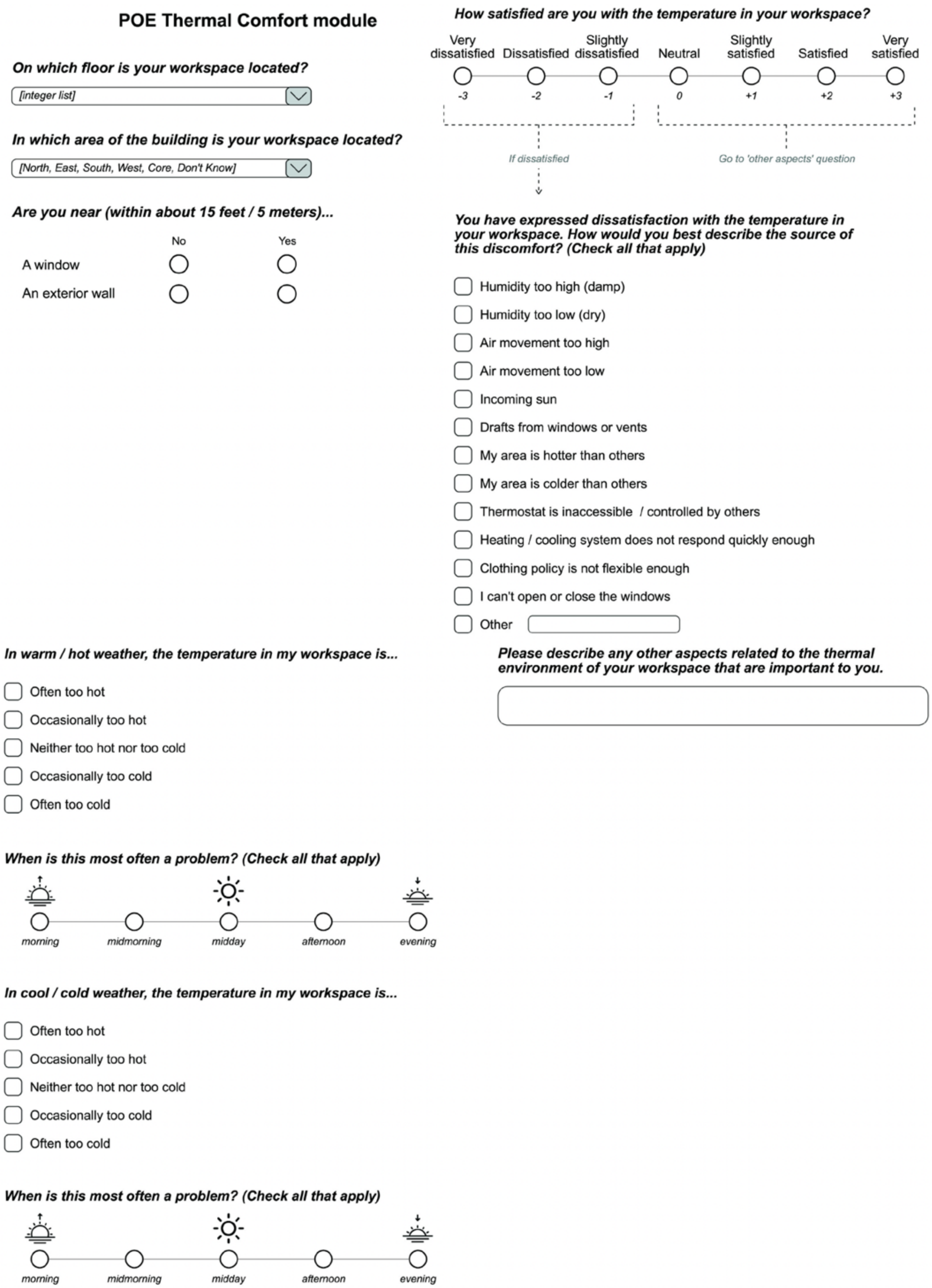
8.2.3.1 Conduct Performance Observation to Establish Location and Basis of Identified Issues. The first step of the procedure is to review previous plans and data. The plan developed during Basic Evaluation may have identified spaces in the building that need diagnostic measurements. Such spaces can also be identified from observations made during the walk-through inspection. In addition, they can be extracted from the satisfaction survey results, as shown in Figure 8.1.

Figure 8.1 presents the thermal comfort satisfaction survey given in ASHRAE Standard 55-2023, Informative Appendix L. It lists branching questions that are asked of the occupant immediately following a dissatisfied vote on the main temperature satisfaction survey. These questions represent a diagnostic checklist of detailed potential causes, allowing the problems to be identified and causes hypothesized.

The survey's anonymity prevents these responses from being associated with individuals or workstations, but a response's general location can be narrowed down to floor, wing, façade orientation, and proximity to exterior walls. In a moderate-sized building, this allows problems to be identified and located within a group of relatively small zones.

The survey also provides space for voluntary, open-ended comments. Commenters frequently discuss the presence of drafts, radiant discomfort near windows, and unresponsive thermostats; their insights are often accurate. As with the diagnostic checklist, the problems described in the comments section can often be narrowed down to a relatively small area of the building.

With this information, it may help to repeat walk-through observations in the identified problem areas to obtain more detail. Observe occupant actions (as at the Basic Evaluation level, but now focus on the problems identified by the survey) such as permanently lowered window shades, cardboard over windows, taped diffusers, modified thermostats, personal heaters and fans, etc. Take photographs of such modifications and document the problems they are addressing. Ask occupants for details concerning why and under what time or climate conditions they took these actions. The problems might then be corrected during the commissioning process.



POE Thermal Comfort module

On which floor is your workspace located?

[integer list]

In which area of the building is your workspace located?

[North, East, South, West, Core, Don't Know]

Are you near (within about 15 feet / 5 meters)...

	No	Yes
A window	○	○
An exterior wall	○	○

In warm / hot weather, the temperature in my workspace is...

- Often too hot
- Occasionally too hot
- Neither too hot nor too cold
- Occasionally too cold
- Often too cold

When is this most often a problem? (Check all that apply)

morning, midmorning, midday, afternoon, evening

In cool / cold weather, the temperature in my workspace is...

- Often too hot
- Occasionally too hot
- Neither too hot nor too cold
- Occasionally too cold
- Often too cold

When is this most often a problem? (Check all that apply)

morning, midmorning, midday, afternoon, evening

How satisfied are you with the temperature in your workspace?

Very dissatisfied	Dissatisfied	Slightly dissatisfied	Neutral	Slightly satisfied	Satisfied	Very satisfied
-3	-2	-1	0	+1	+2	+3

If dissatisfied

Go to 'other aspects' question

You have expressed dissatisfaction with the temperature in your workspace. How would you best describe the source of this discomfort? (Check all that apply)

- Humidity too high (damp)
- Humidity too low (dry)
- Air movement too high
- Air movement too low
- Incoming sun
- Drafts from windows or vents
- My area is hotter than others
- My area is colder than others
- Thermostat is inaccessible / controlled by others
- Heating / cooling system does not respond quickly enough
- Clothing policy is not flexible enough
- I can't open or close the windows
- Other

Please describe any other aspects related to the thermal environment of your workspace that are important to you.

Figure 8.1 Thermal Environment Satisfaction Survey (Source: ASHRAE 55-2023 Figure L-2).

8.2.3.2 Take Physical Measurements. Prepare a plan for taking physical measurements for identified problems. The measurements will depend on the nature of the performance issues identified in the Basic Evaluation. There are two types of physical measurements that provide the data needed for different types of fault detection and performance analysis: spot and time-series. The following describes the typical measurement approaches in each category.

a. Spot Measurements of Observed Functional Flaws: Spot measurements should be taken in locations and at times that the survey or visual inspection has identified as problematic. The measurements should identify functional flaws in the building envelope or HVAC system, such as high velocities from diffusers reaching into the occupied zone, excessive thermal gradients in the space (vertical or horizontal), uncomfortable radiant temperatures, air temperatures and airflows near glass in summer or winter, and direct solar radiation impinging on occupants in their workspaces.

   Spot measurements are generally taken with handheld or tripod-mounted instruments that can be easily moved to capture effects. The visualization of airflows using media such as smoke, water mist, talcum powder, and soap bubbles is especially useful. Airflow sheets or jets often contain large temperature as well as velocity gradients, both of which affect the comfort of occupants encountering the airflow. These can be seen with an infrared camera viewing a lightweight screen suspended in the airflow. The screen picks up the flow temperature without distorting the flow, and its surface temperature is made visible by the infrared camera.

b. Time-Series Measurements in Problem Areas: In addition to instruments that give immediate readout, it is easy and economical to record the thermal environment and HVAC system performance over time. Such data logging is useful in detecting patterns in the thermal environment, which may be linked to diagnosing performance of mechanical equipment, control settings, and the building envelope.

   Time-series data allow intermittent effects to be captured at times when building managers or commissioners are not present. Examples include transient processes such as “Monday morning startup,” solar gain through fenestration, and cycling of mechanical systems. Data loggers with additional channels can record multiple environmental parameters (typically temperature, relative humidity, and light). The data loggers come with computer connections and software for setting measurement time periods and downloading data. Useful time periods range from hours through months. One can use wireless data loggers to avoid manual data downloads and remotely view, access, and share sensor data over the Internet.

   1. Take temperature and humidity readings in the occupied zone at time intervals anywhere between 30 seconds and 10 minutes. In general, there is little need to measure more frequently than once a minute.
   2. Note that “temperature” in comfort standards is expressed as operative temperature (top), which is the average of the air temperature and the mean temperatures of all surrounding surfaces (e.g., wall, ceiling, room furniture, equipment). In most indoor spaces, the surface temperatures, or mean radiant temperature, are close to the air temperature, and a thermometer can by itself approximate operative temperature. However, comfort is sometimes affected by exposure to cold or hot surfaces such as windows or equipment, which may be at temperatures that are significantly different from that of the air. A globe temperature thermometer can be used to minimize this error and provide a reasonable approximation of operative temperature. It can be fabricated by centering a temperature sensor within a table-tennis ball painted primer grey. Alternatively, one can measure the air temperature and radiant surface temperatures independently. True air temperature is measured by shielding the thermometer sensor from radiation using a cylinder of aluminum foil or reflective mylar. The room’s surface temperatures are measured using an infrared sensor or camera. The mean radiant temperature (tr) can then be calculated for simple room geometries using the CBE Thermal Comfort Tool [https://comfort.cbe.berkeley.edu/]. The operative temperature is then the average of the shielded air temperature and the mean radiant temperature.

3. Humidity (generally relative humidity, or RH) can be measured in fewer locations since it does not vary as much as temperature, and it is also less influential than temperature at determining thermal comfort.
4. Air speed measurement is relatively complex. The instruments themselves are complicated and relatively expensive. Only a few types of anemometers are omnidirectional; most must be oriented along the line of flow, which has to be determined prior to measuring. Because there is a wide variety of air flows possible in a room at the same time, the main purposes of the assessment need to be defined. The anemometers must then be positioned to capture a specific air flow effect. In some cases, the goal is to keep air movement low, and in others to determine whether there is enough of it to ensure comfort and good perceived air quality. Whether a given air velocity is comfortable or not depends on the environmental temperature, and on the activity and clothing of the occupants. For example, an exercise gym may require air movement even at cool temperatures, whereas a lounge at the same temperature would require still air to avoid overcooling the occupants. A naturally ventilated lounge in Hawaii would, however, require air movement because the temperature and humidity are expected to be high. These factors are all accounted for using the elevated air movement criteria in ASHRAE Standard 55 and are in practice calculated using open-source tools like the CBE Thermal Comfort Tool [https://comfort.cbe.berkeley.edu/].

c. Building Automation System Measurements: Any physical measurements need to be made with awareness of the state of the building's HVAC system. In simple systems this can be done by controlling the thermostat, but more complex systems may involve coordinating with the operator during the testing. If available, it is helpful to obtain Building Automation System (BAS) trend logs of the system state during the testing period. The merging of BAS measurements with spot-temperature measurements and logged space temperature measurements allows the whole system to be examined. In addition, visual inspection and comparison of Diagnostic Measurement and BAS point values can help identify BAS transducers that are malfunctioning or out of calibration as well as system programming errors.

8.2.3.3 Conduct Point-in-Time Occupant Survey. Point-in-time ("right-now) surveys are usually conducted by specialists. They generally arrange that the request to take the survey comes from the occupants' work management, usually via a pre-scripted email message. The survey is taken within a specified period of time, typically two weeks. A sample point-in-time survey is included in Figure 8.2. It includes a thermal sensation survey that asks occupants to rate their sensation (from "hot" to "cold") on the ASHRAE seven-point thermal sensation scale. The scale units are sometimes designated "TSENS." It also asks, "How satisfied are you with the thermal environment?" with a scale of "very dissatisfied" to "very satisfied." The satisfaction scale is a standard psychometric test in other disciplines and is best divided into seven scale units. Sometimes, preference scales for temperature and air movement are also used.

The surveys are usually completed via the Internet. They can be administered once per occupant, but it is also common to ask an occupant to repeat the survey over a period of a week or more to build up data. Each time the survey is taken, the date/time of response is recorded. Point-in-time surveys should be conducted during times representative of the building's occupancy. To use the survey results to assess comfort acceptability ranges over time, the point-in-time survey should be implemented under multiple thermal conditions and in multiple building operating modes.

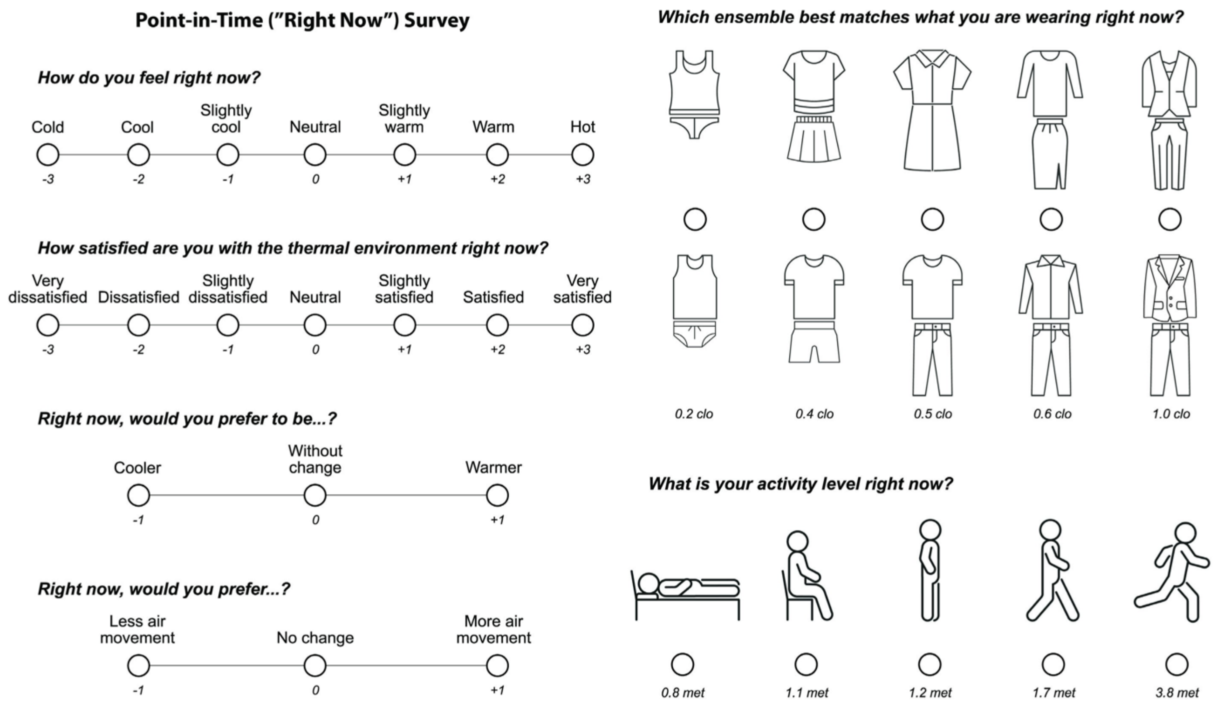


Figure 8.2 Thermal Environment Point-in-Time Survey (Source: ASHRAE 55-2023 Figure L-1).

8.2.4 Level 2: Performance Evaluation and Benchmarks.

8.2.4.1 Evaluation Based on Survey Results (Short-Term). Point-in-time (right-now) surveys can be evaluated using the following measures and criteria:

a. Measures:
   1. Thermal satisfaction votes on a scale expressed from -3 to +3 corresponding to the categories: "very satisfied," "satisfied," "slightly satisfied," "neutral," "slightly dissatisfied," "dissatisfied," and "very dissatisfied."
   2. Thermal sensation (TSENS) votes on a scale expressed from -3 to +3 corresponding to the categories: "cold," "cool," "slightly cool," "neutral," "slightly warm," "warm," and "hot." (When averaged for a population, TSENS votes correspond directly to PMV votes.)
   3. Temperature preference votes (using the three-point scale "cooler," "without change," and "warmer") and air-movement preference votes (using the three-point scale "less," "no change," and "more").

b. Criteria for Passing:
   1. –0.5 to +0.5 on the PMV scale, inclusive, is the Standard 55 criterion for thermal comfort.
   2. Field surveys usually consider TSENS values of –1 and +1 as representing "satisfied"; the break along the categorical seven-point thermal sensation scale is at –1.5 and +1.5, inclusive.

8.2.4.2 Evaluation Based on Environmental Measurements (Short-Term)

a. Mechanically Conditioned Spaces: Use ASHRAE Standard 55-2023, Section 5.3, to determine the comfort of occupants under the measured environmental conditions. Clothing and activity levels of the occupants must be as observed or as expected for the use of the indoor space in question, including the insulation provided by the occupants' chairs. Use Section 5.3.4 to adjust the comfort zone's lower and upper operative temperature limits for elevated air movement. Occupied zone conditions must also conform to requirements for avoiding local thermal discomfort (as specified in Section 5.3.5) and to limits to rate of temperature change over time, as specified in Section 5.3.6.

Criteria for Passing. –0.5 to +0.5 on the PMV scale, inclusive. Expressed as a comfort zone on a psychrometric chart, this represents an operative temperature range 3 K to 5 K (5°F to 8°F) wide, centered on a neutral temperature at which PMV = 0.

b. Occupant-Controlled Naturally Conditioned Spaces: Section 5.4 prescribes the use of the Adaptive Model for determining the comfort zone boundaries. The air movement extensions to the comfort zone's lower and upper operative temperature limits (Table 5-12 in ASHRAE Standard 55-2023) should be used when elevated air movement is present.

   Criteria for Passing. An environmental condition passes if it is within the 80% boundaries predicted by the adaptive model.

The evaluation methods detailed here are integrated into the CBE Thermal Comfort Tool [https://comfort.cbe.berkeley.edu/], a free online resource for thermal comfort calculations. It incorporates major thermal comfort models, such as Predicted Mean Vote (PMV), Standard Effective Temperature (SET), and Adaptive models. This tool allows users to calculate the comfort state of occupants based on a set of input parameters, both environmental and personal.

8.2.4.3 Evaluation Based on Environmental Measurements (Long-Term over Typical Day, Season, or Year). Measures include:

a. Trend logging of physical measurements over time.
b. Temperature and humidity in the occupied zone. Globe temperature (temperature measured within a globe exposed to radiation exchange with surrounding surfaces) closely approximates operative temperature in most indoor situations. For greater accuracy, globe temperature measurements may be combined with shielded air temperature measurements to calculate mean radiant temperature, which, when averaged with the shielded air temperature, provides operative temperature.
c. Measuring indoor air movement over time is very difficult and rarely done. In many indoor situations, the indoor air speed conforms to the still-air conditions of the PMV comfort zone (0.1 m/s [20 fpm]), in which case air speed measurement is not necessary.
d. The number of hours in which local discomfort may be expected is estimated using the local thermal discomfort limits in Section 5. Local discomfort exceedance hours are added to hours in which the comfort zone requirements are exceeded (exceedance occurs when |PMV| > 0.5).

Criteria Metrics in Standard 55-2023:

a. The prescribed metric is the exceedance hour (semantically equivalent to discomfort hour), predicted during occupied hours within any time interval. See the definition in Section 3 and formulas in Section 7.4.2.2.1. Units are in hours. No limits are prescribed.
b. In addition, it is possible to account for the severity of exceedance at any time, using a metric analogous to the familiar degree-day. Weighted exceedance hours (equivalent to degree-of-discomfort hours) are the number of occupied hours within a defined time period in which the environmental conditions in an occupied zone are outside the comfort zone boundary, weighted by the extent of exceedance beyond the boundary. Units are thermal sensation scale units times hours. The formula for the PMV comfort zone uses terms defined in Section 7.4.2.2.1: WEH = [Hdisc (|PMV| – 0.5)]. Units are thermal sensation scale units times hours. This is a useful metric but is not required in Standard 55. No limits are recommended.
c. Temperature-weighted exceedance hours. It may be useful to convert PMV comfort zone WEHs to a temperature times hours scale using the conversion 0.3 (thermal sensation scale units)/°C (0.15 [thermal sensation scale units]/°F). The unit for temperature-weighted exceedance hours is temperature times hours. This is a useful metric but is not required in Standard 55. No limits are recommended.
d. The WEH for the adaptive model also uses a temperature times hours scale: WEH = [H>upper (Top – Tupper) + H<lower (Tlower – Top)] This is a useful metric but is not required in Standard 55. No limits are recommended.
e. Expected number of episodes of discomfort, rate-of-change exceedances, local discomfort exceedances within a time period of interest. These are useful metrics but not required in Standard 55-2023. No limits are recommended.

8.3 Level 3: Advanced Analysis

8.3.1 Level 3: Objective. To provide a comprehensive approach to building performance evaluation, Level 1 evaluates overall satisfaction and benchmarks building performance, while Level 2 diagnoses specific problems based on occupant feedback and spot measurements.

Level 3 focuses on advanced analysis to provide deeper insights into system performance and address complex issues. Objectives include:

a. eliminate sources of local discomfort.
b. Move toward personal comfort control.
c. Implement new design and operation solutions that overcome the comfort and energy-efficiency limitations imposed by existing systems.
d. Conduct a research-grade evaluation of the building for performance benchmarking.

ASHRAE's two comfort models (PMV and Adaptive) predict a person's whole-body comfort. The sensations and comfort for local body parts are not differentiated in these models. Local thermal effects that might exist in the environment are dealt with in the standard only in the context of discomfort that they might provide, and by setting upper limits to local environmental conditions. The methods for evaluating these local effects are prescribed in Standard 55-2023, Section 5.3.5. They are described below.

One can anticipate future advances in comfort analysis beyond what is presented here. Comfort research has in recent years been developing more advanced comfort models than the two in Standard 55, capable of simulating the thermal physiology and comfort sensitivity of several individual body segments, and their effects when experienced in various combinations. They predict both positive and negative comfort resulting from localized thermal environments that are not uniformly distributed around the body, and that might also be changing in time. Such non-uniform environments may be caused by solar radiation, air movement from fans or windows, displacement and underfloor ventilation systems, radiant heating and cooling panels, and personal comfort systems that affect local air temperatures, surface temperatures and air movement. The advanced models also can better simulate the comfort of transient thermal conditions in environments that are changing in time, such as people moving between spaces with different thermal conditions.

Such non-uniform environments have been found to produce positive pleasantness experiences (known as alliesthesia) that exceed the comfort associated with neutral thermal sensations. Since neutral sensation is considered the ideal for comfort in all existing standards, alliesthesia presents an opportunity for the future. Environmental control using its principles offers the possibility of more responsive and comfortable environments, and greater energy efficiency in providing them.

8.3.2 Level 3: Metrics. The Advanced Level addresses localized comfort effects within the region directly surrounding the occupant. In most cases, environmental measurements are taken at finer resolution compared to Level 2. Level 3 identifies sources of local discomfort and assesses occupants' sense of control over their personal thermal environment.

Table 8.4 outlines the specific measurement parameters used at the Advanced Level to evaluate local discomfort in the occupant's immediate environment. These parameters address key aspects of the thermal environment that contribute to local discomfort or dissatisfaction, providing a detailed framework for identifying and assessing potential issues, as further described below.

Table 8.4 Advanced Analysis Measurement Parameters.

Type	Metric	Measurements	Limits
Radiant temperature asymmetry	Plane radiant temperature	PRT, MRT, Solar exposure	ASHRAE Standard 55-2023, Section 5.3.5.2
Ankle air speed	Air speed	Air speed at 0.1m (3.9 in.) above floor, temperature at average body height	ASHRAE Standard 55-2023, Section 5.3.5.3

Vertical air temperature gradient	Temperature difference	Air temperature	ASHRAE Standard 55-2023, Section 5.3.5.4
Floor surface temperature	Temperature	surface temperature	ASHRAE Standard 55-2023, Section 5.3.5.5
Cyclic variations	Temperature change	dT, <0.25 hours	ASHRAE Standard 55-2023, Section 5.3.6.2
Drifts or ramps	Temperature change	dT, >0.25 hours	ASHRAE Standard 55-2023, Section 5.3.6.3
Thermal controls	Thermal environmental control	Test control functionality	ASHRAE Standard 55-2023, Section 6
Thermal control	Availability of controls	Distance to thermostat	ASHRAE Standard 55-2023, Section 6
Excessive air flows, especially during low occupancy	Temperature Local air speed (draft) on occupants	Temperature Air speed	ASHRAE Standard 55-2023, Appendix I

Radiant temperature asymmetry and solar exposure: The thermal radiation field about the body may be non-uniform, due to hot and cold surfaces or to direct sunlight or sky radiation. This asymmetry may cause local discomfort and reduce thermal satisfaction with the space. The vertical radiant temperature asymmetry represents plane radiant temperatures oriented in the upward and downward directions. The horizontal radiant temperature asymmetry is the maximum radiant temperature asymmetry for all horizontal directions.

Floor surface temperature: Hot or cold floors can cause discomfort, especially in areas where occupants are in direct contact with the floor, such as sitting areas or workplaces where people stand for extended periods. Significant differences between floor surface and air temperatures can affect individuals' perception of the overall thermal environment.

Draft: Draft is unwanted local cooling of the body caused by air movement. It is most prevalent when the whole-body thermal sensation is cool (below neutral). Sensitivity to draft is greatest where the skin is not covered by clothing, especially the head region comprising the head, neck, and shoulders and the leg region comprising the ankles, feet, and legs.

Vertical air temperature difference: Thermal stratification, resulting in the air temperature at the head level being warmer than that at the ankle level, may cause thermal discomfort. Thermal stratification in the opposite direction is rare, perceived more favorably by occupants, and is not addressed in Standard 55.

Occupancy: Factors such as occupant seating, proximity to windows and exterior walls and occupancy schedules all influence individuals' local environment and thermal comfort. Information about representative occupant activities (metabolic rate), and clothing policy (clothing insulation) can help identify personal factors and (the limits of) adaptive opportunities.

Thermal environmental control: Occupant-controlled environmental control systems allow individuals to tailor their immediate surroundings according to their preferences and physiological needs. ASHRAE Standard 55, Section 6, provides a thermal environmental control classification to evaluate building spaces based on the level of occupant control over temperature and air speed (e.g., an adjustable thermostat near the occupant, a ceiling fan in a private office).

8.3.3 Level 3: Measurement Methods. The following are examples of measurement methods for Level 3. The Level 2 diagnostics section lists measurement methods and equipment that can also be used for Level 3.

a. Air temperature and average air speed should be measured at the 0.1, 0.6, and 1.1 m above the floor (4, 24, and 43 in.) levels for seated occupants.
b. Measurements for standing occupants should be made at the 0.1, 1.1, and 1.7 m (4, 43, and 67 in.) levels, and measurements for horizontal occupants should be made at the mean height of the body.

c. Operative temperature or PMV should be measured or calculated at the 0.6 m (24 in.) level for seated occupants, the 1.1 m (43 in.) level for standing occupants, and the mean height of the body for horizontal occupants (e.g., a bedridden patient).
d. The surrounding surface temperatures of a space are expressed as mean radiant temperature (MRT), which equals long-wave mean radiant temperature when no solar radiation is present.
e. Radiant temperature asymmetry should be measured in the affected occupants' locations, with the sensor oriented to capture the greatest surface temperature difference.
f. Generally, the radiant temperature asymmetry is determined at waist level, 0.6 m (24 in.) for a seated occupant and 1.1 m (43 in.) for a standing occupant.
g. Floor temperature should be measured at the surface by contact thermometer or infrared thermometer.
h. For predicting sun position, a variety of devices produce fish-eye images with sun path overlays. Images are typically taken facing upward from occupants' workstation. An image shows the areas of the window surface through which the sky is visible from a workstation. The superposed sun path diagram shows the portion of the window surface through which direct sunlight reaches the workstation in clear weather, as well as the time periods (hours of the day for each month of the year) during which this occurs.
i. Floor plan: Thermal environment measurements should be made at a representative sample of locations where the occupants are known to, or are expected to, spend their time. When performing evaluation of similar spaces in a building, the occupants should select a representative sample of such spaces.
j. For occupant metabolic rate (met) and clothing (clo) observations, refer to Chapter 5 of Standard 55: Occupants for specific occupancy measurement methods.
k. Control measures for environmental factors: thermal environmental control classification level should be documented for each space type, indicating the control measure(s) for environmental factors, the means of control, and the degree to which control changes the environmental factor.

8.3.4 Level 3: Performance Evaluation and Benchmarks. Thermal comfort may also be analyzed using the criteria and requirements in thermal comfort standards. These include:

a. Radiant temperature asymmetry:
    1. Allowable radiant temperature asymmetry in ASHRAE Standard 55-2023, Table 5-10 is primarily used for limiting longwave radiation from building surfaces. When direct-beam solar radiation falls on building occupants, the radiant temperature asymmetry should account for the solar contribution by following the calculation method in ASHRAE Standard 55-2023 (Section 5.3.5.2 and Appendix C).
b. Floor surface temperature:
    1. For occupants seated with their feet in contact with the floor, floor surface temperatures within the occupied zone should range from 19°C to 29°C (66°F to 84°F).
    2. Standard 55 gives the percentage of occupants expected to be dissatisfied due to floor temperature based on people wearing shoes. The standard does not address the floor temperature required for people not wearing shoes or sitting on the floor.
c. Draft:
    1. Draft at the lower-leg region may occur in buildings conditioned by thermally stratified systems like displacement ventilation or underfloor air distribution, or those with cold-dropping airflow along external walls and/or windows.
    2. Manufacturers of air diffusers intended for stratified systems often provide diffuser performance data that can assist designers in predicting ankle air speed.
    3. Air-movement comfort provisions are provided in ASHRAE Standard 55-2023. Note that although the ADPI index [Refer to ASHRAE Standard 113] uses air-movement limits for rating the performance of overhead mixing diffusers in laboratory tests, its limits do not represent thermal comfort requirements in actual occupied spaces.
    4. Supply air diffusers typically include baffles and vanes that use the airflow momentum to direct and diffuse the supply air jet. Avoiding 'diffuser dumping' of cooled supply air has for years

been a major concern of HVAC designers, causing them to limit the supply volume turn-down to assure forceful diffuser mixing. The ASHRAE RP 1515 project examining diffuser effects on comfort showed that in practice, draft discomfort was rarely caused by low supply air flows, but instead by overcooling during low load situations caused by maintaining high flows to prevent dumping (Arens et al. 2015). Maintaining comfortable diffuser flows in VAV systems involves adopting dual max control sequences in the air handling system (ref ASHRAE RP 1455, GPC 36, ASHRAE Std 90.1-2013).

d. Vertical air temperature difference:
   1. Allowable gradients of the air temperature between head level and ankle level should be within the shaded region of Figure 8.3 (Adopted from ASHRAE Standard 55-2023, Figure 5-8). The maximum air temperature gradient is deduced from the predicted percentage dissatisfied with vertical air temperature gradient.

e. Occupancy and exposure:
   1. Refer to Chapter 5, Occupants.

f. Thermal environmental control:
   1. Each control measure for environmental factors should be readily accessible to occupants, capable of changing the thermal environment of the space of individual occupants by the magnitude specified in Standard 55-2023.

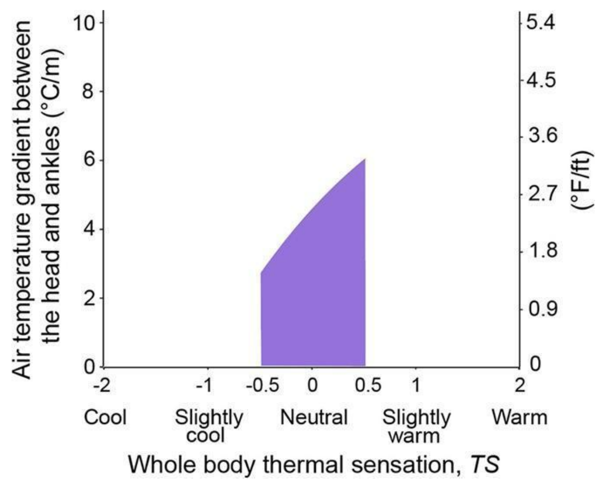


Figure 8.3 Vertical Air Temperature Gradient Limit as a Function of Whole-Body Thermal Sensation. (Source: ASHRAE Standard 55-2023, Figure 5-8)

9. INDOOR AIR QUALITY

9.0 General Introduction and Background

9.0.1 Introduction. This section describes the procedures for performance assessment of indoor air quality (IAQ) from the simplest to the most complex levels of effort: Basic, Diagnostic and Advanced. The users of this guideline can determine what level of performance assessment best fits the project needs, their level of expertise, and available resources.

Level 1 (Section 9.1) describes the Basic Evaluation Procedures for characterizing IAQ at the most basic level, and for identifying and correcting problems. Every facility should perform these basic procedures before going on with the more complex procedures of Levels 2 and 3.

Level 2 (Section 9.2) describes the Diagnostic Measurement Procedures for characterizing IAQ more broadly, and for optimizing operation of the ventilation system. It is recommended that these procedures be implemented before using Level 3 procedures.

Level 3 (Section 9.3) describes the Advanced Measurement Procedures for measuring and managing comprehensive IAQ conditions over time. These procedures represent the most encompassing procedures that have been publicly documented and/or published in peer-reviewed journals.

9.0.2 Background. Considerable public interest in the quality of the indoor environment began in the 1970s, owing to the appearance of building-related subclinical health symptoms — also known as Sick Building Syndrome (SBS) symptoms (e.g., headache, shortness of breath, fatigue, eye and throat irritation) and outbreaks of several acute incidents, such as carbon monoxide poisoning (Wright, 2002) and Legionnaires' disease (Fraser et al. 1977). These were often the result of policies for conserving energy in buildings implemented during the 1970s energy crisis, such as tightening the building envelope to reduce uncontrolled outdoor air infiltration without using mechanical ventilation, which reduced the amount of outdoor air supplied indoors. As a result, modern buildings are typically built to be more airtight compared to older structures (Murray and Burmaster, 1995; Jones, 1999).

Modern health concerns related to air pollutant exposure in buildings have been exacerbated owing to several additional factors. First, the amount of time that people in developed regions spend indoors has been continuously increasing and often exceeds 90% (Klepeis et al. 2001). Additionally, owing to advances in construction technology and widespread development of the chemical industry, there is an increasing influx of synthetic chemicals into indoor environments (Weschler, 2009; Salthammer 2020). For as much as 95% of chemicals used in building construction, there is a lack of information on human health effects (Torgal et al. 2012). As a result, buildings more readily produce and accumulate indoor air pollutants than ever before. A number of studies have shown that the concentration of many air pollutants is higher indoors than outdoors, sometimes reaching two orders of magnitude higher (Wallace, 2000; Weisel et al 2005), and generally ranging from 2 to 5 times higher (US EPA, 2024a). Therefore, most human daily air pollutant exposure, even to air pollutants of outdoor origin, occurs indoors (Kim et al. 2005; Liu et al. 2007; Nazaroff 2018), and those concentrations can exceed health-based standards for acute and chronic exposures (Logue et al. 2011). Air pollutant exposure indoors not only impacts health, but also impacts overall human well-being, work performance, and learning (Wargocki et al. 2002; Seppänen et al. 2005) with enormous economic implications (Fisk et al. 2011). Furthermore, despite the progress in the development of building ventilation and IAQ standards, occupant satisfaction surveys conducted in hundreds of buildings worldwide indicate that the percentage of people satisfied with the quality of indoor air is significantly lower than that prescribed by building guidelines (Graham et al. 2021).

According to Nazaroff (2013), there are four core principles for achieving good IAQ, ranked in the order of priority: 1) Minimize indoor emissions; 2) Keep buildings dry [or better, regulate the relative humidity]; 3) Ventilate well; and 4) Protect against outdoor pollution. Indoor contaminants may come from outside or from sources in the building, which may include processes, equipment, activities, people, materials; they can also be the result of chemical transformations involving reactions with reactive species such as ozone or hydroxyl radicals (OH-) (Wu et al. 2024). Indoor source pollutants are best controlled by eliminating or reducing sources (or eliminating the risk for chemical transformations and reactions); this should be considered as a primary method for controlling levels of pollutants indoors, though it may not always be feasible. The levels of indoor pollutants may also be controlled by general ventilation to dilute and extract contaminants (assuming that outdoor air is clean), local exhaust ventilation, filtration and air cleaning, isolation, or other capture techniques. The measurement protocols outlined in this guideline will help to verify that efforts to limit indoor air pollutant concentrations are working, and the indoor environment is free of risks associated with health, comfort, work performance, learning and disturbed sleep of building occupants.

It is important to distinguish between the IAQ design and monitoring functions. While monitoring indoor contaminant levels is not necessary to design and construct a building with good IAQ, monitoring can contribute to improved IAQ by identifying conditions needing corrective actions such as source control or increased ventilation, with enhanced filtration and air cleaning when outdoor conditions are suboptimal. Many airborne contaminants found in buildings lack authoritative guidance or regulatory limits, which makes interpreting monitoring results challenging. Short-term monitoring results provide only a snapshot of the environment and do not necessarily capture spatial-temporal variations of IAQ. Therefore, more comprehensive, repetitive and continuous air pollution measurements are recommended at the Diagnostic (Level 2) and Advanced (Level 3) levels. At all three levels of IAQ assessment, an examination of the design and construction features in relation to the principles of good IAQ, as covered in ASHRAE (2009), should be conducted. This should be coupled with measurements of outdoor airflows for a realistic and reliable method of evaluation.

In the context of IAQ performance measurement, it is essential to distinguish between the health impacts of IAQ and perceived IAQ. ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, defines "acceptable indoor air quality" as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" (ASHRAE 2022a). The "no known contaminants" portion relates to toxic pollutants and associated health aspects of IAQ, whereas "majority of people exposed do not express dissatisfaction" (based on the presence of odors and irritants) relates to sensory comfort or perceived IAQ. The assessment of perceived IAQ is addressed at the Basic Level (Level 1) and further expanded at Level 2. Concerning health impacts, in the indoor air quality procedure (IAQP) of ASHRAE 62.1 (2022a), acceptable indoor concentration limits are needed for particles and design compounds, defined as indoor chemical compounds that have the potential to reduce acceptability of the air (see the design limits in Table 6-5 of ASHRAE 62.1-2022). At present, no single organization develops acceptable concentration limits for all substances in indoor air, nor are limits available for all potential design compounds or particles. However, cognizant authorities, such as the United States Environmental Protection Agency (U.S. EPA), California EPA, and the Committee for Health-Related Evaluation of Building Products (AgBB) publish concentration limits for compounds, many of which may be present in the indoor environment.

As suggested by ASHRAE Standard 62.1, there is no quantitative definition of acceptable IAQ that can necessarily be met by measuring one or more contaminants (ASHRAE, 2022a). With thousands of gases, particles, and microbiological contaminants that can be in the air, direct measurement of most of these constituents is impractical and expensive. There is a lack of epidemiological or toxicological information regarding their impact on building occupants, whether present individually or in combinations. Therefore, for many contaminants, benchmark thresholds for safe levels are generally unknown. Striving for "as low as possible" level of contaminants may be impractical and not justified because additional ventilation may be associated with higher energy costs. The existing literature has not fully established the optimal ventilation rate that considers both energy needs and human health.

9.0.3 IAQ Indicators. There are several performance assessment methods that could serve as indicators of IAQ. This guideline proposes various degrees of implementation across the three assessment levels, based on the best fit for the project needs, available level of expertise, and resources. These indicators are as follows:

a. **Ventilation compliance.** The most relevant measurements of indoor and outdoor parameters that affect human health are contaminant concentration levels. Outdoor air ventilation is a driving factor for the control of a broad suite of indoor-generated air contaminants. However, it does not reveal the resultant indoor concentrations. Ventilation is more readily measured than most pollutant levels, though measuring ventilation is still very challenging in many buildings and nearly impossible in some, such as naturally ventilated or mixed-mode buildings with multiple spaces. It should also be noted that the use of ventilation rate measurements as an indicator of IAQ should be accompanied by a thorough review of compliance with the operation and maintenance requirements of ASHRAE Standard 62.1 (2022a). Compliance with ASHRAE Standard 62.1 does not ensure good IAQ, but the components and requirements within the standard are foundational for proper HVAC operation and control, which are a precursor for acceptable IAQ conditions. To be considered a marker of IAQ, ventilation air should be documented to be clean, as well as meeting national air quality standards.

b. **Outdoor air quality.** An important caveat is that, in most urban contexts, the use of outdoor air for ventilation is based on the misleading assumption that outdoor air is clean. A recent study showed that outdoor-originating pollutants (especially $PM_{2.5}$) provoke most of the damage to human health in terms of disability-adjusted life years (DALYs) (Belias and Licina, 2024). It should, therefore, be an established principle that outdoor air does not correspond to clean air by default. While the dilution of indoor contaminants is achieved by supplying outdoor air, this outdoor air can increase risks of exposure to pollutants present outdoors.

c. **Site inspection.** Another indicator of IAQ is a visual inspection of ventilation systems equipment and associated components, as well as building materials, potential strong pollution sources, leakages, and visual signs of moisture/mold. Building and system characteristics, especially the condition and operation of HVAC systems, are useful for identifying physical problems that may cause or contribute to unacceptable IAQ. They are also useful for identifying areas to adjust and optimize ventilation systems to improve IAQ or to reduce energy without affecting IAQ. ASHRAE Guideline 42-2023 (2023), Enhanced Indoor Air Quality in Commercial and Institutional Buildings, provides commissioning recommendations, after a building has been turned over to the owner, which apply to buildings, their ventilation systems, and their components. Recommendations include, but are not limited to, reevaluating ventilation systems after a building alteration or change of use, identifying contaminants introduced by occupants or through maintenance services that were not previously accounted for through source control or ventilation, and inspecting spaces after pipes breaking, natural disasters, or other unforeseen events.

d. **Occupant surveys.** The next indicator of IAQ can be obtained from occupant surveys. The minimum ventilation rates presented in ASHRAE Standard 62.1 (2022a) were historically established with the support of chamber studies that determine ventilation rates needed to control odors originating from human bioeffluents and to alleviate stuffiness. This is because the human nose is an efficient odor detector, assuming it is not fatigued. Generally, if an odor is discernible in terms of intensity and is deemed unpleasant (which is subjective since what may be disagreeable to some could be pleasing to others), it often serves as an indication of an underlying issue. However, pleasant smells may mask harmful contaminants. Moreover, factors such as the time of day and other social contexts may impact the perceptions of IAQ, including the duration of exposures.

   A carefully designed, administered, and analyzed occupant survey can provide useful information as an indicator of IAQ. It is important to note, however, that many air pollutants cannot be effectively detected by the human nose and that satisfied occupants do not necessarily guarantee acceptable IAQ. Also, occupant evaluations can be biased by personal preferences, health conditions, and other parameters not normally associated with IAQ, such as temperature, relative humidity or noise. Therefore, while an occupant survey is a valuable tool, it alone is an insufficient indicator of IAQ if it is based on the building occupants' perception of odor. These surveys can also provide information on sensory irritation and nuisances not necessarily related to odor perception.

e. **IAQ measurements.** Measurements of specific indoor air pollutants, such as volatile (VOCs) and semi-volatile (SVOCs) organic compounds (and potentially total volatile organic compounds (TVOCs)), fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}), ozone, and some inorganic gases, can provide some useful information about IAQ. In addition, as noted in ASHRAE 62.1-2022, measurement of dew points on surfaces are useful because surfaces with elevated dew points can contribute to mold and fungal growth. Moreover, indoor moisture and humid conditions may promote the accumulation and growth of microbial pathogens, including bacteria and dust mites. These pathogens can lead to odors and can cause respiratory irritation and allergies in sensitive individuals. Measurements of these pollutants over time can also provide a baseline for responses to complaints or suspected health effects. These measurements can also help to determine the relations between IAQ complaints, changing perceptions of air quality, abnormal HVAC system operation, or other suspected IAQ problems. In addition, these measurements may suggest adjustments in ventilation rates to address elevated levels of these indoor pollutants.

   Physical complexities of measurements of air pollutants include time and spatial variation, broad size range (for particles), chemical and biological specificity. At present, there are no IAQ measurement techniques routinely deployed in buildings that can address all dimensions of complexity. Practical complexities include physical access (e.g., tenant space), cost, instrument accuracy and calibration, selection of zones and spaces for measurement, and interpretation of results. For example, TVOCs are used as a proxy of exposure to volatile organic compounds (VOCs). However, measured TVOC should only be used in a relative, not absolute, sense because no standard definition of TVOC exists. Furthermore, no single method can detect all VOCs that may be of interest. Therefore, TVOC should not be used as the sole indicator for IAQ. Measurement of indoor CO_2 concentrations can, under some circumstances, be used as an indicator of outdoor air ventilation rates (in spaces occupied by people), but there are many important limitations of using CO_2 for this purpose that are often not appreciated (for details see ASTM Standard D6245 (ASTM 2018) and ASHRAE Position Document on CO_2 (ASHRAE 2022b)). The recent advent of low-cost sensors is enabling rapid expansion of monitoring air pollutants such as CO_2, TVOC, ozone and $PM_{2.5}$ with high spatial-temporal granularity, yet many measurement conditions need to be considered, including precision, calibration (incl. autocalibration), etc.

In addition to direct IAQ measurements, it is crucial to consider elements that can affect both the physical and perceived aspects of IAQ. The quality of outdoor air, for instance, plays a significant role. Additionally, environmental factors such as thermal conditions, acoustics, and lighting also have notable impacts on IAQ, particularly perceived IAQ. Discrepancies often arise between measured concentrations of indoor air contaminants and the subjective perception of IAQ, as indicated in previous studies (Langer et al., 2017; Boso et al., 2020; Licina and Langer, 2021). Particularly, thermal conditions can influence occupant perceptions of IAQ and, in some instances, lead to an increased reporting of symptoms associated with Sick Building Syndrome (SBS). Extreme thermal conditions may even contribute to the creation of unhealthy environments. Therefore, understanding the intricate relationships between thermal conditions and contaminant considerations is essential (refer to Section 12 IEQ Interaction and Integration).

9.0.4 Measurement of IAQ Performance: Characterizing and Quantifying IAQ. The prevailing body of literature and industry practices indicate that IAQ performance measurements typically revolve around six fundamental tasks. Of these tasks, some will be applicable at the Basic, Diagnostic, and Advanced levels. A general overview is presented below, with detailed explanations provided in subsequent sections.

a. **Ventilation compliance.** Characterization of IAQ performance according to this protocol should include an assessment of outdoor air ventilation rates and other requirements in ASHRAE Standard 62.1 (ASHRAE 2022a). This guideline focuses on compliance with the Ventilation Rate Procedure of ASHRAE Standard 62.1 as an indicator of adequate ventilation. Compliance can be ensured through measurement of outside airflow rates (Level 1), and measurement of ventilation air distribution in all ventilated (or conditioned) zones of the building (Level 2).

b. **Outdoor air quality.** Because the outdoor air should not be considered clean by default, the basic level of effort (Level 1) aims to determine if the building is in an EPA non-attainment zone using National Ambient Air Quality Standards (NAAQS) and U.S. Weather Service data. For the next level of assessment, existing local air quality data can be used to determine whether the building is in an EPA non-attainment zone. Finally, the most advanced method (Level 3) provides real-time local outdoor air quality measurements at the building site, combining hourly indoor air quality data with weather data to gain better insight into the dependency on outdoor air.

c. **Site inspection.** Site inspection is part of the basic evaluation procedure (Level 1) to assess the design, installation, and operation of building systems affecting IAQ. Table 8-1 of ASHRAE 62.1 (2022) provides a detailed summary of inspection tasks for ventilation system equipment and components. The ASHRAE IAQ Guide (2009) outlines control measures for moisture and contaminants related to mechanical systems. Including IAQ complaint logs from building occupants for review is also recommended. It is also recommended referring to the EPA BASE protocol presented in the publication entitled “Data on Indoor Air Quality in Public and Commercial Buildings” (US EPA 2006). Also, Appendix B and TAB V of the EPA publication “Building Air Quality Guide: A Guide for Building Owners and Facility Managers” (US EPA 1991), should be consulted to determine the parameters of the building and site inspection.

d. **Occupant surveys.** Occupant surveys help to identify IAQ problems in building areas. The surveys can help to highlight areas that require attention by denoting occupant acceptability and satisfaction.

These surveys can focus attention on conditions where IAQ is considered to be unacceptable, allowing for correlation with environmental measurements. This guideline includes assessment of occupant acceptability and satisfaction at Levels 1 and 2. Specifically, Level 1 evaluates occupants' ratings of IAQ acceptability and satisfaction, comparing them with previous field observations. Level 2 involves more frequent assessments, identifying potential causes of dissatisfaction, and benchmarking against peer buildings.

e. **IAQ measurements.** This guideline distinguishes between continuous, time-integrated, and targeted measurements. Continuous measurements are always recommended, not just when a specific problem is identified. Targeted measurements involve spot-checks in specific building areas where issues are suspected or indicated by occupant complaints. Depending on the type of indoor air pollutant, time-integrated measurements may be conducted once or periodically. The three assessment levels vary in comprehensiveness and cost. Besides direct IAQ measurements, it is crucial to consider factors affecting both the physical and perceived aspects of IAQ. In this guideline's IAQ section, we will focus on air temperature as an influencing non-IAQ variable.
f. **Analysis and reporting.** Analysis and reporting involve conducting an in-depth analysis and presenting the findings comprehensively. This includes a thorough discussion and interpretation of both measured and perceived IAQ results, identifying potential causes for any deviations from accepted criteria. The report should also address brief yet intense exposures or episodic events. It is essential that all technical aspects, such as the development of sampling protocols, data interpretation, and the final signed report, are documented by individuals with specialized training and experience in assessing IAQ in non-industrial buildings, such as certified industrial hygienist (CIH).

9.0.5 Scoping IAQ Monitoring with Regard to Cost and Outcomes. Early decisions on budgeting and scoping are important (CIBSE, 2022). While it is preferred to conduct extensive IAQ measurements (e.g., gathering comprehensive data continuously and everywhere), this may not be economically viable and sometimes it is not necessary. It is important to note that initial cost alone may not correspond to long-term costs because of maintenance and management of monitoring systems. Additionally, large amounts of data are challenging to store, process and utilize, and measurements may require specific permissions regarding data storage. Therefore, the benefits related to efforts invested in a higher level of IAQ assessment should be justified. It is more useful to have limited IAQ measurements whose outputs are useful for better building operation than to have too many complex datasets that are not used.

9.0.6 Target Audience. The protocols presented in this guide may be used by various groups. The target audience for the IAQ measurement methods depends on the purpose of the measurement: benchmarking, IAQ audits, responding to complaints, retro-commissioning, capital planning, new building commissioning, controls and operation, financial audits, sustainability reporting, tenant attraction (e.g., employee recruitment and retention), big data analysis or research. For each of these use cases, there are different users of the data, including: tenants/occupants, building owners/owner's reps., architects, consulting engineers/facility managers, building raters, government agencies/legal counsel, building service companies, manufacturers/product suppliers, commissioning specialists and researchers.

The basic protocols (Level 1) are intended for building owners and operators, facility managers, architects and designers, and government officials to obtain a high-level Indication of the building's performance. Facility or energy managers and engineers, commissioning specialists, and building rating assessors, all with a significant level of technical knowledge and expertise, are likely to use the diagnostic (Level 2) and advanced (Level 3) levels to obtain a more detailed, comprehensive, and precise assessment of building IAQ performance. Additional users of the more advanced levels will include researchers interested in whole-building performance (energy and indoor environmental quality).

9.1 Level 1: Basic Evaluation

9.1.1 Level 1: Objective. The basic evaluation procedure aims to characterize IAQ and occupant responses of acceptability and satisfaction at the basic level, and to identify and correct problems. The specific objectives are:

a. **Ventilation compliance**. Verify compliance with the Ventilation Rate Procedure in ASHRAE Standard 62.1 (ASHRAE 2022).

b. **Outdoor air quality**. Determine whether the building is in an EPA non-attainment zone, per NAAQS (US EPA 2024c) and U.S. Weather Service data.
c. **Site inspection**. Collect building data and conduct a facility pre-evaluation by walking through the building and identifying any sources of problems, such as visual signs of moisture/mold. Also, prepare for site assessment by reviewing complaint logs.
d. **Occupant survey**. Determine occupants' ratings of acceptability and satisfaction with the building's IAQ and compare with previous field observations.
e. **IAQ measurements**. Conduct continuous measurements of a few air contaminants in major occupied locations, and targeted measurements of carbon monoxide (CO) in the vicinity of combustion sources if present.

9.1.2 Level 1: Metrics. For the Level 1 – Basic IAQ assessment, the following items should be measured:

a. **Ventilation compliance**. On an annual basis, measure outdoor airflow rates at each fan system intake under design conditions. These airflow rates should meet the minimum specified in ASHRAE Standard 62.1.
b. **Outdoor air quality**. If the building is in a non-attainment zone, as determined by the NAAQS data for the location (US EPA 2024c), verify that appropriate filters for ozone and particulates are in place for outdoor air (OA) intakes, per the requirements in ASHRAE Standard 62.1 (ASHRAE 2022a).
c. **Site inspection**. Report building and HVAC system configuration and conditions, as well as observations of potential moisture/mold problems on an annual basis, as an indication of potential IAQ problems; report actions taken to resolve them. Review report of occupant complaints of poor IAQ, as well as actions taken to resolve them.
d. **Occupant survey**. Report results of the occupant survey of IAQ over a period of a minimum of a few months, and compare them to the same surveys previously conducted, if available. Report actions taken to resolve any problems identified.
e. **IAQ measurements**. Install CO_2, air temperature, and relative humidity sensors for continuous monitoring in major occupied spaces. When sources of combustion are identified, conduct measurements of carbon monoxide (CO). The resulting values are generally analyzed using descriptive statistical parameters, including average (mean), maximum, minimum, and distributions (arithmetic, geometric). Additionally, it is customary to represent pollutant concentrations using a time series diagram, illustrating variations in pollutant concentrations over time.

9.1.3 Level 1: Measurement Methods. For the Basic (Level 1) Evaluation, adopt the following methods to gather information about the building, IAQ conditions, and occupants' responses to the environment.

9.1.3.1. Verify Compliance with the Ventilation Standards. To ensure compliance with ASHRAE Standard 62.1, ventilation rates should be measured at the OA intake to each HVAC fan system using a pitot tube traverse or a flow meter. This rate should be measured annually at design airflow conditions, with any dynamic reset control disabled. For variable-air-volume (VAV) systems, controls should be set to the design minimum. Direct measurements should be made; indirect measurements, such as CO_2 concentration balance at the mixing plenum, are not recommended because of accuracy problems. OA measurement techniques and expected accuracies are discussed in Fisk et al. (2005).

For single-zone systems, if measurement at the OA intake cannot be accomplished, OA can be measured at the air-handling unit (AHU). However, this may require taking the difference between velocity traverses in the supply and return ducts, which can be extremely inaccurate if the OA intake fraction is small. To determine proper OA distribution in multizone systems, the measurement is complex. The most accurate way is to use the multiple spaces equation in the spreadsheet distributed with the ASHRAE Standard 62.1 User's Manual, along with OA flow and space airflow measurements. A simpler conservative estimate can be obtained using the procedure in Informative Appendix G of the ASHRAE Standard 62.1 User's Manual.

9.1.3.2. Determine the Outdoor Air Quality Compliance. Determine the quality of outdoor air (OA) compliance in accordance with ASHRAE 62.1 (2022a). Obtain and document NAAQS data (US EPA 2024c). For instance, the National Aeronautics and Space Administration (NASA) maintains Tropospheric Emissions: Monitoring of Pollution (TEMPO) that will measure air pollution hourly for sites throughout North America, starting late 2023 (TEMPO, 2024). For sites outside the United States, use applicable national or state standards for OA quality. If the site is in a nonattainment zone, check whether proper filters for ozone and particulates are installed, as required in ASHRAE Standard 62.1 (ASHRAE 2022a).

9.1.3.3. Conduct a Facility Pre-Evaluation and Site Inspection. The following information about the facility needs to be collected and recorded for the Basic level:

a. Review facility operational documentation. Review building and tenant descriptions, as-built drawings, and information on the facility construction. Document the occupancy types and operations for each space type in the facility. Review building plans, including HVAC designs. Note any remodeling and HVAC projects in progress or completed since occupancy, recommissioning, or the last occupant acceptability and satisfaction survey.
b. Prepare for a site assessment. Contact building managers and tenant facility coordinators for the purpose of conducting a telephone or virtual in-briefing. Obtain HVAC system attribute information. The attribute list provided by the building owner should include systems that affect IAQ, scheduled operation, typical setpoints, mechanical filter ratings, and control of OA. Ensure all pertinent facility information is provided by the building owner prior to initiating the site visit.
c. Inspect mechanical rooms and check OA damper operation, HVAC distribution system (check drain pan for drainage, coil cleanliness, condition of the duct liner and return air plenum and confirm filter specifications, filter bypass and proper Minimum Efficiency Reporting Value [MERV] level), building exterior, roofs, and occupied spaces to verify HVAC system attributes, condition, and proper operation, specifically with respect to compliance with ASHRAE Standard 62.1 (2022a). An example checklist that considers HVAC system operation is provided in Informative Appendix I1.
d. Inspect for staining that may indicate moisture/mold problems and inspect for combustion sources. Note any conditions that could affect air quality, such as improperly located OA intakes, water damage, or similar variations. Examine perimeter walls, especially in corners and under windows, for signs of moisture/mold. Inspectors may refer to the National Institute for Occupational Safety and Health (NIOSH) Dampness and Mold assessment tool for walk-through (NIOSH, 2018).
e. Review IAQ complaints log and similar reports of continuing or episodic concerns, previous occupant satisfaction surveys, and/or IAQ audits, as well as related environmental, health, and safety surveys. Document responses and actions taken.

Persons conducting a walk-through assessment can use the EPA checklist to conduct thorough assessments of the entire building (EPA, 2022).

9.1.3.4. Conduct Occupant IAQ Survey. Conduct an annual occupant survey in a completed and substantially occupied building to assess occupant ratings of acceptability and satisfaction with IAQ, and to compare them with past ratings. Existing surveys, such as the CBE (2024) or BUS (2024), include IAQ questions that may be used to develop the survey.

Anonymous surveys with neutrally framed questions provide the best responses. When conducting an evaluation of adapted occupants, respondents should record their perception of zone air quality after 30 minutes of residency in the occupied zone. Occupants in each regularly occupied zone of a building should be surveyed.

In addition to questions related to acceptability and satisfaction with indoor air quality, the survey questions may also include perceptions of fresh air, stuffiness, the presence and intensity of odors, their pleasantness, etc. An example of the acceptability question could be "*Do you perceive the air quality in your environment to be acceptable or unacceptable?*". An example of a satisfaction question could be "*How satisfied are you with the air quality in your building?*" The satisfaction ratings can be evaluated on a 7-point Likert scale; from –3 (very dissatisfied) to +3 (very satisfied), where zero denotes neutral state (neither satisfied nor dissatisfied).

Occupant surveys can be executed through web-based, paper-based, or interview-based methods. Web-based surveys have gained popularity due to their ability to significantly reduce administration costs, and to expedite data collection and analysis. All surveys should aim for a representative sample size and a high response rate across the occupied spaces. A minimum 30% response rate is desirable, assuming substantial occupancy. A 40% response rate to a general survey of all occupants is generally considered sufficient.

The occupant survey conducted at this level focuses on ratings of acceptability and satisfaction, specifically assessing the IAQ response of building occupants over a designated period (e.g., 6 or 12 months). In the case of a new building, the first IAQ survey may be conducted approximately six months after occupancy – late enough to avoid assessing the effects of commissioning but early enough to identify and address any long-term building issues that may have escaped detection during commissioning.

If the results are communicated to building occupants, it should be done on an aggregated basis, so that no individual occupants can be identified.

9.1.3.5. Conduct IAQ Measurements. Prepare a sampling plan for collecting physical measurements of several indoor air pollutants. At the Level 1 evaluation, there are two types of measurements that provide the data needed for IAQ performance analysis and source identification: continuous and targeted real-time measurements. The following describes the measurement approaches in each of these two categories.

a. **Continuous measurements.** Parameters to be continuously measured at the three levels of assessment are summarized in Informative Appendix I2. At Level 1, carbon dioxide (CO_2), air temperature and relative humidity are measured and logged, the first and the last being useful indicators of IAQ which can show if unwanted IAQ conditions exist. Basic protocols use low-cost continuous instruments which may operate online or offline. Sensor technical specification requirements for these measurements are summarized in Table D.2 of Informative Appendix D5. Measurements should be carried out under typical occupied building conditions, based on a minimum recommended placement density. Details on suggested air monitoring data coverage (spatial and temporal) are available in the Informative Appendix I3. Information pertaining to sensor naming schema, data analytics, and reporting can be found in the Informative Appendix I4.
   Periodic calibration of continuous measuring devices is essential for all ongoing monitoring activities. Although this guideline does not provide detailed calibration procedures, Informative Appendix D5 summarizes a relevant CO_2 sensor calibration procedure.
b. **Targeted real-time measurements.** If combustion sources are present in or near the building, targeted real-time measurements of CO concentrations should be conducted in occupied spaces and compared to the EPA ambient air levels (EPA 2024c), i.e., 9 parts per million (ppm) for 8 hours and 35 ppm for 1 hour. The measurements should be collected at least once per 10 minutes. While other contaminants (nitrogen oxides [NOx], particulates, benzene, and formaldehyde) are emitted from combustion sources, CO is immediately dangerous and it can be readily measured. If combustion takes place in particular spaces, these places should be isolated from other spaces (by pressurization, airflows, self-closing doors, etc.). Measurements of a broader suite of air pollutants are addressed in Level 2 and Level 3 below.

9.1.4 Level 1: Performance Evaluation and Benchmarks. The following evaluation criteria should be confirmed:

a. **Ventilation compliance.** Compliance with the ventilation rate requirements prescribed by ASHRAE Standard 62.1 (2022a) is the minimum performance target of interest.
b. **Outdoor air quality.** If the outdoor air quality is deemed unacceptable, as determined by the NAAQS data for the location (EPA 2024c), additional filtering of OA for ozone and/or particulate matter may be required as Section 4 of ASHRAE Standard 62.1 (2022a). Users of this guideline may also opt to use the WHO (2021) guideline as a benchmark for compliance.
c. **Site inspection.** Compare documented building and HVAC systems and moisture/mold problematic conditions for compliance with ASHRAE Standard 62.1 (2022a).
d. **Occupant survey.** In an occupant acceptability and satisfaction survey, occupants' perceived IAQ can be evaluated using the percentage of acceptability and dissatisfied criteria in each occupied zone. "Acceptability" can be judged through a simple "Yes" or "No" criterion. "Dissatisfaction" may be interpreted by counting responses from the 7-point scale (from –3 to 3), from scale units –3 to 0. The survey test results should demonstrate occupant level of acceptability of 80% or more within each occupied zone. Similarly, the results should ensure that 80% or more of the surveyed occupants do not express dissatisfaction with the quality of the air. If previous occupant surveys exist, compare the

current survey data to that of the previous survey. Any degradation in occupant satisfaction should be noted for follow-up.

e. **IAQ measurements.** As stated in the ASHRAE Position Document on Indoor Carbon Dioxide (ASHRAE 2022b) many countries have proposed mandates or guidelines for indoor CO_2 on the order of 1000 ppm to 1500 ppm. However, the rationale to support these limits is not provided. CO_2 levels exceeding these limits are often considered indicative of inadequate ventilation to control odor and concentrations of other human metabolic products; such conditions signal a need to investigate and take corrective action. CO_2 levels for compliance with ASHRAE Standard 62.1 (2022a) are not defined.

   To determine if the continuous IAQ measurements are compliant with benchmarks, relative humidity should stay within the 30-60% range during all hours, ideally without the need for humidification. It should be noted that ASHRAE Standard 62.1 (2022a) requires that systems that are cooled by mechanical means or indirect evaporation need to maintain indoor humidity to a maximum dew point of 15°C (60°F) during both occupied and unoccupied hours, whenever the outdoor dew point is above 15°C (60°F). The CO levels should not exceed the US EPA's threshold of 9 ppm averaged over 8 hours or 35 ppm averaged over one hour. To ensure early detection and prevent hazardous exposure, if the 1-hour average CO concentration exceeds 5 ppm, the source should be investigated by a qualified professional (engaged by the building owner or manager). This lower threshold is intended as a precautionary action level, not a regulatory limit, and may indicate ventilation issues or the presence of combustion sources requiring corrective measures.

9.2 Level 2: Diagnostic Measurement

9.2.1 Level 2: Objective. Diagnostic measurements (Level 2) aim to provide IAQ evaluations with a higher level of confidence compared to Level 1, ensuring good indoor air quality IAQ is achieved. Before proceeding with a Level 2 assessment, all steps listed under Level 1 assessment should be completed. The specific objectives are as follows:

a. **Ventilation compliance.** Determine whether ventilation rates are adequate (in compliance with ASHRAE Standard 62.1 (2022a)) in all ventilated (or conditioned) zones.
b. **Outdoor air quality.** Using existing local air quality data, determine whether the building is in an EPA non-attainment zone per NAAQS (US EPA 2024c). If local air quality data is not available or if a strong local contaminant source is suspected, take measurements at the building site.
c. **Occupant survey.** Determine occupants' ratings of acceptability and satisfaction with the building's IAQ on a seasonal basis and identify potential causes in case of dissatisfaction. Rate the building's occupant acceptability and satisfaction levels both in comparison with the previous field observations and against benchmarks in a database providing ratings in the peer buildings where the measurements were conducted.
d. **IAQ measurements.** Conduct a combination of continuous and targeted real-time measurements of multiple air contaminants with higher spatial granularity (compared to Level 1) in major occupied locations and in the vicinity of known air pollution sources.

9.2.2 Level 2: Metrics. For the Level 2 – Diagnostic IAQ assessment, the following tasks should be completed:

a. **Ventilation compliance.** Measured OA flow rates should at least meet the minimum rates specified in ASHRAE Standard 62.1 (ASHRAE 2022a), not only at the building level but also in different building zones.
b. **Outdoor air quality.** Determine whether the quality of outdoor air exceeds pollutant criteria based on existing local ambient data. If so, verify and report whether mitigation measures are in place by the presence of appropriate filters and air cleaners in OA intakes.
c. **Occupant survey.** Report results of occupant IAQ surveys as experienced over distinct seasons, and compare the results to past performance (Level 1). Include diagnostic questions that offer insight into the nature of dissatisfaction. In addition, rate the building's satisfaction levels against benchmarks in a database of previously measured peer buildings. Report actions to be taken to resolve any problems identified.

d. **IAQ measurements.** For measured air pollutants, provide the same descriptive statistical values as described in Level 1 metrics. Conditions of measured air pollutant levels exceeding design condition concentrations should be reported, and corrective action should be taken as necessary.

9.2.3 Level 2: Measurement Methods

9.2.3.1 Determine Adequacy of Ventilation Compliance. Evaluate interior source locations and note any separate exhaust/ ventilation systems. Pay particular attention to systems for combustion, cooking, gymnasiums, natatoriums, etc. If a potential air pollution source is identified, using measured OA flow rates (see the discussion at the Level 1 assessment), calculate the difference between supply and exhaust flow rates and building pressure differential to confirm that exhaust ducts are under negative pressure to avoid air pollutant movement into the building.

In addition to the directly measured flow rates at the OA intakes collected as part of at Level 1, measure zone-to-outdoor air differential CO_2 levels in the return air ducts of representative temperature control zones, and in selected spaces in these zones, to capture the diversity in space functions. Sensors may be placed in the space or in the return air duct or plenum. Such measurements can be useful in assessing OA ventilation relative to occupancy levels, i.e., to determine whether the effective OA rate per person meets the rate required at design. However, note that CO_2 is a poor metric of ventilation in many circumstances, including but not limited to, sparsely occupied spaces, spaces with rapidly varying occupancy and ventilation rates, and those with significant amounts of pollutant-emitting building components. Space selection should concentrate on those spaces with atypical activities, such as loading docks, chemical and product storage, copying centers, or high public-traffic areas. Unoccupied or sparsely occupied spaces should be monitored only if there are reported concerns. ASTM Standard D6245 (ASTM 2018) should be consulted to ensure proper measurement approaches.

These measurements should be made continuously in selected zones and spaces under design and off-design (steady-state) occupancies for at least a one-week period. One-week short-term monitoring is intended to cover normal conditions of operation, not to capture all excursions from normal or design conditions.

In multi zone systems, the CO_2 measurements are used to detect OA distribution fault conditions in the critical zone, provided that all other zones are properly ventilated at design conditions.

Expected CO_2 concentrations (i.e., expected design levels under default conditions) for ventilation monitoring or demand-controlled ventilation can range from 800 to over 3000 ppm. Note, however, that these values are based on several assumptions, including steady state in a single zone, the default design occupancy and activity levels, an air distribution effectiveness of 1.0, and an assumed ambient (or outdoor) concentration of 400 ppm. On-site observations should verify these assumptions before these measurements are used to draw any conclusions about the adequacy of ventilation rates.

While indoor CO_2 measurements may, under limited circumstances, be used to determine adequate ventilation for controlling people-generated bioeffluents, CO_2 levels cannot be used to assess overall IAQ.

9.2.3.2 Determine the Outdoor Air Quality at the Site. The quality of outdoor air (OA) at the site should be determined using local air quality data sourced from nearby ambient monitoring stations. Ideally, data on outdoor levels of ozone, particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide, sulfur dioxide, and nitrogen dioxide should be available at intervals of at least once per hour from a data-gathering station located within 4 kilometers (2.5 miles) of the building—the closer, the better. These six criteria pollutants are regulated by the EPA's NAAQS and are used to calculate the Air Quality Index (AQI). Daily particulate concentrations and maximum 1-hour, or 8-hour values for other pollutants, reported within a 24-h period, are used to determine AQI. A similar local measurement and reporting approach can be implemented by a government or private entity, following EPA-developed protocols (US EPA, 2023). This data should be documented to supplement the NAAQS data for the site obtained at Level 1.

If the monitored buildings are in areas inadequately covered by existing local weather stations—such as urban heat islands or locales with significant local air pollution sources—it is advisable to conduct targeted measurements of the six criteria pollutants. These six pollutants alone may not capture all local pollutants of concern, so an observational survey of the building site and its surroundings should be conducted to identify additional local air pollutants. The EPA provides guidelines on optimal locations for local air monitoring stations (US EPA, 2024b), and Section 4 of ASHRAE Standard 62.1 (2022a) outlines procedures for this. If measurements indicate poor air quality (e.g., unacceptable AQI), ensure that proper filters for ozone and particulates are installed on OA intakes, as required by ASHRAE Standard 62.1 (2022a).

9.2.3.3 Conduct Occupant IAQ Survey. Conduct a seasonal occupant survey, such as the CBE (2024) or BUS (2024), to assess occupant acceptability and satisfaction with IAQ as experienced by them over a period of minimum of a few months. Level 2 methods include the basics of those from Level 1 but increase the frequency and detail of the surveys. Using seasonal surveys and adding diagnostic questions in the Diagnostic measurement procedures offer insight into the nature and timing of any dissatisfaction.

If an occupant expresses some level of dissatisfaction with the IAQ in their workspace, the satisfaction survey asks a second level of questions to diagnose the source of the dissatisfaction. The following example questions help identify the nature of the problem, the features of the building, and the building's operations that may contribute to that problem.

a. Is the air stuffy/stale?
b. Is the air not clean?
c. Does the air smell bad (odor)?

If there is an odor problem, the question should be asked to indicate which of the following contributes to the problem:

a. Tobacco smoke
b. Photocopiers
c. Printers
d. Food
e. Carpet or furniture
f. Other people
g. Personal care products
h. Cleaning products
i. Outdoor odors (car exhaust, smog)
j. Plants and the use of fertilizer/chemicals
k. Pets and service animals (if allowed)
l. Other (to be specified)

The final step is to compare the results with the previous field observations and against benchmarks in a database of previously measured peer buildings.

9.2.3.4 Conduct IAQ Measurements. Prepare a plan for taking physical measurements of indoor air quality. Some measurements will be routine, whereas some will depend on the nature of the performance issues identified in the Level 1 – Basic assessment. At Level 2 – Diagnostic assessment, there are two types of physical measurements that provide the data needed for IAQ performance analysis and source identification: continuous and targeted real-time measurements. The following describes the typical measurement approaches in each category.

a. **Continuous measurements.** At Level 2 assessment, continuous measurements of the following indoor air pollutants are recommended: carbon dioxide (CO_2), air temperature, relative humidity, particulate matter smaller than 2.5 µm ($PM_{2.5}$), and total volatile organic compounds (TVOC).
   Similar to Level 1, the continuous instruments may be operated online or offline. Sensor technical specification requirements are summarized in Table D.2 of Informative Appendix D5. Measurements should be carried out under typical occupied building conditions with a placement density higher than at Level 1, as specified in Informative Appendix I3. Measurement locations should correspond to those described in Level 1 (see Informative Appendix I3).
b. **Targeted real-time measurements.** In addition to CO, Level 2 assessment should include targeted real-time measurements of nitrogen dioxide (NO_2) and ozone (O_3), particularly if indoor air pollution sources are suspected or if occupant surveys indicate problems.
   This pollutant should be monitored for at least 8 hours. Sensor specification requirements for NO_2 and O_3 are summarized in Table D.2 of Informative Appendix D5. Because strong seasonal variations

may exist, measurements are recommended to capture at least one period in both the heating and the non-heating seasons.

9.2.4 Level 2: Performance Evaluation and Benchmarks. The following evaluation criteria should be applied:

a. **Ventilation compliance.** Compliance with ASHRAE Standard 62.1 (2022a) ventilation rates is the minimum performance target of interest. Direct measurements of OA flows indicate whether these rates are met. Continuous CO_2 measurements can serve as an additional possible indicator of compliance with these ventilation rates, though CO_2 measurements come with a significant margin of uncertainty.

b. **Outdoor air quality.** To determine if the continuous and targeted IAQ measurements are compliant with benchmarks, use the same benchmarking criteria as in Level 1.

c. **Occupant survey.** In an occupant satisfaction survey, use the same "dissatisfaction" criteria and comparison to past performance as established in Level 1. In addition, IAQ satisfaction survey metrics should be evaluated against a database of identical or similar questions from earlier surveys. One of the most prominent current databases for long-term satisfaction results is for the CBE (Center for the Built Environment) survey (2024), which has benchmarking scores for office and other building types. Results should be tabulated according to mean scores for occupant satisfaction with IAQ. The comparison can be against all buildings or against a filtered subset of buildings of similar type or characteristic. Filtering for peers is accomplished as follows: the IAQ questions can be subdivided into office buildings, schools, retail locations (answered by employees, usually not customers), hospitals (answered by nurses and staff, not patients), and laboratories.

Benchmarking performance should be visualized using graphics such as those that show cumulative distributions of the building's survey responses or histograms with standard deviation bars. These graphics are automatically generated by the survey (see example: https://cbe.berkeley.edu/research/occupant-survey-and-building-benchmarking/).

d. **IAQ measurements.** For CO_2, relative humidity and CO, use the same benchmarking criteria as in Level 1. To determine if the continuous IAQ measurements are compliant with benchmarks, at least 90% of each sensor's dataset in occupiable spaces for $PM_{2.5}$, including intervals with missing data, should meet the recent EPA's threshold of 9 $\mu g/m^3$.

Note that TVOCs can be defined in various ways, leading to different results for the same air sample, based on data collection and processing methods. Therefore, measured TVOC should only be used in a relative, not absolute, sense because no standard definition of TVOC exists. If certain occupied spaces have significantly higher TVOC levels compared to others, this should prompt further diagnostics.

For targeted real-time measurements of NO_2, EPA's one-hour mean thresholds of 188 $\mu g/m^3$ (100 ppb), and WHO's 24-hour mean threshold of 25 $\mu g/m^3$ (13 ppb) should not be exceeded (US EPA 2024c, WHO 2021). For O_3, the WHO's eight-hour threshold of 100 $\mu g/m^3$ (50 ppb) should not be exceeded (WHO 2021).

9.3 Level 3: Advanced Analysis

9.3.1 Level 3: Objective. Advanced level measurements are intended to represent the most encompassing procedures that have been publicly documented and/or published in peer-reviewed journals. Building on Levels 1 and 2, the following additional objectives should be pursued:

a. **Outdoor air quality.** Provide outdoor air quality measurements at the building site to inform building operations. Combine hourly IAQ data with coincident hourly weather data to gain better insight into hourly outdoor air dependence. Use continuous monitoring to identify atypical events that result in higher than typical outdoor concentrations of criteria pollutants.

b. **IAQ measurements.** Establish a combination of continuous, time-integrated and targeted measurements for air pollutants that may be emitted from materials and processes, or introduced by occupant activities, so as to identify events that need further investigation and/or corrective action.

9.3.2 Level 3: Metrics. In addition to the Diagnostic level measurements, the following steps should be taken at Level 3:

a. **Indoor and outdoor air quality measurements.** Report concentrations of pollutants measured continuously indoors and outdoors, targeted indoor real-time measurements, or indoor time-integrated measurements, as well as any corrective action taken. For air pollutants measured in real-time, provide the same descriptive statistical values as in Levels 1 and 2.

9.3.3 Level 3: Measurement Methods. Prepare a plan for taking physical measurements of indoor and outdoor air quality. Some measurements will be routine, while others will depend on the performance issues identified in Levels 1 and 2. At the Level 3 – Advanced assessment, three types of physical measurements provide data for IAQ performance analysis and source identification: continuous, targeted real-time, and time-integrated measurements. For outdoor air quality characterization, only continuous measurements are applicable. The following describes the typical measurement approaches in each category.

a. **Continuous measurements.** For indoor assessments, apply the same measurements as conducted at Level 2 assessment, with the addition of particulate matter smaller than 10 µm (PM_{10}). However, at this level the measurements should be conducted with a higher placement density as specified in Informative Appendix I3.
   Integrating indoor measurements with outdoor data is essential for a comprehensive understanding. For outdoor assessment, the six criteria air pollutants specified in Level 2 should be continuously monitored at the building site. Continuous outdoor air quality monitoring at the site should follow EPA guidelines to ensure accurate data collection. Monitoring equipment should be positioned away from direct sources of pollution such as parking spaces and exhaust vents. The monitoring equipment should also be shielded from precipitation and direct solar radiation using suitable protective measures to prevent data interference. The equipment should be placed at a height that represents typical breathing zones, typically 2 to 15 meters (6.6 to 49.2 ft) above ground level, and in an open area with unrestricted airflow to avoid localized pollutant concentrations that could skew the results.
b. **Targeted real-time measurements.** Apply the same measurements as conducted at Level 2 assessment, particularly if air pollution sources are suspected or if occupant surveys indicate problems.
c. **Time-integrated measurements.** Time-integrated measurements are applied for relevant air pollutants where robust continuous measurements are not plausible. For Level 3 assessments, the measurands include formaldehyde, acetaldehyde, individual VOCs (other than formaldehyde and acetaldehyde), and radon. For each air pollutant tested (except for radon), the number of testing locations should correspond to those summarized in Informative Appendix I3. Except for radon, these tests should be conducted on an annual basis, and more frequently in case of major retrofits in occupied spaces.
   1. For formaldehyde and acetaldehyde, samples should be taken through an active collection in accordance with ISO 16000-3, ASTM D5197, NIOSH 2016, EPA TO-11 (or 11A) or EPA Compendium Method IP-6 (or 6A). Sampling should be a minimum of one continuous hour, or the duration of sampling volume prescribed by the referenced testing methodology. A minimum of one exposure field blank sample should be prepared and analyzed per day of sampling.
   2. For individual VOCs (except formaldehyde, acetaldehyde and acetone), samples are to be collected through an active collection in accordance with ISO 16000-6, EPA IP-1, EPA TO-17, ISO 16017-1, ISO 16017-2, and ASTM D6345-10. Test duration should correspond to a minimum of one continuous hour, or the duration of sampling volume prescribed by the referenced testing methodology. A minimum of one exposure field blank sample per day of sampling should be prepared and analyzed.
   3. Measurements of radon are only required in the lowest occupied level of the building. If the building does not include the ground floor or any below-grade floors, radon testing is not required. Similarly, if the radon levels are below the exposure thresholds specified under Section 9.3.4., further radon testing is not required. Radon measurements could be conducted both through active and time-integrated testing samples. For time-integrated testing, a minimum of 7 days (up to 3 months) is recommended during the heating season.

9.3.4 Level 3: Performance Evaluation and Benchmarks. The following evaluation criteria should be applied:

a. **IAQ measurements.** To determine if the continuous and targeted IAQ measurements are compliant with benchmarks, use the same benchmarking criteria as in Levels 1 and 2. The PM10 concentrations should meet the recent WHO annual guideline level of 15 $\mu g/m^3$ (WHO 2021). For formaldehyde, the 30-minute average measured concentrations should be below the WHO's guideline value of 100 $\mu g/m^3$. For acetaldehyde, the 8-hour concentration should be below California Office of Environmental Health Hazard Assessment's limit of 140 $\mu g/m^3$ (OEHHA 2024). Thresholds for other VOCs should be set in accordance with OEHHA's 8-hour and Chronic Reference Exposure Level (REL) (OEHHA 2024). Average radon concentrations should be below US EPA's action level of 150 Bq/m^3 (4 pCi/L).
b. **Outdoor air quality measurements.** To determine if the continuous outdoor air quality measurements are compliant with benchmarks, we recommend using either the NAAQS thresholds (US EPA 2024c) or the WHO's 2021 air quality guidelines. Note that these two guidelines are not perfectly aligned.

10. VISUAL ENVIRONMENT

10.0 Introduction. The visual environment comprises factors such as lighting design (electric and daylighting), glare, window views, color rendering, and non-visual effects, and therefore plays a crucial role in the quality of the indoor environment. Proper visual design can improve worker productivity, enhance the aesthetic appeal of a space, improve tenant and employee retention, increase retail sales, facilitate education, and create the desired mood for visitors. Improper visual environmental settings may have a negative influence on each of these domains, or in extreme cases even compromise occupants' health and well-being.

This guideline will address evaluation of the visual environment in five domains (visual acuity, glare, non-visual effects, view, and miscellaneous technical issues) and in three levels of protocols to cover from basic to advanced involvement.

10.0.1 Industry Standards and Other Sources. The following references and sources discuss, among other topics, the recommended performance targets regarding lighting quality.

a. EN 17037: Daylight (CEN/TC 169, 2018)
b. EN 14500: Blinds and shutters - Thermal and visual comfort - Test and calculation methods (CEN/TC 33, 2021)
c. ANSI/IES LM-83-23: Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) (IES, 2023a)
d. ANSI/IES Recommended Practice (RP)-1-22: Lighting Office Spaces (IES, 2022)
e. LEED v4.1 (USGBC, 2020) - EQ Credit: Daylight, Quality Views
f. BREEAM (BRE Global Limited, 2018) - Hea 01 Visual comfort
g. WELL v2 (IWBI, 2023) - Light and Mind

10.0.2 Fundamentals of Measured Light Parameters and Factors of Consideration.

10.0.2.1 Illuminance. Illuminance is a measure of how much light is incident on a surface. Illuminance is measured in lumens per unit area, where lumens are the basic metric used for the output of lighting equipment. In Systéme International (SI) units, illuminance is measured in lux, where one lux equals one lumen per square meter. In Inch-Pound (IP) units, illuminance is measured in lumens per square foot, where one lumen per square foot equals one footcandle (fc). In measuring illuminance, the lighting practitioner is generally attempting to answer the following questions:

a. How much light is falling on the surfaces (horizontal, vertical, or sloped) of interest, and is that light sufficient for the tasks being performed there?
b. How uniform is that light being distributed over the surface? Note: lighting specifications are frequently expressed as a minimum average illuminance and a uniformity metric (often expressed either as maximum-to-minimum or average-to-minimum ratio).

c. What effect is any daylighting having on this metric?
d. What effect are any lighting controls having on this metric?
e. Does the illuminance on a vertical plane at the eye level exceed thresholds associated with discomfort? Note: this topic overlaps with glare, discussed below.

Because of the proven effects of illuminance on visual acuity, proper levels of indoor illuminance are essential to promoting the objectives of a space.

10.0.2.2 Color Rendering. In addition to the quantity of light, color rendering can be an important component of lighting quality for occupants to accurately perceive color of objects with regard to how they appear in daylight or another reference condition. Color Rendering Index (CRI) is a common color rendering metric. CRI is not the same as Correlated Color Temperature (CCT), which is how the color of the light source itself appears. CRI expresses how the spectral power distribution of a light source renders the color appearance of objects. With occupant age, less light reaches the retina, more light is scattered within the eye, and colors become altered. This results in reduced color discrimination. The CRI value of a light source is often found on the product specifications. There are multiple limitations of CRI; one primary limitation is the color palette used to calculate CRI contains only eight pastel color samples. The colors (both in quantity and hue) are not representative of the world. With the advent of light emitting diode (LED) lamps, the limitations of CRI were fully on display and new color metrics were necessary.

The Illuminating Engineering Society (IES) developed the Technical Memorandum (TM) 30 (IES, 2020b) with more advanced guidance for color metrics, including gamut index (R_g) and fidelity index (R_f). TM-30 includes 99 color samples and provides data about the richness and accuracy of color. Despite being available since 2015, TM-30 metrics are less reported and currently not widely adopted for product specifications.

10.0.2.3 Luminance. Luminance is the amount of light emitted from a point in a given direction Colloquially, this is what is meant by the brightness of an object; however, this confuses a photometric term (luminance) with a sensation (brightness) that depends on the state of adaptation of the viewer. Luminance for sources that don't emit light by function (e.g., luminaires) is a function of how much light falls on a surface and the reflectance characteristics of the surface, including both the percentage of light reflected and the pattern of reflection. For example, a mirror and a matte (diffuse) white wall may both reflect 90% of the light, but the mirror will reflect that light primarily in one direction (specular reflection) while a matte wall will reflect it roughly the same in all directions. Most lighting analysis is done assuming that all room surfaces are matte, that is, that they reflect light to all directions. Under this assumption, the key questions are the same as for illuminance, but to this is added the need to examine the ratio of luminances between various points in the space, such as the luminance of the task itself compared to that of the immediate area of the surface where the task is located. One should also compare that task luminance to that of the nearby surfaces such as the walls, windows, and ceiling. Large differences in surface luminances within the field of view may be a source of glare, as discussed in the respective sections. This may be more pronounced in cases where the background luminance significantly exceeds the foreground luminance, or in the case of presence of small sources of high luminances (e.g., specular reflections or luminaires). Luminance is measured in candelas per square meter (cd/m^2), while there is no equivalent unit used in the IP system.

10.0.2.4 Glare. Glare has been the focus of visual comfort research since electric light sources were developed and even centuries before when daylight was the only light source. Glare can affect occupant satisfaction, productivity and well-being. Glare can be caused by luminance values in the field of view that are sufficiently greater than the adaptation level of the occupants' eyes, with the result ranging from mild annoyance to reduced vision and even health hazards when it comes to sources of extreme luminance in the visual field (e.g., the sun). Based on its severity, glare can be classified into two main categories: (i) discomfort glare, mainly in the form of a psychological sensation leading to distraction or annoyance; and (ii) disability glare, caused by the factual loss of retinal image contrast as a result of intraocular light scatter. Both main categories are to be prevented in well-designed and operated buildings.

Although disability glare is more severe, its assessment can be simpler, because of its extreme nature that does not allow ambiguity. On the other hand, because discomfort glare sensation can significantly differ among occupants, the metrics to describe it are of more probabilistic nature. Glare is normally evaluated using luminance-based metrics, such as Daylight Glare Probability (DGP) (Wienold and Christoffersen, 2006) and Unified Glare Rating (UGR) (CIE, 1995), as the latter can better capture contrast compared to illuminance. However, illuminance values have also been widely used to approximate glare, either in the vertical plane at the eye level, e.g., vertical illuminance or DGP simplified (DGPs), a function of vertical illuminance, or on the workplane, such as Useful Daylight Illuminance (UDI) (Nabil and Mardaljevic, 2005).

10.0.2.5 Non-Visual (e.g., Circadian) Effects. Non-visual (e.g., circadian) effects refer to properties of light that are used by the visual system, but affect the body. Circadian rhythm is the human body's close to 24-hour cycle, and light helps signal the 24-hour cycles to the body. Light is one of the indicators our circadian system uses to configure our sleep-alertness cycle. Over time, receiving a high circadian exposure at the same time each day (in the morning for those with a typical sleep schedule) suppresses melatonin, whereas a low circadian exposure at the same time each day (in the evening for those with a typical sleep schedule) allows the body to produce melatonin. This regular high-low melatonin cycle promotes high quality sleep.

Three metrics used in the industry for non-visual lighting effects are **Circadian Stimulus (CS), Equivalent Melanopic Lux (EML), and Melanopic Equivalent Daylight Illuminance (MEDI)**. CS is based on the response to light in terms of suppressing melatonin and EML and MEDI are based on the response to light in terms of producing melanopsin. Both CS and EML use weighted functions of the Spectral Power Distribution (SPD) and illuminance of the light source. EML is equal to MEDI multiplied by a factor of 1.1 (Allied Scientific Pro, n.d.). These metrics are typically measured at the vertical plane to simulate entering the eye when facing forward.

Research has found that bright light exposure in the morning has a positive impact on cognition and sleep (Huiberts et al. (2015); Iskra-Golec and Smith (2009); and Kaida et al. (2006)). However, there are studies that have conflicting results; for example, Peeters et al. (2021) found that greater illuminance from electric light in the morning resulted in worse subjective sleep, mood, and fatigue responses. Therefore, the lighting industry's understanding of non-visual effects of light and related photoreceptors is still developing. A recent study by D'Souza et al. (2022) found that, in addition to photoreceptors known to be stimulated by energy predominantly in the low-end (i.e., 410 - 500 nanometers [nm]) of the visual spectrum (commonly referred to as "blue"), humans have photoreceptors that are stimulated by energy in the very low-end (i.e., 380 - 410 nm) of the visual spectrum (commonly referred to as "violet") and even some energy below the visual spectrum in the upper end of the ultraviolet (UV) spectrum (i.e., 330 - 380 nm); these receptors prevent myopia and entrain circadian rhythms (Lan et al. 2021). Most windows block violet visible light and ultraviolet light. Most electric lighting does not produce UV unless specifically designed to do so. Therefore, stimulating photoreceptors attuned to the UV spectrum is difficult in interior lighting conditions. Future research is needed to provide the lighting community a deeper understanding of non-visual effects of light.

There are many challenges around measuring the visual and non-visual effects of light. Unlike air quality, thermal comfort, and acoustic metrics, light metrics are very sensitive to the direction of the sensor. For non-visual lighting in particular, it's very difficult to take measurements that represent what occupants are experiencing, because the direction that an occupant is looking is variable. A further challenge is that occupants in some building types (e.g., hospitals, transportation facilities, etc.) do not have fixed work locations. A study by van Duijnhoven et al. (2019) found significant differences in vertical illuminance and CCT for different measurement angles in windowed-spaces. Furthermore, lighting conditions of windows change significantly throughout the day and year based on weather and geographic location. Measuring continuous data may not be possible in operational buildings because sensors must be placed where occupants are located, which would interfere with their activities.

People can achieve sufficient daily circadian exposure within a 1–2-hour timeframe (Figueiro et al. 2016 at UL 2019), which is a small enough window of time that someone may not get from their primary work location, but can get from hallways, break rooms, conference rooms or other spaces. Additionally, what is displayed on lit computer monitors can have an impact on circadian lighting values. For example, a 27.5-inch (in) monitor with white application settings can provide ~88 EML or 0.08 to 0.12 CS (Huguet-Ferran et al., 2022). Even if every space in a building is evaluated, it is challenging to model locations occupants will visit and where they will be looking in those locations.

10.0.2.6 Window View. Window view quality can be defined as the quality of the visual connection to the outdoors that satisfies building occupants (Ko et al., 2022). The view from a window can have a profound impact on physiology and psychology through a range of positive effects on health and wellbeing (Aries et al., 2010; Hartig et al., 2003; Kaplan, 1993), cognitive performance (Ko et al., 2020), spatial satisfaction (Yildirim et al., 2007), discomfort and stress (Aries et al., 2010; Ulrich, 1984), and emotion (Ko et al., 2020). Views inside buildings occur when (day)light reflects off outdoor surfaces and this visual information is transmitted through windows (Tregenza & Wilson, 2013). Therefore, window views have a close relationship to daylight and can be considered an integrated entity. This guideline presents an overview of the assessment method of window views while considering the effect of daylight that is generally applicable to buildings. The concept of window view quality is subjective because it is occupant-dependent, and therefore influenced by contextual factors (e.g., surrounding landscape, cultural milieu, building types). Depending on the spatial characteristics and function of the space, the design guidelines summarized in this section may not be applicable, or may require careful consideration, when assessing the window view quality. Examples of the exceptions include: 1) spaces that require a high level of privacy (e.g., bedrooms, lavatories), 2) spaces that do not require window views (e.g., theaters), and 3) spaces that have high potential to be seen by people outdoors (e.g., a ground floor space close to pedestrians or a space that has window views to the neighboring buildings a short distance away). Further research is necessary to develop a measurement method that guides specific building types and conditions.

10.0.2.7 Miscellaneous Technical Issues. Miscellaneous technical issues that are connected to the equipment related to the visual environment may significantly compromise occupants' experience and the overall objectives of a space. The term flicker is often used to describe visual perceptions or responses to Temporal Light Modulation (TLM). Electric light sources may exhibit TLM, defined as the measurable change of the light level or spectral distribution of light from a luminaire over time (CIE, 2021). The frequency (measured in hertz [Hz]) characterizes the type of TLM. The stroboscopic effect, flicker, and after images are all examples of TLM. Flicker was a major issue with fluorescent technology operating on magnetic ballasts. The introduction of high-frequency (>20,000 Hz) electronic ballasts reduced the flicker sensation for many. Flicker is also a known issue with LED lamps. LED lamps operate near or above 120 Hz, but many still experience flicker / TLM. In addition, the shape of the waveform (e.g., square wave vs. sine wave) from LEDs results in some occupants experiencing flicker from LED lamps.

The presence of flicker or TLM in interior environments may result in undesired visual and non-visual responses from occupants, with negative impacts on human perception, health, performance, and safety. Known visual responses to TLM flicker include the direct flicker effect (detectable at frequencies 3 to 80 Hz, characterized by the flicker perception metric Mp), the stroboscopic effect (80 to 2000 Hz, characterized by the stroboscopic visibility measure, SVM), and the phantom array effect (80 to 15,000 Hz). In an industrial or sports setting, flicker may interact with moving machinery or moving balls and produce an effect where that object appears to be moving at a different speed or is stopped. This can result in a dangerous situation. Responses to flicker vary notably between individuals; flicker may be hardly detectable by some while others may experience discomfort, distraction, and potentially unwanted health effects.

10.0.2.8 Lighting Controls. Lighting Controls are either required by energy codes or deployed in buildings to benefit the occupants. Lighting controls include **daylight harvesting** (dimming of (or turning off) electric light when sufficient daylight is available), **occupancy/vacancy sensors** (reduction (dimming or turning off) the lights based on occupancy), **scheduling** (turning on/off the lights based on time), **white level tuning** based on modulating CCT and intensity in compatible light fixtures, and **shading controls** based on algorithms of varying complexity, with or without the need for additional feedback sensors.

While these controls might vary significantly in complexity, they are most commonly rule-based, designed to maintain certain thresholds or react to predetermined events. For example, a simple schedule-based control may deactivate the lights at a predetermined time, while an occupancy sensor might reverse this action when triggered by a person entering the room after hours. Tunable white systems may also be scheduled, with CCT transitioning to warmer values as the day progresses. Regarding shading, controls are commonly based on solar tracking, aiming to prevent direct sunlight penetrating the occupied area of the floorplan, and scheduling. Less often, additional sensors on the facade are employed to provide feedback for more efficient operation. Such systems can address limitations of solar path tracking by reducing unneeded shading operations in cases of overcast skies.

Due to the complexity of interactions between hardware, software, and occupant overrides, it is common for such automations to present issues. These may include occupancy sensing being falsely triggered by irrelevant factors (e.g., air from diffusers), scheduling errors for predetermined on/off events, and commissioning errors regarding the dimming levels in daylighting modes and the shade position operation, as well as the placement of sensors for the aforementioned operations. Such issues may result in dark or extremely bright conditions, glare, or compromised comfort and overall satisfaction, as well as the energy efficient operation of a space.

10.0.3 Selecting Measurement Location Guide. A guide for selecting measurement locations is presented below. This method is referred to in multiple lighting sub-categories across all Levels in the remainder of this section. The approach aims to represent all space types of interest for the assessment of the visual environmental quality, reflecting a diverse set of geometry and topology details that significantly affect visual environmental quality. The proposed approach for the measurement location selection is as follows:

a. Identify the total number of measurement locations needed. In the example, one measurement location per 70 square meters (m^2) (700 square feet [ft^2]) of floor area is recommended - this value will be provided in each section that refers to this guide below.
b. Calculate the total floor area of the space being assessed. The example space is 630 m^2 (6,300 ft^2) office suite. Dividing 630 m^2 (6,300 ft^2) by one location per 70 m^2 (700 ft^2) yields nine locations to measure. If the result is not a whole number, round up to the nearest whole number.
c. The selected nine workplaces on the floor plan should represent all available room types (e.g., open office marked as green, conference room marked as blue, enclosed office marked as buff colored in Figure 10.1), perimeter vs core, orientation (e.g., North, Northwest, East), and regions (e.g., floors, wings). Ancillary spaces such as restrooms, closets, mechanical rooms, or hallways that are not regularly occupied should not be selected.
d. Select the recommended nine locations for this scenario on a floor plan and rearrange until a good representation of these factors is met. Figure 10.1 shows the final plan for this example. The nine locations marked on the floor plan represent five of the 22 private office cubicles, two of the five open offices, and two conference rooms, one perimeter and one core. There are two locations on the southern facade, which is the longest facade with work locations, one on the north and the east, and two on the west facade. There are six perimeter locations and three core locations. The ancillary spaces (copy room, restrooms) are neglected.

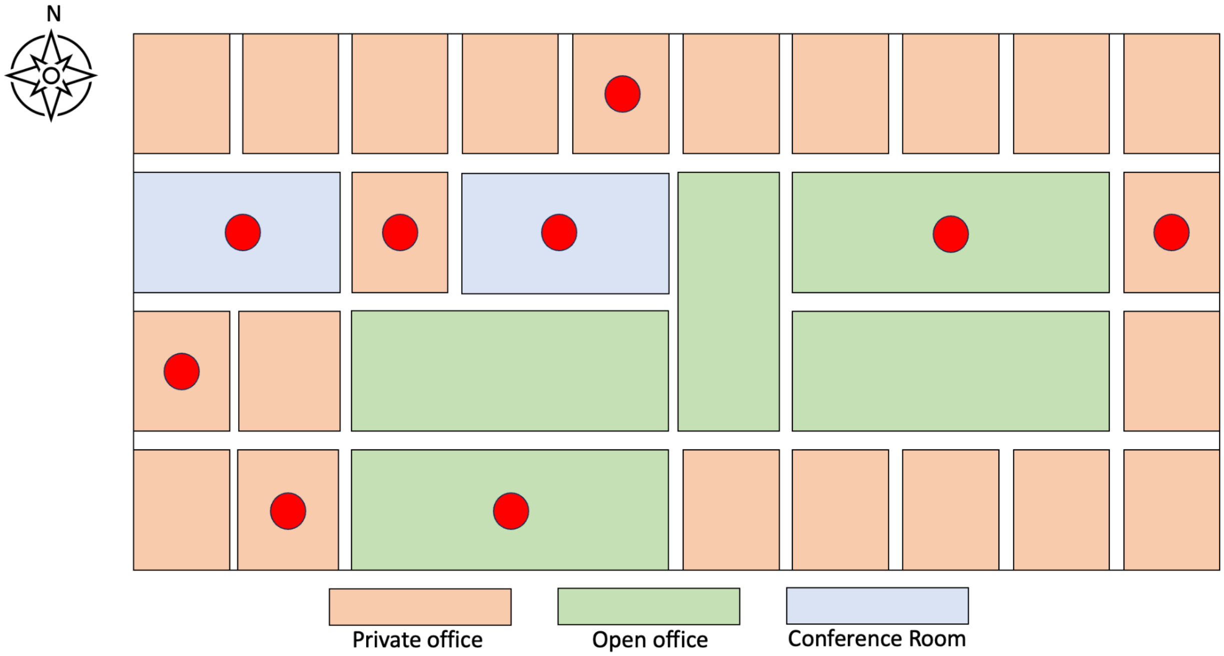


Figure 10.1 Example Measurement Location Guide Auxiliary Sketch.

10.1 Level 1: Basic Evaluation. Visual environmental quality at the Basic level involves the following:

a. Determination of building occupants' satisfaction with their visual environment in terms of acuity, glare, non-visual effects, view, and other issues, and rating of the occupants' satisfaction.
b. Identification of problems with the visual environment and clues to their causes, using occupant responses to diagnostic questions.
c. Collection of sensor measurements at selected workstations to provide a basic understanding of the light levels and color rendering in the building.

The five visual environment characteristics of Visual Acuity, Glare, Non-Visual Effects, View, and Miscellaneous Technical Issues (Table 10.1) are addressed below in sequence.

Table 10.1 Summary of Level 1 Visual Environment Characteristics.

Category	Metric	Method	Granularity	Notes
Visual Acuity, Glare	Horizontal illuminance	Illuminance light meter	1 per 100 m^2 (1000 ft^2)	
Glare (from daylight)	DGP_s (function of Vertical on-eye illuminance)	Illuminance light meter	1 per 100 m^2 (1000 ft^2)	Care should be taken to include measurements near the windows - Measuring of electric light glare is beyond the scope of Level 1
Non-visual Effects	None			Measuring non-visual metrics is beyond the scope of Level 1

View	Window availability	Draw a direct line of sight to the outdoors (including sky or external objects) on the plans	Ideally each enclosed space (regularly occupied spaces only)	
All	Checklist questions		Ideally open to all occupants	
All	Survey questions		Ideally open to all occupants.	

10.1.1 Visual Acuity

10.1.1.1 Objectives. The main objective for Level One is to assess whether the illuminance levels on the horizontal workplane are adequate to promote the objectives of the space. An occupant survey and building checklist are used to supplement this effort.

10.1.1.2 Metrics. By using the methods listed below, the following lighting-related parameters of the building should be measured:

a. Horizontal illuminance
b. Checklist of issues
c. Occupant satisfaction survey

10.1.1.3 Measurement Methods. The methods summarized below document the visual characteristics of the building, and the occupants' responses thereto.

a. **Illuminance measurements:** At Level 1, it is recommended that spot measurements be made of horizontal illuminance at a low spatial granularity to provide a basic understanding of the visual acuity performance. The following recommended protocols should be used when making these measurements.
    1. Take at least one measurement per every 100 m^2 (1,000 ft^2) of floor area. Follow the guidance in the Selecting a Measurement Location Guide section (10.0.3).
    2. For each location, select a representative workplace. The light meter should be set at the level of the work plane, or 0.75m (27 in).
    3. Avoid shadows on the detector; however, illuminance values at the point of work should be measured with the worker in his or her normal working position.
    4. Stand far enough away from the detector (especially when wearing light-colored clothing) to avoid adding reflected light onto the detector.
    5. When possible, document the electric lighting at night so that daylight does not conflate the values. However, if measuring during the day, daylight conditions should be recorded as time of day, day of year, and weather conditions. Areas exposed to direct sunlight should be clearly noted. It is advisable to repeat measurements over a range of daylight conditions.
b. **Benchmarking:** The IES RP (Recommended Practice) series, available for purchase, has target horizontal illuminance and CRI values for each building type. The recommended levels vary based on the room type and activities being conducted. WELL v2 (IWBI, 2023) in L02 Visual Lighting Design also provides general recommended horizontal illuminance targets in various space types.
c. **Occupant satisfaction survey:** Occupants can be surveyed about their satisfaction with the visual conditions in their workspace, from task lighting and overhead lighting. This can reveal complaints, for example, too dim, too bright, flicker, or automatic timers turning off early. Questions that could be used in such surveys are included in the Informative Appendix J. In addition, there are standardized survey questions available, for example through the Center for the Built Environment's (CBE) Occupant Environmental Quality Survey (Graham et al., 2021). This survey covers several indoor environmental quality issues, including lighting.

    The results of the survey should be accumulated and reviewed. The owner or facility manager should identify recurrent themes and severe problem areas. Attention should be given to the fact that responses may vary significantly based on individual preferences. The same light level in the same room might be a problem for one group of employees while others might be satisfied with it. It must be decided whether individual modifications in the light fixtures or office layout will be allowed to address such findings. For the CBE survey, there is a database available, based on previous responses to the survey (Graham et al., 2021).

d. **Checklist:** Although visual acuity can be quantified or approximated by specific lighting parameters (e.g., horizontal illuminance), a brief checklist can be used to determine the occurrence of any visual issues in the space. These questions are associated with lighting design best practices and corrections can be made to meet as many of these conditions as possible.
   1. Is there uniformity in spacing between overhead lights? Is there less than 2.5-3 m (7.5-9 ft) spacing between overhead fixtures?
      i. If overhead lights are not evenly spaced or if they do not align with work stations, this can cause some areas to be overlit or underlit inconsistently.
   2. Do occupants have access to local task lighting?
      i. Providing task lighting gives occupants greater control of their lighted environment if they would like to modify the amount of light.
   3. Are the surfaces (walls, ceilings, furniture) generally light tones that reflect light to create a bright ambiance?
      i. More reflective surface materials can increase the light on the horizontal work plane.
   4. Are overhead light fixtures regularly cleaned and repaired?
      i. Light fixtures depreciate over time and should be dusted every year and replaced if they become too dim or burn out.
   5. Are there any temporary means to block excessive light (e.g., cardboards on windows or desk, etc.) set up by the occupants?
      i. If occupants are taking excessive means to improve their lighting conditions, it may mean the system should be re-designed to meet their needs.

10.1.2 Glare

10.1.2.1 Objectives. The main objective for basic glare benchmarking is to identify issues that compromise occupants' comfort, without the need for detailed measurements, expensive equipment and high expertise. Basic methods are used to provide a quick, overall evaluation of glare issues in the building. Specific objectives include the following:

a. Determining occupants' satisfaction with their visual environment.
b. Identifying problems with glare and obtaining clues to their causes using occupant responses to diagnostic questions. The problems identified may be further diagnosed at the intermediate and advanced levels. Issues of concern include both discomfort and disability glare, from both daylight and electric lighting.

10.1.2.2 Metrics. By using the methods listed below, the following lighting-related parameters will be measured:

a. Horizontal illuminance
b. Vertical illuminance
c. Checklist
d. Occupant satisfaction survey

10.1.2.3 Measurement Methods. The methods summarized below may be used to obtain information about the glare characteristics of the building, and the occupants' responses to those characteristics.

a. **Basic assessment for discomfort glare from daylight through illuminance measurements:** As illuminance measurements are overall simpler and less costly, for the basic level of consideration (Level 1), daylight glare assessment is mainly based on this approach. In that direction, and based on the ranges of UDI (Nabil and Mardaljevic, 2006) and DGPs (Wienold, 2009), spot measurements of horizontal and vertical illuminance levels in the space may approximate glare sensation due to daylight. A list of recommended protocols to be used when making lighting measurements is provided as follows:

1. Take at least one measurement per every 100 m^2 (1,000 ft^2) of floor area. Follow the guidance in the Selecting a Measurement Location Guide section at the beginning of the lighting section.
2. Detectors should be cosine and color corrected (see more in Informative Appendix D6).
3. Temperatures should stay between 15 degrees Celsius (°C) and 50 °C (60 degrees Fahrenheit (°F) and 120 °F)
4. The light-sensitive cell of the measuring instrument should be located at an angle that coincides with the angle of the tasks being performed and/or the parameters that are measured.
5. Avoid shadows on the detector; however, illuminance values at the point of work should be measured with the worker in his or her normal working position.
6. Stand far enough away from the detector (especially when wearing light-colored clothing) to avoid adding reflected light onto the detector.
7. The light meter should be set at the height of the work plane at 0.75 m (27 in) for horizontal measurements or the height of the occupant's head at a typical seating height of 1.2 m (3.6 ft) for vertical illuminance measurements.
8. Daylight conditions should be recorded as time of day, day of year, and weather conditions, as they can significantly affect photometric measurements. Areas exposed to direct sunlight must be clearly noted. It is advisable to repeat measurements over a range of daylight conditions when possible.

b. **Preliminary evaluation for glare caused by electric lighting:**
   1. For workstations, desks, and other seating areas, locate bare lamps and luminaire surfaces that are more than 53 degrees above the center of view (degrees above horizontal) and cross-check with the diagnostic survey to determine potential electric light glare issues; the ones that are suspected to be responsible for glare should be further measured according to practices presented in the intermediate level.
   2. For other spaces, locate unshielded lamps and cross-check with the diagnostic survey for cases of glare complaints.

c. **Occupant satisfaction survey:** A diagnostic survey is an ideal way to obtain preliminary detection and understanding of glare occurrences. Administering the survey to all occupants would be necessary to narrow down problematic areas. Questions related to glare that could be used in a survey are included in the Informative Appendix J, while standardized surveys such as the CBE Occupant Environmental Quality Survey (Graham et al., 2021) could be also used as a diagnostic tool to reveal potential glare issues. Issues detected should prompt actions to determine the exact cause of glare; these are further described in the intermediate and advanced section.

d. **Checklist:** Although glare can be quantified or approximated by specific lighting parameters (e.g., luminance distribution, vertical illuminance, and respective metrics), a brief checklist can be used to determine the occurrence of any often-encountered glare issues in the space.
   1. Are there any bare lamps that are more than 53 degrees above the center of view (degrees above horizontal)?
      i. If yes, this could be a trigger for glare and should be measured with a luminance spot meter to determine if it is above 8,000 cd/m^2
   2. Is there direct sunlight reaching any workstations?
      i. If yes, this could at times lead to excessive contrast/ discomfort glare
   3. Do any occupants have the sun (or sun reflection) within their visual field at any time of the day?
      i. If yes, this should be addressed as it would cause disability glare. Even if that happens for brief amounts of time, it should still be considered to be a problem.
   4. Do occupants have sufficient control over the daylight that reaches their workstations?
      i. If they have control, then the survey results would clarify whether there are conditions of concern or not, as it may be possible for the occupants to adjust their workstations as they please.

5. Have workstations been properly situated so as to avoid reflections of the daylight on computer screens and to avoid direct glare for the occupants?
6. Are there any window attachments (e.g., blinds, shades, etc.) available, and do they appear to be operational?
   i. If shading systems seem to be non-operational and at the same time direct sunlight can be observed penetrating the space, that could indicate malfunctions in the automation (please refer to the Miscellaneous Technical Issues section)
7. Are there any means to block excessive light (e.g., cardboards on windows or desk, etc.) set up from the occupants?
   i. If such interventions can be found in the workspace, that should indicate glare issues that need to be addressed more effectively.

e. **Benchmarking:** Horizontal illuminance values should comply with the UDI thresholds (Nabil and Mardaljevic, 2006) and the total vertical illuminance on the eye should be associated with a DGPs that is associated with imperceptible glare (Wienold, 2009). Horizontal illuminance levels of over 1000 lux (90 fc) in directly lighted areas of the workplane can also be considered as a potential glare factor, as this threshold is suggested in LM-83 (IES Daylight Metrics Committee, 2012) for the Annual Sunlight Exposure (ASE) index that is used for glare assessment. Therefore, if corroborated by complaints in the survey, this condition should be further evaluated. Guidelines regarding electric lighting glare can be found in ANSI/IES RP-1-22. (IES, 2022)

10.1.3 Non-Visual Effects

10.1.3.1 Objectives. Identify basic issues in lighting performance to achieve acceptable conditions. This can be done with an occupant survey and checklist. Lighting sensor measurements for CS, MEDI, and EML are beyond the scope of Level 1 and will be recommended for Level 2 and Level 3.

10.1.3.2 Metrics. By using the methods listed below, the following lighting-related information should be collected and assessed:

a. Occupant satisfaction survey
b. Checklist

10.1.3.3 Measurement Methods.

a. **Occupant satisfaction survey:** An occupant survey can be used to ask how satisfied the occupants are with the visual conditions in their workspace from daylight. However, daylight is not the only way to promote non-visual lighting quality, nor is it a direct measure of non-visual lighting, but it is the only way to be indicated by an occupant survey. Questions related to non-visual effects are included in the Informative Appendix J. There are also standardized survey questions available, such as the CBE Occupant Environmental Quality Survey (Graham et al., 2021). The results of the survey should be accumulated and reviewed for recurring themes, considering that responses may vary significantly based on individual preferences.

   If the survey results do not meet this recommended satisfaction level, it is prudent to pursue design solutions to increase access to daylight, or to conduct a Level 2 or Level 3 assessment to see if the lighting conditions are sufficient despite low satisfaction. Satisfaction with, and access to, daylight are indicators of the non-visual quality of lighting, but electric light can achieve high performance with minimal or no daylight, and occupants typically are not acutely aware of the non-visual quality of light and its effect on them; therefore a Level 2 evaluation is recommended if there is doubt concerning the performance.

b. **Checklist:** Although visual acuity can be quantified or approximated by specific lighting parameters (e.g., horizontal illuminance), a brief checklist can be used to determine the occurrence of any visual issues.
   1. Are the surfaces (walls, ceilings, floors, furniture) generally light tones that reflect light to create a bright ambiance?
      i. Surfaces that reflect more light will provide greater illuminance on the vertical plane.
   2. What percentage of workstations have direct line-of-sight to a window that provides daylight?

        i. WELL v2 (IWBI, 2023) Feature L05 recommends that 70% or more of workstations have access to daylight, e.g., a direct line of sight less than 8 m (25 ft) to an exterior window.
    3. Are open work areas designed to allow daylight to penetrate deep into the area using translucent or low partitions?
        i. Putting open office areas instead of enclosed offices near the perimeter will allow more occupants to have regular window access. If enclosed offices are at the perimeter, they can be designed to have translucent walls to allow the daylight to reach beyond that room.

The above are design questions, and can be indicators of actual lighting performance, however it is important to note that the non-visual lighting quality could be sufficient while not meeting these criteria, or less than sufficient while still meeting these criteria. If one or more of the questions does not meet the recommended criteria, it is prudent to re-design the space or to conduct a Level 2 or Level 3 assessment to see if the lighting conditions are sufficient despite not meeting the criteria of this checklist.

10.1.4 View

10.1.4.1 Objectives. Identify basic issues in window views to meet the minimum acceptable conditions. This will include a simple floor plan check, walk-throughs in the space, surveys and complaint logs if there is window access in the occupied floor area. This can be done with a checklist and occupant survey.

10.1.4.2 Metrics. By using the methods listed below, the following view-related parameters may be measured:

a. Checklist
b. Occupant satisfaction survey

10.1.4.3 Measurement Methods.

a. **Checklist:** A checklist can be used to evaluate the view at Level 1. There is one checklist question for this category:
    1. Do the regularly occupied areas (e.g., work stations) have visual access to window(s)?
        i. The first step is reviewing floor plans to see if there is any area that does not have window access (i.e., a direct line of sight to the outdoors).
        ii. If yes, during the initial walk-throughs in the spaces, any space where window access is limited or blocked by fixed objects (e.g., furniture) should be identified.
        iii. LEED v4 - Quality Views (USGBC, 2019) requires 75% of all regularly occupied floor areas with a direct line of sight to the outdoors. The percentage can be calculated by dividing the number of workstations with direct access to the window(s) by the total number of workstations.
b. **Occupant satisfaction survey:** A survey of occupants can be conducted to inquire about their access to a window view and gauge their satisfaction with it. Basic questions for this purpose are provided in the Informative Appendix J, and they can also be incorporated into standardized surveys such as The CBE Occupant Environmental Quality Survey (Graham et al., 2021). Using these surveys can aid in pinpointing areas where there are access issues to views. A more comprehensive evaluation of the quality of window views is presented in the intermediate and advanced sections.

10.1.5 Miscellaneous Technical Issues

10.1.5.1 Objectives. The main objective for basic benchmarking of other technical issues is to identify instances of flicker or control issues that may be inconvenient or even dangerous to occupants. Basic assessment of such issues does not require detailed measurements or high expertise and may be completed in combination with other lighting assessments. Specific objectives include the following:

a. Visually observe any instances of perceivable flicker resulting from the lighting system through items on the lighting checklist.
b. Visually observe any instances of control faults. Examples include, but are not limited to, shading that is not applied while direct sun is penetrating the workplane levels, occupancy sensing that fails to detect occupancy, dark conditions with artificial lighting seemingly turned off, and available manual switches that do not override dimming or shading levels.

c. Through diagnostic questions determine any occupant dissatisfaction with the visual environment that may result from perceived flicker from the lighting system. (The problems identified may be further diagnosed using the methods described in the Level 2 and Level 3 assessments).

10.1.5.2 Metrics. Occupant satisfaction with the visual environment as it relates to flicker and automation issues can be assessed using an administered survey. Specific flicker metrics are included as part of the Level 2 and Level 3 assessments.

Light Loss Factors (LLFs) can cause a decrease in performance of lighting systems. The main LLFs include:

Common to all light sources

a. Lamp lumen depreciation: As a light source is operated over time, its luminous flux gradually decreases.
b. Luminaire dirt depreciation: Dirt and dust are present in almost all spaces and may accumulate on lamps and luminaires.
c. Luminaire surface depreciation: This refers to effects on luminaire reflecting and transmitting surfaces that are permanent and therefore cannot be recovered by cleaning.
d. Room surface dirt depreciation: Dirt and dust are present in almost all spaces and may accumulate on room surfaces, such as ceilings, walls, and floors.

Less common / source specific:

a. Luminaire ambient temperature: Ambient temperature may increase as a maintenance consideration due to the lighting systems.
b. Voltage to luminaire: A luminaire may reduce the voltage of the electrical circuit, which will reduce the light output relative to the rated value of the lamps.
c. Lamp burnout factor: A lamp (or light source) burnout affects illuminance, lighting uniformity, and space appearance. This is less common with LED sources.
d. Ballast factor: Luminaire ballasts can cause an increase or decrease in light output compared to the rated value of the lamps.

More information on LLFs can be found in IES RP-36-24 Recommended Practice: Lighting Maintenance. (IES, 2024)

10.1.5.3 Measurement Methods.

a. **Checklist:**
   1. With the electric lighting system on, is "flicker" an issue at any workstations? Flicker may be visually detected through observation, either in the direct line of sight or the periphery of an occupant at a given workstation.
      i. If so, is it inconvenient, meaning flicker may be distracting to occupants as they conduct their professional duties (Y/N)?
      ii. If so, is it dangerous, meaning flicker may hinder occupants as they conduct their professional duties (Y/N)?
   2. Are there any light fixtures that seem to be dimmed or turned off?
      i. If so, do they seem to operate this way as a group of an overall section (e.g., entire row near the window), or does this behavior appear to be individual? (Group/Isolated)
      ii. Also, does the fact that they are off/dimmed seem to cause dark conditions? (Y/N)
   3. In an empty room, do the fixtures turn on when the first person enters the space? (Y/N).
      i. If they don't turn on, does that seem to cause apparently dark conditions? (Y/N)
   4. If the electric lighting is operated with a time clock, are there any lights that appear to be on outside the scheduled hours?
      i. If so, has the system logged any occupancy event near the observation time? (Y/N)
      ii. If so, was there an actual occupancy event at that time? (Y/N)
   5. In a space with automated shading, are workstations near the window exposed to direct sunlight? (Y/N)

i. If so, are the shades partly deployed, or do they seem to be completely open? If they are partly deployed, that could indicate commissioning errors. If they are fully open, that could be a result of communication errors with the BMS.

It is important to note that individuals have varying sensitivities to flicker, and flicker may go undetected if visually assessed by a single person as part of the checklist. Surveying a number of occupants may be useful for identifying the presence of flicker for more sensitive individuals.

b. **Occupant satisfaction survey:** Surveying occupants may be helpful for identifying the presence of flicker for more sensitive individuals, as well as detecting control issues that would be difficult to identify in a single walkthrough. It is possible that some individuals will not detect flicker at all, some may detect flicker but remain unbothered by it, and some will experience undesired effects on their perception, health, performance, or safety. The same applies to control issues that can lead to either under lighted conditions (reduced visual acuity, safety, or productivity) or glare (causing discomfort or even becoming hazardous). Survey questions should be used to:
   1. Identify the presence of flicker at occupant workstations through visual observation
   2. Rate the severity and/or frequency of perceived flicker. For example: "How frequently do you experience at your typical workstation (ranging from never to very frequently)?"
   3. Indicate whether the presence of flicker hinders the ability of occupants to perform their professional duties
   4. Assess the effectiveness of automated shading with respect to glare protection
   5. Indicate faulty operation of occupancy sensors when entering the room
   6. Indicate the potential of poorly commissioned daylight harvesting dimming controls that under- or over-light the space, based on the responders impression of perceived lighting.

   Surveys should be re-administered once per year or as the occupant population and electric lighting system changes. Related questions are included in the Informative Appendix J.

10.2 Level 2: Diagnostic Measurement. Intermediate measurements for the assessment of the visual environment include:

a. A diagnostic survey of occupant visual satisfaction
b. Illuminance and luminance measurements and determination of discomfort glare with medium spatial granularity
c. CRI from lamp product specs
d. Photopic illuminance and spectral irradiance measurements with medium spatial granularity
e. View assessment in terms of content, access and clarity
f. Assessment of flicker through measurements of electrical lighting systems and/or light sources

The five visual environment characteristics of Visual Acuity, Glare, Non-Visual Effects, View, and Miscellaneous Technical Issues (Table 10.2) are addressed below in sequence.

Table 10.2 Summary of Level 2 Visual Environment Characteristics.

Category	Metric	Method	Granularity
Visual Acuity	CRI (OR R_f and R_g if available)	Lamp specs from manufacturer	Every predominant lamp product type
Visual Acuity, Glare	Horizontal illuminance	Illuminance light meter OR Lumen Method	1 per 70 m^2 (700 ft^2)
Glare	Vertical Illuminance Luminance ratio Luminance	Illuminance light meter Luminance spot meter	3 viewing angles per 70 m^2 (700 ft^2), and additionally for every workstation that has access to a window
Non-visual Lighting	Equivalent Melanopic Lux, Circadian Stimulus	Illuminance light meter with light spectrum	3 viewing angles per 100 m^2 (1,000 ft^2)
View	Presence of view layers, view angles, glazing and shade optical properties	View layers, Horizontal and vertical angles Optical properties	4 orientations across 3 floor levels (low, medium, high) at a

			window distance of 2.5 m (7.5 ft).
Flicker	Percent Flicker, Stroboscopic Visibility Measure	Hand-held flicker meter or smartphone application	1 per luminaire type per space.

10.2.1 Visual Acuity

10.2.1.1 Objectives. The main objective for Level 2 is to collect a sample of lighting measurements at a greater spatial density than Level 1. Follow the instructions for horizontal illuminance measurements under the Level 1 section, with the exception of increasing the measurement density from one measurement per 100 m^2 (1,000 ft^2) to one measurement per 70 m^2 (700 ft^2) The occupant survey and lighting checklist from Level 1 should be included in a Level 2 assessment as well. Refer to the Visual Acuity section under Level 1 for more information.

As an alternative to horizontal illuminance sensor measurements, the Zonal Cavity Method (sometimes known as the Lumen Method) is a way to calculate the expected illuminance based on lighting system and room factors. This method is achievable under the scope of a Level 2 assessment. However, this method is only applicable if there is uniform overhead fixture spacing, non-sloped ceilings, and no variation in overhead fixture type. If this is not the case for the spaces to be measured, then sensor measurements must be used. This method will not account for contributions from daylighting or task lighting either, so the results must be interpreted as baseline illuminance levels, not actual illuminance levels.

The equation for estimating the average horizontal illuminance (EH) in a room using the Zonal Cavity Method is:

$$E_H = \frac{(No.\,luminaires) * (\frac{lamps}{luminaire}) * (\frac{lumens}{lamp}) * CU * LLF}{work\ plane\ area}$$

where:

E_H is the average horizontal illuminance across the entire room,

CU is the Coefficient of Utilization. The CU accounts for the light loss due to the fixture design and inter-reflections of the space (*e.g.,* light reflecting off the ceiling, wall, and floor), and

LLF is the Light Loss Factor(s), which is the product of several factors such as lamp lumen depreciation, luminaire dirt depreciation, and ballast factor.

More information, including CU values, is available in ANSI/IES LS-6-20: Lighting Science: Calculation of Light and its Effects (IES, 2020a).

In addition to horizontal illuminance, Level 2 includes collecting CRI values, which can be collected from product specification of all predominant lamp products in the building. Fidelity index(R_f) and Gamut index (R_g) should also be collected if those specifications are available from the manufacturer product specs. If there is no record of the lighting products in use, or if the fixtures are older with the bulbs having been replaced before, the manufacturer and product name can be obtained by inspecting each lamp type for the brand and product name and looking up the product specs on the manufacturers' websites. If it is not possible to obtain CRI data, when the lamps are replaced, products with CRI specs, and ideally R_f and R_g as well, should be purchased and a log of each lamp type and location should be kept with color rendering data, as well as other lighting quality, quantity, and energy specifications.

10.2.1.2 Metrics. (To be completed)

10.2.1.3 Measurement Methods. (To be completed)

For the intermediate level, the same procedures articulated in the basic level still apply, but in a higher granularity of 1 measurement per 70 m^2 (700 ft^2).

10.2.1.4 Performance Evaluation and Benchmarks (To be completed)

10.2.2 Glare

10.2.2.1 Objectives. The objectives for the intermediate level of glare evaluation focus on identifying complex issues and solutions for the operation of electric lighting and dynamic daylight glare control systems. Although the goals are similar to the ones of Level 1, the resolution is higher, while the use of more specialized equipment, as well as computer modeling, is introduced. The occupant survey and lighting checklist from Level 1 should be included in Level 2.

10.2.2.2 Metrics. By using the procedures listed above, the following glare-related parameters will be measured:

a. Illuminance levels in a complete usable grid in evaluated spaces
b. Luminance and Luminance ratios
c. Daylight Glare Probability simplified or DGPs (Wienold, 2009) for daylight glare in the selected grid
d. Status indicators of dynamic envelope components
e. Occupant point-in-time satisfaction survey

10.2.2.3 Measurement Methods

a. **Evaluation of glare caused by unshielded electric lighting:**
    1. For workstations, desks, and other seating areas, bare lamps and luminaire surfaces that are more than 53 degrees above the center of view (degrees above horizontal) need to have luminance of less than 8000 cd/m^2.
    2. For other spaces, locate unshielded lamps and cross-check with the Occupant Satisfaction Survey for cases of glare complaints.
b. **Spatial illuminance measurements for saturation daylight glare assessment:** Take at least one illuminance measurement per every 70 m^2 (700 ft^2) of floor area. Follow the guidance in the Selecting a Measurement Location Guide section (10.0.3). In addition, three viewing directions (straight and +/– 45 degrees horizontally to the right and left) are used to cover the surface under consideration, both in terms of horizontal and vertical (on eye) illuminance, based on the logic discussed in section 10.0. Due to the sensitivity of perimeter zone workstations to glare, all workstations in the perimeter zone should be assessed. Horizontal illuminance is associated with widely used metrics (e.g., UDI), while vertical levels are associated with DGP_s. The height of these points needs to be desk level for horizontal illuminance (0.75 m [2.25 ft.]), and seated eye level for vertical illuminance (1.2 m [3.6 ft.]). For different space types different objectives should be considered based on IES recommendations for each space type.
c. **Spatial luminance measurements for contrast-based glare assessment:** Take at least one measurement per every 70 m^2 (700 ft^2) of floor area. Follow the guidance in the Selecting a Measurement Location Guide section (10.0.3).
    Determine maximum luminance and calculate luminance ratios at various locations in the room grid and between various surfaces in the room. To limit the effects of adaptation and disability glare, luminance ratios measured between two different locations should not exceed the following:
    1. Over the task itself: 1.4 to 1
    2. Between the task and an adjacent screen: 3 to 1 (or 1 to 3)
    3. Between the task and the immediate surroundings: 3 to 1 (or 1 to 3)
    4. Between the task and remote surfaces: 10 to 1 (or 1 to 10)

    However, it should be considered that it is generally not desirable to maintain these last three ratios throughout the entire space. To maintain visual interest and distant eye focus, small areas exceeding those ratios are not only allowed but desirable. Such areas might include artwork, accent finishes on room surfaces, windows and furniture, and accent lighting. The measurement should be based on the most common viewing angle (e.g., towards a computer screen), and at 45 degrees off this viewing angle horizontally in both directions to account for a drifting adaptive zone of view (Jakubiec and Reinhart, 2012).
d. **Spatial calculation of simplified daylight glare probability glare (DGP_s):** At the Intermediate level, the readings for vertical illuminance values on the spatial grid can be converted to DGP_s (Wienold, 2009). The simplified metric uses vertical illuminance as its only independent variable,

and can be used for glare approximations where direct sunlight does not reach the eyes of the occupants.

e. **Point-in-time satisfaction survey:** Surveys in the same nature as that addressed in the Level 1 evaluation should be administered three times a day for two days (overcast and clear), and for at least two different seasons (winter and summer). Depending on the orientation of the examined space, the impact of daylighting can significantly affect the readings and occupants' responses.
South facades are mostly impacted in winter time, so it is necessary to deploy surveys at that time of the year. East and West facades are more uniform throughout the year, while North facades are commonly not affected by glare issues, other than specular reflections from adjacent buildings or objects. In that regard, they should still be investigated since common building controls do not address such issues. In terms of time of day, South facades face all-day exposure, while East and West are more prone to morning and afternoon, respectively. In that regard, three measurements are recommended per measuring day (morning, noon, late afternoon), unless the building's occupancy characteristics dictate otherwise. Although modern envelope and lighting controls are trending towards smart and individualized control, it is common for conflicting objectives within the space to create issues in certain workstations, which need to be identified and addressed.

f. **Performance Evaluation and Benchmarks:** The documents described in the Basic section still apply for the intermediate level; horizontal illuminance values should comply with the UDI thresholds (Nabil and Mardaljevic, 2006) and the total vertical illuminance on the eye should be associated with a DGP_s value that is associated with imperceptible glare (Wienold, 2009). Levels of over 1000 lux (90 fc) in directly lighted areas of the workplane can be also considered as a potential glare issue, as this threshold is suggested in LM-83-23 (IES, 2023a) for the Annual Sunlight Exposure (ASE) Index that is used for glare assessment. Therefore, if corroborated by complaints in the survey, these should be further evaluated. Guidelines regarding electric lighting glare can be found in ANSI/IES RP-1-22. (IES, 2022). The IES RP (Recommended Practice) series, available for purchase, has CRI values for each building type. L08 Electric Light Quality has targets for CRI. IES TM-30 has recommended thresholds for color fidelity index (Rf > 85) and gamut index (Rg > 100).

10.2.3 Non-Visual Effects

10.2.3.1 Objectives. This level includes spot measurements for photopic illuminance and spectral irradiance with medium spatial granularity. CS, EML, or MEDI can be calculated from illuminance and/or spectral irradiance; some lighting sensor technologies calculate these metrics directly.

The approach for the assessment in this level is to use location-based measurements, i.e., collecting point-in-time data at a sample of locations throughout the building. As discussed in the introduction to this section, research suggests that people benefit from 1–2 hours of high circadian stimulus in the morning (Figueiro et al. 2016 and UL 2019). Thus, it is recommended that buildings provide sufficient circadian lighting at workstations.

It is recommended that measurements be taken at workstations angled directly forward for the most common viewing angle (e.g., towards a computer screen), and at 45 degrees horizontally in both directions to account for a drifting adaptive zone of view (Jakubiec and Reinhart, 2012) and using the maximum of the three values because peak exposure is more important than average exposure for these metrics.

The occupant survey and lighting checklist from Level 1 should be included in Level 2.

10.2.3.2 Metrics. By using the methods listed below, at least one of the following lighting-related parameters should be measured (all defined above in Chapter 3).

a. CS
b. EML
c. MEDI

10.2.3.3 Measurement Methods

a. **General Guidelines:**
   1. One measurement location per 100 m^2 (1,000 ft^2) of occupied floor area during occupied hours. Follow the guidance in the Selecting a Measurement Location Guide section (10.0.3).

2. Measurements should be taken at regularly occupied workstations. This means if the workstation is being used during the assessment, the occupant may need to be politely asked to stand up for a few minutes for the duration of the measurements.
3. For buildings that operate a typical 8 AM to 5 PM schedule or similar, measurements should be conducted during the workday. Areas that are occupied regularly at day and at night should repeat measurements during the day and at night. Do not count locations where occupants are sleeping, such as patient rooms in a hospital, as night occupancy.
4. Lighting conditions in zones with exterior windows can change significantly based on the weather and so the measurements should be recorded with time of day, day of year, and weather conditions. It is important to understand the range of non-visual lighting metrics that the occupants are exposed to. For measured workstations within 15 ft of an exterior window, the measurements should be repeated across typical cloud cover conditions in both summer and winter.
5. The light-sensitive cell of the measuring instrument should be pointed towards (perpendicular to) the vertical plane (i.e., facing a wall instead of the ceiling or floor), coinciding with the location of the tasks being conducted by occupant(s). Direct the lens of the sensor towards where the occupant(s) would typically be facing (e.g., a computer screen). Take a measurement at this angle and repeat at approximately 45-degree angles in both directions. Record the maximum of these three values for each location.
6. The sensor should be mounted on a tripod and equipped with a bubble level to provide measurements to establish a consistent height, between 0.9 to 1.2 m (2.7 to 3.6 ft), if occupants are typically seated at this location, and 1.5 to 2 m (4.5 to 6 ft) from floor level for standing occupants.
7. Turn on overhead lights (unless daylight harvesting is used) and open blinds (unless that causes uncomfortable glare, in which case leave closed or how the occupants would have them). For night measurements or dimly lit areas, turn on task lighting. For workstations with computers, turn on the monitor and navigate a screen with typical brightness, such as an internet browser.
8. Any fluorescent or high-intensity discharge (HID) system should be turned on for a minimum of one hour before taking measurements.
9. In new installations, the system should have at least 100 hours of burn time before measuring.
10. Sensor illuminance range should be of 1 lux to 10,000 lux (0.09 fc to 900 fc) or better and calibrated across the range within 1 year prior.
11. Spectral irradiance wavelength range of the sensor should be 380 nm to 780 nm, with measurement interval of no greater than 1 nm.

b. **Performance Evaluation and Benchmarks:** Research on non-visual lighting effects and suitable benchmarks is developing and there is currently no industry consensus. There are some resources available for contextualizing circadian metrics to understand the impact measured lighting conditions have on occupants. WELL v2 (IWBI, 2023) in L03 Circadian Lighting Design provides general recommended EML targets in various space types. The UL DG 24480: Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People (UL, 2019) recommends that occupants achieve a CS value of 0.3 for at least two hours during the day. Note that this guidance is based on measurements from sensors placed on people's bodies throughout the day. However, the assessment approach in this is location-based measurements, which may not capture sources of high circadian stimulus outside of the workstation. It is recommended to use the current benchmarking resources available as helpful context for interpreting CS, MEDI, and EML data, rather than hard-and-fast thresholds for judging performance. More recently IES has published ANSI/IES RP-46-23: Recommended Practice for Supporting the Physiological and Behavioral Effects of Lighting in Daytime Environments. (IES, 2023b)

10.2.4 View

10.2.4.1 Objectives. Review the primary variables (content, access, clarity) of window view quality and identify the issues associated with each variable. This will include building site context, the geometric relationship between the windows and occupied area, and the operational status of glazing and shading devices. The definition of each variable is included below and described in Figure 10.2.

a. Content is the visual features seen in the window view (e.g., buildings, people, and/or sky).
b. Access is the amount of the window view an occupant can see from the viewing position. Access primarily depends on the window size and viewpoint distance from the window.
c. Clarity addresses how clearly the content appears in the window through mullion, shades, and glazing.

Figure 10.2 The Primary Variables for Driving View Quality: Content, Access, and Clarity (Ko et al., 2021).

10.2.4.2 Metrics.

a. Content: Presence of three view layers (sky, landscape, and ground; Figure 10.3), and water or green spaces.
b. Access: View angles (horizontal and vertical)[4].
c. Clarity: Glazing and shade optical properties[5].

(a) Ground layer (b) Landscape layer (c) Sky layer

[4] For access, window proximity, window-to-wall ratio (WWR) and the solid angle of the window(s) from an occupant's viewing direction were proposed as alternative metrics by researchers (Turan et al., 2021; Ko et al., 2023) and also introduced in green certification systems. However, these metrics require further validation. The above section summarizes the metrics that are currently being used in building standards and voluntary building rating systems.

[5] For clarity, visible light transmittance, solar reflectance, openness factor (fabric shade only), the shade solid-to-void ratio, and shading schedule were discussed as potential metrics by researchers (Konstantzos et al., 2015) but these require further developments to be used in this guideline. The above section introduces the metrics that are currently used in standards.

Figure 10.3 Three View Layers: Ground, Landscape, and Sky Layers (Ko et al., 2021).

10.2.4.3 Measurement Methods

a. Content: The presence of three view layers, along with water or green spaces for representative floor levels (low, mid, high), and occupied areas (four orientations) within the midpoint of the perimeter zone (2.5 m [7.5 ft.] from the windows). The measurement should be taken at seated eye level at 1.2 m (3.6 ft.) within the relevant building areas.
b. Access: View angles are the angles from the occupant's viewing position to the vertical or horizontal perimeters (e.g., frame) of a window. They can be measured from representative floor levels of each orientation of the building. Horizontal angles can be measured in cross sections and vertical angles can be measured in floor plans.
c. Clarity: The clarity of window materials is based on the glazing and shade material inventory. Their optical properties can be found in the manufacturers' specification.

10.2.4.4 Performance Evaluation and Benchmarks

a. Content:
    1. EN 17037 Daylight: Section 5.2 "Assessment of view out" (CEN/TC 169, 2018): View layers and natural elements seen from inside, and their distance between the window object(s)
    2. WELL v2 Building Standard, Section M02 "Nature and Place", Part 1 Provide Connection to Nature (IWBI, 2023): Views of natural areas, such as green spaces, blue spaces or other nature-made formations or landscapes
    3. LEED v4.1: Quality Views (USGBC, 2020): Contents including nature, sky or movements
b. Access:
    1. EN 17037 Daylight: Section 5.2 "Assessment of view out" (CEN/TC 169, 2018): Horizontal view angle
    2. BREEAM (BRE, 2018): Window-to-wall ratio (WWR), the ratio of the window area to the gross area of the surrounding wall, depending on the distance in open-plan offices
    3. LEED v4.1: Quality Views (USGBC, 2020): Multiple lines of sight; View factor of 3 or greater, as defined in "Windows and Offices; A Study of Office Worker Performance and the Indoor Environment.") (USGBC, 2019)
c. Clarity
    1. EN 14501 Blinds and shutters - Thermal and visual comfort - Performance characteristics and classification: Section 6.5 "Visual contact with the outside" (CEN/TC 33, 2021b) Normal/normal light transmittance and normal/diffuse light transmittance

10.2.5 Miscellaneous Technical Issues

10.2.5.1 Objectives. At the intermediate level, assessments of flicker should include measurement of electrical lighting systems and/or light sources with an acceptable smartphone application, in addition to visual and occupant assessments. Smartphone applications will have a lower level of performance compared to dedicated flicker meters but can be useful for identifying problems with electric lighting, leading to follow up testing with a more robust device (Leon et al., 2018). Advanced assessments, included in Level 3, will include dedicated flicker metering equipment.

The occupant survey and lighting checklist from Level 1 should be included in Level 2.

10.2.5.2 Metrics

a. Percent flicker (PF)
b. Stroboscopic visibility measure (SVM) - visibility measure derived from measurements of the TLM of the light source or lighting system.

10.2.5.3 Measurement Methods. Simple flicker detection can be accomplished using a hand-held flicker meter or smartphone applications, although the capabilities and accuracy of these devices can vary. Acceptable flicker smartphone applications use the camera to capture measurements. In general, the device sensor/camera should be placed within 0.30 to 0.45 m (0.9 to 1.5 feet) of the electric light source suspected of producing flicker, limiting any contribution of daylight. If the lighting system is capable of dimming, measurements should be taken at full output and the minimum output that will be used. SVM should not exceed 1.6 and/or PF should not exceed 100% for electric light sources (IES TM-39, under review).

10.3 Level 3: Advanced Analysis. The methods described for the Basic and Intermediate levels are sufficient for a great number of spaces and use cases. However, technology is moving visual environmental design practice toward systems that are more dynamic and subject to frequent changes in the visual conditions through the use of frequent switching, daylight harvesting, and individual addressability. For such systems use of these methodologies makes the measurement of lighting metrics by conventional means a very long, laborious process, hence more sophisticated approaches are presented here.

The five visual environment characteristics of Visual Acuity, Glare, Non-Visual Effects, View, and Miscellaneous Technical Issues (Table 10.3) are addressed below in sequence.

Table 10.3 Summary of Level 3 Visual Environment Metrics.

Category	Metric	Method	Granularity
Visual Acuity, Glare	Horizontal illuminance	Illuminance light meter OR simulation	1 per 20 m^2 (200 ft^2)
Glare	DGP UGR Luminance ratios	High Dynamic Range Imaging and Simulations	3 viewing angles per 20 m^2 (200 ft^2) and additionally for every workstation that has access to a window
Visual Acuity	CRI Illuminance mapping	Illuminance light meter with light spectrum and Simulations	1 per 20 m^2 (200 ft^2)
Non-visual Lighting	EML, MEDI, CS	Location-based sensor measurements OR lighting simulations OR Person-Bound Measurement	3 viewing angles per 20 m^2 (200 ft^2) -location-based sensor measurements and lighting simulation 20% of regular occupants (Person-Bound Measurement)
View	Presence of view contents in a window view, View Score View angles, View Access Index, Spatial View Access Visual contact with the outside — Classification, View Clarity Index	2D analysis, 3D analysis, and Temporal analysis	2D analysis: 4 orientations across 3 floor levels (low, medium, high) at 2 window distances of 5 m (15 ft) and 8 m (24 ft) 3D analysis: ideally for 1 per every workstation that has access to a window.
Flicker	Shape of light source waveform, Flicker perception metric (M_p) and SVM	Hand-held flicker meter	1 per luminaire type per space.

10.3.1 Visual Acuity

10.3.1.1 Objectives. The main objective for Level 3 is to collect a sample of lighting measurements at a greater spatial density than Level 2 and Level 1.

10.3.1.2 Metrics. By using the methods listed below, the following lighting-related parameters of the building should be measured, as mentioned in the basic and intermediate levels.

a. Horizontal illuminance
b. Checklist of issues
c. Occupant satisfaction survey

10.3.1.3 Measurement Methods. Follow the instructions for horizontal illuminance measurements under the Level 1 section, with the exception of increasing from one measurement per 100 m^2 (1,000 ft^2). to one measurement per 20 m^2 (200 ft^2). If that leads to more locations than there are occupied workstations, limit measurements to the total number of occupied workstations. The occupant survey and lighting checklist from Level 1 and color rendering content from Level 2 should be included in a Level 3 assessment as well. Refer to the Visual Acuity section under Level 1 and Level 2 for more information.

As an alternative to horizontal illuminance sensor measurements, lighting simulation programs can be employed to estimate horizontal illuminance and are an appropriate measurement technique for Level 3. Follow the same guidance for measurement locations, measurement granularity of one workstation every 20 m^2 (200 ft^2) of occupied floor area, and benchmarking for Level 3 sensor measurements.

There are several software programs that can be used for lighting simulations, such as AGi-32, Radiance, and ClimateStudio, each with their own benefits. Note that a simulation provides only an approximation, and actual illuminance values may vary based on the assumptions used in the model.

To use lighting simulation, the following information will need to be collected:

a. Dimensions of the room.
b. Number of lamps, position, orientation, angle, mounting type, and height of each luminaire in the room
c. Lamp type, e.g., fluorescent, LED, halogen; lamp and ballast manufacturer information; and lamp rated lumen output for each bulb in the room.
d. Reflectance values and LLFs
    1. If not known, the reflectance values of the ceiling, walls, and floor are typically estimated to be 80%, 50%, and 20%, respectively, and a LLF of 0.70 is recommended for most situations, which will account for normal depreciation in the amount of light, both generated from the light source as it ages and reflected in the room.

An IES file can be used to represent the photometric properties of each lamp. IES developed a standard file format to characterize light sources. These files define the light distribution in all directions from the source, based on photometric laboratory measurements. If the manufacturer and model data are known for the light sources in the room, it is often possible to get the associated ".IES" file from the manufacturer or from a file database. However, if the exact model or very similar lighting file cannot be obtained for a light source, sensor measurements should be used for the rooms with those light sources.

10.3.1.4 Performance Evaluation and Benchmarks. Follow the same benchmarking details as in Level 1.

10.3.2 Glare

10.3.2.1 Objectives. The Advanced level is intended to identify glare occurrences and issues that often cannot be captured by the methodologies described in the previous levels. Glare from daylight can be unpredictable due to specular reflections coming from both indoors and outdoors, with such occurrences often being time-sensitive and impossible to detect if measurements only take place once. Indoor reflections may be a result of specular materials either on the window (e.g., frame) or inside furniture, while exterior reflections are often caused by adjacent buildings, cars etc. Unlike electric lighting where specifications can be used to determine the intensity and characteristics, daylight luminance data are harder to obtain through measurements, and also involve high computational cost in simulations. However, because promoting occupant comfort and performance requires mitigating glare occurrences, it is often necessary to use these more advanced methods. To that end, this section will discuss obtaining:

a. Detailed luminance and contrast data through luminance distribution maps (full fisheye images)
b. Glare metrics through high dynamic range (HDR) imaging and simulation

10.3.2.2 Metrics. By using HDR photography (see below) and simulations, the following parameters will be measured or calculated:

a. Contrast through luminance ratios

b. Isolated extreme luminance sources (e.g., the sun, or lasting specular reflections)
c. Adaptation luminance
d. DGP
e. UGR

10.3.2.3 Measurement and Simulation Methods

a. **High Dynamic Range Imaging to Obtain Luminance Maps:** HDR imaging is a technique that has been proposed by Inanici (2005) towards luminance map acquisitions using standard photographic equipment.
   HDR imaging involves capturing a scene in a series of multiple exposures that are merged into one high dynamic range image. With the application of proper calibration functions, this image can produce a pixel-by-pixel translation to absolute luminance values, allowing further analysis of the picture. The latter can include calculation of average luminance of certain surfaces of interest (e.g., screen, window, etc.), contrast analysis between them, descriptive statistics of the luminance of the visual field, background luminance, and as a result, the calculation of multiple glare metrics.
   HDR imaging is a method that can be supported by combinations of instrumentation and software packages. Instrumentation can range from costly dedicated pre-calibrated image-based sensors to conventional cameras that can be calibrated to that end. In a similar manner, software also ranges from expensive, dedicated software suites to open-source tools. For the purposes of this guideline, combinations of low-cost hardware and open-source software will be examined, as dedicated commercial solutions in most cases will not be feasible for a commercial facility manager. A description of the main workflow can be found in the Appendix, while more details are outlined in a recent study by Pierson et al. (2021).
   The pipeline begins by capturing low dynamic range, single-exposure photos and merging them into HDR. The latter are then manipulated through Radiance (Ward, 2024) software towards resizing and cropping to appropriate dimensions. After that, corrections are implemented to account for the distortion of the circular fisheye lens, as well as the vignetting effect (gradual decrease of resulting luminance at increasing distances from the center of the lens). Then, the response function of the specific combination of camera and lens is applied on the image, effectively producing a luminance map that can be an input for Evalglare software. The latter can perform a series of calculations on the HDR images, including vertical illuminance, average luminance, and all major glare metrics. Inanici and Galvin's (2004) report measured average error rates under a variety of light sources, including daylight under different sky conditions. These ranged from 2.6% (a dark room under high-pressure sodium lights) to 11.1% (a dark room under T5 fluorescent lights) with a correlation factor (R^2) of 98.8%.
b. **Full Grid Glare Measurements and Simulations:** At least one measurement position is required for every 20 m^2 (200 ft^2) of floor area. Follow the guidance in the Selecting a Measurement Location Guide section (10.0.3). In addition, three viewing directions (straight and +/- 45 degrees to the right and left) are used to cover the surface under consideration, based on the logic discussed in section 10.0. Due to the sensitivity of perimeter zone workstations on glare, all workstations in the perimeter zone should be assessed. To validate the HDR imaging methodology, a reading for vertical on-eye illuminance next to the camera's lens should be also obtained and then compared with the respective Evalglare output. As the calibrated images will comprise complete luminance maps for every position and view direction, a similar process described in Level 2 should be followed for obtaining luminance ratios, without the need for the use of a spot meter.
c. **Spatial Calculation of UGR, Including Electric Lighting:** Lighting design software can be used with a grid of at least one sensor for every 20 m^2 (200 ft^2) to calculate UGR and DGP for each position and three view directions. Electric luminaires should be included in the simulation based on their specifications and placement details. There are a variety of software suites that are capable of covering glare simulations, ranging from user-friendly commercial packages (e.g., AGi-32, Dialux) to more research-oriented solutions based on detailed ray-tracing algorithms. Simulation can also be obtained based on DGP and UGR metrics.

10.3.2.4 Benchmarking: Although there is no complete consensus for the universal adoption of any of the available glare metrics, recent research by Wienold et al. (2018) has determined DGP to be the most widely applicable glare predictor for daylight, while UGR is also included in other documents. The recent European EN 17037 standard on Daylighting in Buildings includes details, metrics, and thresholds for glare, while the IES LM-83-23 (IES, 2023a) discusses spatial daylighting simulations and objectives for daylight autonomy.

10.3.3 Non-Visual Effects

10.3.3.1 Objectives. Identify complex issues and novel solutions to optimize occupant comfort and performance. There are three approaches to achieve this:

a. **Sensor measurements** with high spatial granularity to completely capture all workstations
b. **Computer simulations** to estimate light metrics
c. **Person-bound measurement (PBM)** strategy to attach wearable light sensors (see Appendix for general light meter specifications) to occupants to measure their exposure

Computer simulations have the advantage that they do not require disturbing occupants and it is easier to account for changes in light levels throughout the day and year, whereas sensor measurements and PBMs require significant effort to repeat multiple times. A disadvantage of computer simulations is that they require detailed specs on the lamps, including spectral power distribution, or assumptions if not available, whereas sensor measurements and PBMs do not. PBM strategies have been used in research studies to investigate the light that the occupants would receive, which would include at their primary workstations as well as ancillary spaces and walking between locations. This is beneficial because it is capturing the light that the occupants are actually exposed to, whereas sensor measurements and computer simulations make assumptions as to where occupants are located and which direction they are facing. The disadvantage of a PBM study is that it requires participants to volunteer to complete the study.

10.3.3.2 Metrics. By using the methods listed below, at least one of the following lighting-related parameters (discussed in detail in Chapter 3 above) should be measured or simulated.

a. CS
b. EML
c. MEDI

10.3.3.3 Measurement Methods. Follow the same measurement methods as Level 2, with the exception of determining one measurement location per 20 m^2 (200 ft^2) of occupied floor area. If that leads to more locations than there are occupied workstations, limit measurements to the total number of occupied workstations.

If pursuing simulation techniques in lieu of physical measurements, create a model using software that can calculate CS, MEDI, or EML and follow the same measurement methods as if taking physical measurements to determine locations, orientations, time of day, times of year, and other factors.

a. All regularly occupied work areas should be included in the model.
b. If surface reflectances cannot be measured, use 80% for the ceilings, 50% for the walls, and 20% for the floors.
c. If LLFs cannot be determined for each fixture in the model, use 0.85 for LED lamps and 0.74 for fluorescent lights.
d. Model computer screens as emitting 250 to 350 cd/m^2 of vertical luminance.

For PBM studies, at least 20% of regular occupants should participate for meaningful results. If the results are being used to assess the entire building, the workstations of the research participants should represent all floors, orientations, and core and perimeter zones.

10.3.3.4 Performance Evaluation and Benchmarking. Follow the same benchmarking guidance as in Level 2.

10.3.4 View

10.3.4.1 Objectives. Identify complex issues and novel solutions to optimize occupant impact, including health, well-being, and performance, through the application of simulation techniques such as 2-D or 3-D modeling, alongside HDR imaging. Utilize 2-D simulations in cases where 3-D data is limited, while 3-D simulations are preferable when comprehensive site and building information is accessible. Enhance the accuracy of 3-D simulations by integrating climate-based daylight analysis with typical meteorological year (TMY) weather data. Additionally, incorporate HDR imaging to assess visual discomfort, particularly in addressing glare concerns as outlined in the preceding section.

10.3.4.2 Metrics

a. Content:
   1. 2-D analysis (point analysis): Presence of view contents in a window view, namely the sky, landscape, ground, and nature (water or green spaces) from representative points on a floor plan, namely the sky, landscape, ground, and nature (water or green spaces).
      i. Detailed analysis: View Score, the percentage of each view contents occupying an individual's field of view (Li & Samuelson, 2020)
   2. 3-D analysis (spatial analysis): Presence of view contents in a window view. The fraction of floor area that meets a minimum of view content requirements.

b. Access:
   1. 2-D analysis (point analysis):
      i. View angles (horizontal and vertical) of regularly occupied area (USGBC, 2019)
      ii. View Access Index (Ko et al., 2023)
   2. 3-D analysis (spatial analysis):
      i. Spatial View Access (SVA): The fraction of floor area that meets a minimum of view angles (Turan et al., 2021)

c. Clarity:
   1. 2-D analysis (point analysis): Optical properties of fenestration and shading systems
      i. Fabric shades: EN 14501 (CEN/TC 33) and View Clarity Index (Konstanzos et al., 2015)
   2. Temporal analysis: The percentage of occupied hours that have no dynamic shade utilized
      i. Field observation of dynamic building envelope (e.g., shade) control schedule
      ii. Simulations: based on IES LM-83-23 guidelines (IES, 2023a) using a typical meteorological year (TMY) file

10.3.4.3 Measurement Methods.

a. Content:
   1. 2-D analysis: Quantifying the presence of view contents in a window view at specific reference points involves considering a combination of factors: two distances from the window (5 m [15 ft] and 8 m [24 ft]), four orientations, and three representative floor levels (low, medium, high). For more detailed analysis, the percentage of window view area occupied by specific view contents can be calculated using the "View Score" method proposed by Li and Samuelson (Li & Samuelson, 2020), with 2D view simulation in Google Earth Studio or HDR imaging of representative floor levels for each building orientation. AI-based image analysis tools or Adobe Photoshop can also be used for the quantification of each view content within a window view.
   2. 3-D analysis:
      i. Using 3-D modeling and visual scripting plug-ins, such as Rhinoceros 3-D and Grasshopper, the fraction of floor area that meets a minimum view content requirements can be calculated. The tools proposed by researchers (Turan et al., 2021; Kim et al., 2022) can calculate the percentage of total rays cast from one origin point that intersect selected outdoor view elements.

b. Access:
   1. 2-D analysis: Using building floor plans and sections, one can estimate the horizontal and vertical view angles from a viewing position to the window frames. Alternatively, one can calculate the View Access Index based on the WWR, window distance and viewing direction relative to the primary window information from the floor plans and elevations. Employing a 3D scanner offers another viable option that enables the extraction of geometric details pertaining to windows, such as view angles, distances, and sizes. Use software tools like

Autodesk Recap to efficiently process and analyze the acquired data from the 3-D scanner viewer.

2. 3-D analysis:
    i. Using 3-D modeling and visual scripting plugins, such as Rhinoceros 3-D and Grasshopper, one can quantify the proportion of rays cast from one origin point that intersects sky components. This can be done as a whole building analysis in conjunction with the climate-based daylight analysis (Turan et al., 2021; Kim et al., 2022; Ko et al., 2023).

c. Clarity:
    1. Based on the optical properties of fenestration and window shade materials, one can estimate "Visual contact with the outside – Classification" or View Clarity Index. The properties can be obtained from the manufacturer's technical documents or lab measurements following ASHRAE Standard 74-1988 (ASHRAE, 1988).
    2. 3-D analysis (temporal analysis):
        i. Field observations: the dynamic control schedule of the building envelope (e.g., shades).
            (a) For buildings that have an automatic shade control system, the shading schedule can be obtained from the facility manager.
            (b) For buildings that have a manual shade control system, the shading operation of the representative floor levels for each orientation can be analyzed at a representative time of a day or year (9 AM, noon, 3 PM on solstice and equinox). If necessary, the manual shade control can be observed continuously (i.e., time-series data) by a monitoring system (Reinhart & Voss, 2003).
        ii. Simulations: IES LM-83-23 guidelines (IES, 2023a).
            (a) Using building simulation software that has dynamic shading modules (e.g., Rhinoceros 3-D modeling environment and its visual scripting plug-in Grasshopper or Climate Studio), the potential shade operation can be calculated, based on the IES LM-83-23 guidelines (i.e., climate-based daylight analysis) (IES, 2023a). The percentage of annual occupied hours that have no dynamic shade use can be calculated and these percentages can inform the relative performance of the space in terms of view clarity (i.e., no dynamic shade used: high clarity; dynamic shade used: low clarity).

10.3.4.4 Performance Evaluation and Benchmarking. Although there is no consensus for a standardized evaluation method for every facet of window view quality, a few recent research studies proposed metrics, or the recommended thresholds, to consider for window view quality assessment:

a. View Quality Index: conceptual quantification for content, access and clarity (Ko et al., 2022).
b. View Score: geometrical and graphical quantification for content and access, based on 2D information (Li & Samuelson, 2020).
c. Spatial View Access and Seemo-Raycaster: geometric and graphical quantification for content and access, based on 3D information (Turan et al., 2021; Kim et al., 2022).
d. View Access Index: geometric quantification for access, based on 2D or 3D information (Ko et al., 2023).
e. EN 14501 (CEN/TC 33) and View Clarity Index (Konstantzos et al., 2015) for clarity of fabric shade materials based on their optical properties.
f. IES LM-83-23 provides an automatic shading schedule that may influence the temporal characteristics of clarity (IES, 2023a).

10.3.5 Miscellaneous Technical Issues

10.3.5.1 Objectives. The objectives for the advanced level of flicker detection are similar to those at the intermediate level; however, more sophisticated handheld metering equipment is recommended for improved accuracy and a more detailed detection of the type of flicker that may be present. At the advanced level, assessments of flicker focus on identifying instances of direct flicker, the stroboscopic effect, or the phantom array effect from the electric lighting system and/or light sources.

The occupant survey and lighting checklist from Level 1 should be included in Level 3.

10.3.5.2 Metrics. By using the methods listed below, the following flicker-related metrics can be measured, using an advanced flicker meter:

a. Shape of light source waveform – can be used to determine light source frequency, modulation depth or PF, and duty cycle
b. Flicker perception metric (M_p) – quantifies direct flicker visibility in the range of 5 to 80 Hz
c. SVM – predicts the visibility of the stroboscopic effect for frequencies between 80 to 2,000 Hz

10.3.5.3 Measurement Methods. Advanced flicker meter equipment, capable of measuring flicker at higher frequencies (at least 3000 Hz), should be used to characterize the time-based waveform of the light source being measured. Currently there is no metric that adequately characterizes the phantom array effect; however, advanced meters capable of measuring high frequencies may identify whether the phantom array effect is a potential risk.

The same measurement method outlined for Level 2 assessments should be implemented for Level 3 assessments. SVM values should not exceed 1.6 and Mp should not exceed 1.0 (IES TM-39, currently under review).

11. ACOUSTICAL QUALITY

11.0 Introduction. In the following sections, the association between 'acoustics' and 'the occupant' is maintained with the use of proper vernacular. The need for such a clarification is rooted in the understanding that the former is the study of the physics of sound, which does not consider the perception (psychological and physiological) of sound. The measurement of the impacts of sound on the person falls within the field of psychometrics, or more specifically psychoacoustics.

Herein, this is effectively enabled with the precise use of 'acoustic' and 'acoustical'; the former is used when the term being qualified "designates something that has the properties, dimensions, or physical characteristics associated with sound waves" (i.e., quantitative), while the latter is used when the term being qualified "does not designate explicitly something which has such properties, dimensions or physical characteristics" (i.e., qualitative) [1]. While nuanced, the distinction can empower the communication of more complex principles and is critically necessary in developing a higher level of understanding.

By way of example, there are numerous terms used to refer to the acoustic and acoustical environment. First, reference to the 'acoustic environment' pertains to measurable properties of the environment. In contrast, the 'acoustical environment' would be in reference to experiential facets, such as satisfaction. While this could lead to confusion—, the benefit is realized in understanding the difference between an objective that is either 'quantitative' (measurable) and 'qualitative' (needing interpretation).

This chapter presents procedures that can be used to measure and infer about the 'quality' of the acoustic environment in principal categories that relate to occupants' satisfaction, productivity, health, and wellbeing. More explicitly, a framework is provided to benchmark buildings, based on three levels of resolution, which is designed to remain consistent with existing acoustical standards of different grades—survey, engineering, and precision—but is not the only criterion for the different levels of assessment:

a. Level 1 (Basic)
    1. A broad screening-level assessment focused on general observations and initial diagnostics, using basic sound level meters (SLMs) meeting Type 2 standards (per IEC 61672 series), informal noise surveys, and subjective occupant feedback.
    2. Measurements at this level serve as a qualitative or semi-quantitative assessment to verify compliance with industry standards, establish baseline conditions and identify potential issues.
    3. Data collection methods are typically rapid, non-intrusive, and rely on averaged conditions rather than highly controlled measurements.
b. Level 2 (Intermediate)
    1. A structured measurement approach designed for repeatability and increased reliability in characterizing the acoustic environment.

2. This level involves Type 1 SLMs (per IEC 61672 series), frequency spectrum analysis, and spatially distributed sound measurements, addressing temporal (e.g., impulse response), spectral (e.g., frequency weighting), and spatial characteristics of sound.
3. Data collected at this level follows controlled protocols, ensuring traceability to reference standards and enabling comparative benchmarking for design evaluation, compliance verification, or optimization.

c. Level 3 (Advanced)
1. A high-fidelity assessment requiring calibrated, such as Type 1 SLMs and/or laboratory-grade equipment and controlled measurement conditions.
2. Employ state-of-the-art methods, such as binaural impulse response measurements, auralization techniques, long-term environmental monitoring, predictive modeling (e.g., ray tracing simulations), and numerical methods (e.g., boundary element analysis, computational fluid dynamics for aeroacoustics).
3. Data at this level supports diagnostics, forensic acoustics, detailed remediation strategies, and scientific research, ensuring the highest level of measurement accuracy, reproducibility, and standardization.

Each successive level builds on the insights gained from previous assessments. To effectively evaluate at an advanced level, it is essential that the foundational evaluations at Levels 1 and 2 have been completed, ensuring a holistic understanding of the environment and its acoustic properties.

Table 1 presents an additional parameter, the proportion of the environment (spaces, features, etc.) that is targeted in evaluations according to different levels. The reference "Minimum Number of Reasonable Rooms" (MNRR) is introduced to allow for re-consideration of the granularity of spatial resolution needed for testing. By way of example, 10% of five rooms or 1,000 identical rooms may present uniquely challenging conditions (e.g., workload) such that completing testing is not feasible.

(To be completed: Introduce additional guidelines on how to use this information)

Table 11.1 Target Proportions for Testing Aspects of the Acoustic Evaluation. Minimum Number of Reasonable Rooms (MNRR).

Topic	Level 1	Level 2	Level 3
11.2 **11.2 Health and Wellbeing**	N/A		
0 11.2.1 Occupational Health and Safety: **Noise Exposure**	$x \leq 10\%$ or MNRR	$x \geq 10\%$ or MNRR	$x > 10\%$ or MNRR
0 Hearing Protection and Conservation	$x \leq 10\%$ or MNRR	$x \geq 10\%$ or MNRR	$x > 10\%$ or MNRR
0 Noise Sensitivity	N/A		
0 Indoor Noise from Building Systems, Services and/or **Utilities**	$x \leq 10\%$ or MNRR	$x \geq 10\%$ or MNRR	$x > 10\%$ or MNRR
0 Environmental Noise: Intrusion from outside the building	$x \leq 10\%$ or MNRR	$x \geq 10\%$ or MNRR	$x > 10\%$ or MNRR
0 Noise Emitted to surroundings	$x \leq 10\%$ or MNRR	$x \geq 10\%$ or MNRR	$x > 10\%$ or MNRR
11.3 Acoustical Comfort	N/A		
0 Room Acoustics: Absorption, Reflection, and **Diffusion**	$x \leq 10\%$ or MNRR	$x \geq 10\%$ or MNRR	$x > 10\%$ or MNRR
0 Electronically Generated Masking **Sound**	See section for guidance.		
0 Occupant-Generated Noise	$x \leq 10\%$ or MNRR	$x \geq 10\%$ or MNRR	$x > 10\%$ or MNRR
11.4 Error! Reference source not found.	N/A		

0 Sound Insulation from Exterior	x ≤ 10% or MNRR	x ≥ 10% or MNRR	x > 10% or MNRR
0 eech Privacy and Speech Security	x ≤ 10% or MNRR	x ≥ 10% or MNRR	x > 10% or MNRR
0 Sound Insulation between Interior Spaces	x ≤ 10% or MNRR	x ≥ 10% or MNRR	x > 10% or MNRR
0 Structure-Borne Noise: Vibration and Impacts	x ≤ 10% or MNRR	x ≥ 10% or MNRR	x > 10% or MNRR
0 Footfall Noise	x ≤ 10% or MNRR	x ≥ 10% or MNRR	x > 10% or MNRR
11.5 Communication		N/A	
0 Intelligibility and Good Listening **Conditions**	x ≤ 10% or MNRR	x ≥ 10% or MNRR	x > 10% or MNRR

Though this document is prepared for the international audience, readers may identify more appropriate acoustical standards, guidelines and/or resources for their jurisdictions. However, the structure of the document provides a holistic summary of the acoustic and acoustical environment.

Readers will find consistency between increasing levels and complexity of measurements, and with interpretation of results, which is affected by extenuating factors (e.g., cost, time, local jurisdictional requirements). Users are encouraged to review the referenced resources to understand 'how' to correctly interpret the results.

11.0.1 Background. According to a survey of over 300 buildings by the Center for the Built Environment (CBE), acoustics is the factor having the greatest impact on occupant dissatisfaction (i.e., noise and speech-related issues). The acoustical environment can impact the occupant in many ways (i.e., comfort, privacy and communication; e.g., productivity, speech privacy in offices, sleep and privacy in hotels, communication in classrooms, health in industrial settings).

The required acoustic performance for a space is dependent on its use. The principal 'acoustical objectives' (or complaints) in occupied buildings are related to acoustical comfort, acoustical privacy, and communication (including listening conditions). These can be objectively related to 'acoustic parameters,' which generally have 'acoustic metrics' to measure and report aspects of the architectural environment, such as background noise level, reverberation time, sound and impact isolation, speech intelligibility and speech privacy, as well as subjectively related to annoyance, distraction, and discomfort.

Occupant surveys can be effective strategies to qualitatively assess potential acoustic performance issues in a building—subjectively. Information collected using these strategies can be used to address (revisit) the specification of acoustic criteria, which may (should) have been defined in design.

Ambient acoustic conditions in a building are the sum of sound from various sources—both external and internal (e.g., traffic, occupant, building systems). Sounds with excessive tones, level fluctuations, and low frequency "roar" or "rumble" are associated with higher annoyance and distraction. Building envelope and partition construction, room dimensions and shape, surface finishes, and furnishings will affect both the loudness and the quality of sounds inside the space, as well as how the sound is perceived by the occupants. Where the use of the space involves listening to and understanding sounds such as speech, music, warning signals, etc., these sounds must be distinct and distinguishable from the background. This is limited by the acoustical clarity provided by the architectural design and surface finishes, as well as the level of noise from building systems or exterior sources.

Beyond the interior acoustic environment, there is a need to consider sound emitted from sources (e.g., building systems and occupant activities) out to the community. These limits are generally defined and regulated by local jurisdictions. The measurements required to confirm code compliance will depend on the applicable noise regulations.

The following sections will assist the reader in determining which acoustic parameters (and associated metrics) are necessary to determine the acoustical quality of a building's spaces. The user of this Guideline will discover methodologies of increasing complexity as they pursue higher levels of analysis. Increasing complexity is, generally, a function of the difficulty of the measurement method, granularity and usefulness of the data provided, characteristics of sound (temporal, spectral and spatial) and precision of instrumentation and metrics.

11.0.2 Acoustical Objectives and Metrics, and Characteristics of Sound. Readers are encouraged to practice communication with precise use of acoustical vernacular, to achieve a clear understanding of the intentions for a space and its performance.

By way of example, spaces should have clear expectations (i.e., acoustical objectives; e.g., acoustical comfort). When these expectations are defined, it becomes possible to specify acoustic criteria (referencing appropriate acoustic metrics—e.g., noise rating systems) for acoustic parameters (e.g., background noise).

The following Venn diagram, in Figure 11.1, presents the three most common sources of acoustical (dis)satisfaction with spaces.

(To be completed:insert Figure mapping acoustical objectives as a priority)
Figure 11.1: A proposed conceptual framework… [2]

Figure 11.2 presents principal categories of acoustic parameters (simplified for the purposes of the graphic) that demonstrate the dependence of acoustic objectives on these variables. The thick solid line represents variables that are directly part of the formulation to calculate or evaluate the acoustical objectives. The thick dashed lines show relationships that indirectly influence other acoustic parameters impacting acoustical objectives. Finally, the faint dashed lines show relationships that are more difficult to quantify, but can impact the acoustical objectives.

(To be completed:insert figure mapping acoustical objectives and acoustic metrics)
Figure 11.2: [xxx]

(To be completed: add explanation around coordinating levels and priorities)

11.0.3 Operational Programming. To achieve the greatest level of occupant satisfaction, acoustical considerations should be integrated into the planning and ongoing operation of a building. Although there are not yet any standards offering guidance on operational programing of acoustical matters, the development and documentation of policies and procedures allows for Standard Operating Procedures (SOPs). The goal is to ensure that acoustic performance is part of the operational objectives, and that the acoustic environment meets requirements based on the purpose of spaces.

a. Early-stage design and construction
   1. Site selection.
   2. Define acoustic objectives by setting explicit goals for the acoustic environment based on the space's purpose.
   3. Incorporate acoustic modeling and simulation during the design phase.
   4. Adopt acoustical considerations from the acoustical planning stage by aligning material selection, structural design, and building-related systems and services with acoustic goals.

b. Workflow and space functionality
   1. Different operational spaces have different acoustic needs, necessitating specification of activity-based expectations and associated acoustic criteria.
   2. Operational programming needs to assess typical noise sources within the space and plan their layout or activity schedule to mitigate noise impact.

c. User experience and feedback loop
   1. Actively gather feedback from occupants to systematically adjust operations of spaces and facilities, accordingly.
   2. Adapt aspects of the acoustic environment to changes in the needs of a space.

d. Monitoring of operations and maintenance

        1. Acoustic monitoring and adjustment could involve periodic acoustic assessments (e.g., noise level measurements). These measurements ensure that the space continues to meet its acoustic goals as activities and equipment evolve.
        2. Plans should include ongoing noise control strategies for managing unexpected noise intrusions (e.g., from equipment or external sources).
    e. Decommissioning
        1. Address noise impacts to vulnerable stakeholders during decommissioning of building facilities

To ensure the acoustic performance of spaces, it is necessary to include acoustical topics in long-term planning. Each phase of the life cycle of the building may necessitate action to meet the acoustical needs and/or expectations of the space's users over time.

11.0.4 Target Audience. The target audience for this Guideline is competent persons in the field of acoustics, however all projects' stakeholders will benefit from an understanding of the acoustical framework. Specifically, the acoustical chapter systematically addresses acoustical objectives impacting acoustical satisfaction. This is accomplished by guiding users to measure, assess and/or study the impact of acoustic measures (i.e., background noise, masking sound, sound insulation, vibration isolation, absorption) affecting acoustical objectives (i.e., acoustical comfort, acoustical privacy, communication).

11.0.5 Cost Considerations in Acoustic Analysis and Design. The cost of acoustic analysis is directly correlated with the level of detail and precision required. As the granularity of measurements increases—whether for background noise levels, sound insulation, reverberation time, or speech privacy—so does the complexity of data collection and interpretation, influencing overall costs. However, a strategic approach to acoustical evaluation can help manage these costs by focusing on broader acoustical objectives of speech privacy, communication effectiveness.

11.0.5.1 Cost Allocation & Responsibilities. It is important to recognize that acoustical consultants should not be responsible for estimating the costs of architectural or mechanical interventions. While consultants provide the necessary technical assessments, benchmarking, and performance criteria, the financial responsibility for specific interventions—such as specialized materials, isolation systems, or noise control elements—falls on manufacturers, suppliers, and contractors. The consultant's role is to establish performance targets, ensuring that proposed solutions are evaluated based on their ability to meet the project's acoustical objectives.

11.0.5.2 Early Integration vs. Retrofitting Costs. A well-planned acoustical design should not significantly increase project costs when integrated early in the design phase. However, delaying acoustical considerations introduces hidden risks and escalating costs due to potential post-construction remediation. Some of the primary risks associated with deprioritizing acoustics during initial planning include:

    a. Limited Solutions: Retrofitting acoustic elements often means fewer viable options, as structural constraints or design aesthetics may restrict effective modifications.
    b. Higher Costs: Acoustic remediation strategies—such as adding absorption panels, upgrading partitions, or reworking mechanical systems—are often more expensive than if those elements were included in the original design.

While upfront costs for enhanced acoustical performance may seem higher in the early phases of the building's life cycle, the long-term financial impact of poor acoustic environments—productivity losses, tenant dissatisfaction, legal liabilities—far outweighs the cost of proactive design measures.

11.0.5.3 Risk Assessment and Cost Mitigation. Managing costs in acoustical design requires effective risk assessment and planning. The primary cost factors include:

    a. Testing & Verification: Measurement procedures incur costs but also provide objective benchmarks that mitigate future disputes or failures.
    b. Material & System Selection: Certain acoustical treatments (e.g., high-performing ceilings, walls with enhanced sound insulation performance) carry an added cost but are essential to meeting occupant expectations and regulatory requirements.
    c. Construction Coordination: Ensuring that contractors correctly implement acoustical strategies prevents costly errors that would require post-construction correction.

11.0.5.4 Value Proposition: Acoustical Design as an Investment. Acoustic performance should not be treated as a luxury or add-alternate for high-budget projects—it is a fundamental component of occupant satisfaction and building functionality. Despite the observation that acoustical upgrades increase costs, the reality is that acoustics consistently ranks among the top factors influencing occupant satisfaction and productivity.

When considering long-term operational value, tenant retention, and overall project success, the investment in acoustically effective environments proves its value every time.

11.1 Documentation. Acoustical reports should detail all information relevant to the application of generally accepted engineering best practices. These reports serve to demonstrate and document the completion of work by a competent professional specializing in the field of acoustics. Most international testing standards explicitly define the reporting requirements, ensuring that values are documented in accordance with the specifications of the relevant standard.

This level of information, particularly with regards to raw data and its analysis, may go beyond what most clients will accept as a usefully succinct report. However, the purpose of a report—whether general (e.g., memorandum) or technical (i.e., comprehensive)—must be scaled to the targeted audience. The raw data may be relegated to an appendix or offered as supplemental material.

Reports should include, but are not limited to:

a. Specification of measurement conditions, such as environmental factors (e.g., temperature, humidity), site conditions, and any deviations from the standard methodology.
b. Full details of the instruments used (including calibration records).
c. Reference to the international standards that governed the test (e.g., ISO, ANSI, ASTM) and clear outline (including deviations) of the procedures followed.
d. Raw data along with a detailed analysis, including how the results align with or deviate from expected performance metrics.

For measurements not following standards, the following guidelines should be referred for reporting:

a. Level 1 (Basic):
    1. Summarize testing equipment used with a description of the methodology followed.
    2. Clear presentation of measured values (e.g., sound pressure levels) with minimal analysis.
    3. As applicable, inclusion of occupant feedback via informal survey methods.
b. Level 2 (Intermediate):
    1. Detailed documentation of the testing conditions, equipment calibration, and any specific deviations from standard methods.
    2. Detailed reporting on intermediate metrics and a thorough analysis comparing results to benchmarks or expected performance.
    3. Detailed analysis of construction conditions and/or causes exploring performance variances that deviate from building code expectations, design guidelines or community regulation.
    4. Compliance verification for both national and international standards with expanded commentary on potential variables affecting results.
    5. As applicable, inclusion of occupant feedback via informal and/or standardized survey methods.
c. Level 3 (Advanced):
    1. Comprehensive documentation of the testing process, including environmental conditions, equipment specifications, and test setup.
    2. Reference to advanced metrics with in-depth reporting and interpretation of results.
    3. Statements of compliance with multiple relevant standards and full analysis of any discrepancies or outliers, ensuring the most stringent requirements are met.
    4. A statement (consistent with those required by the reporting sections of test methodologies) documenting uncertainties and their impact on the measurements, analysis, and conclusions.
    5. As applicable, inclusion of occupant feedback via formal and standardized survey methods.

Surveys conducted as part of the benchmarking process should be directly relevant to the acoustical parameters being tested and evaluated. They should align with the objectives of the testing standard, ensuring that the data collected accurately reflects the performance of the building in relation to its intended design and functional requirements. Clear and targeted survey questions can enhance the reliability of the findings and support meaningful comparisons across benchmarking criteria. Crafting well-developed survey questions is essential to ensure objective, reliable, and meaningful data collection. Poorly designed questions—those that are leading, ambiguous, or biased—can distort responses, compromise validity, and undermine decision-making. The science of survey methodology, closely linked to metrology (the study of measurement), emphasizes neutral phrasing, clarity, and reproducibility. A properly structured survey enhances data integrity, comparability, and the ability to draw valid conclusions.

11.1.1 Acoustical Glossary. Acoustical terminology is well-defined across a range of international and industry standards, ensuring consistency and clarity in measurement, evaluation, and design practice. Organizations such as ASHRAE, ISO, ASA/ANSI, and ASTM have established rigorous definitions for key acoustical concepts, aligning with their respective frameworks for building performance, environmental noise, and material properties. Rather than redefining these terms, this glossary serves to provide a reference to commonly used acoustical terminology while maintaining alignment with the authoritative standards set by these organizations.

11.1.2 General Guidance Relating to Measurement Instrumentation. The accuracy and reliability of acoustical measurements depend on the selection and proper use of instrumentation that meets established international standards. ISO/IEC 61672 defines the performance specifications for sound level meters, categorizing them into Type 1 (precision) and Type 2 (general-purpose) instruments. Type 1 meters offer higher accuracy and stricter tolerances, making them suitable for engineering and research applications, while Type 2 meters are typically used for general surveys and environmental noise assessments where precision requirements are less stringent.

11.1.3 Understanding Measurement Quality: Accuracy, Precision, and Reliability. Acoustical measurements are evaluated not only for their numerical values but also for the quality and reliability of the data. International standards, such as those from ASTM and ISO, define key concepts that differentiate aspects of measurement performance:

a. Accuracy vs. Precision: Accuracy refers to how close a measurement is to the true or accepted value, while precision refers to the consistency of repeated measurements, regardless of whether they are close to the true value. A Type 1 sound level meter (ISO/IEC 61672) is designed to provide both high accuracy and high precision, while a Type 2 meter may be precise but less accurate in certain conditions.
b. Trueness vs. Precision: Trueness describes the degree to which an average of multiple measurements reflects the actual value, while precision refers to how closely individual measurements agree with each other. A sound level meter may have high precision (low variation) but low trueness if it consistently underestimates or overestimates sound levels due to calibration errors.
c. Repeatability vs. Reproducibility: Repeatability describes the consistency of results when the same instrument, operator, and conditions are maintained, whereas reproducibility refers to how well results match when measured under different conditions—such as different instruments, operators, or locations. ASTM E90 (Sound Transmission Loss testing) emphasizes reproducibility by specifying controlled test conditions to ensure that results from different laboratories remain comparable.

Understanding these distinctions is crucial when interpreting acoustical data, ensuring that measurements are not only consistent but also accurate and applicable across different testing conditions. However, the reader may notice slight nuances in the application of these concepts across different standardization organizations.

11.2 Health and Wellbeing. The extent to which health and wellbeing is considered in this document is limited to the auditory and non-auditory effects of sound (i.e., noise) on the person. The former considers the direct effects of sound on physiology (i.e., the auditory system; e.g., temporary and permanent hearing loss, tinnitus), while the latter considers the associated effects resulting from the perception of sound (i.e., psychological, and also associated physiological effects).

The noteworthy takeaway is the differentiation between noise exposure (i.e., exposure to noise defined by having ‘greater’ levels of sound) and noise sensitivity (i.e., exposure to noise defined by having ‘lower’ levels of sound). The threshold between ‘greater’ and ‘lesser’ is loosely taken about the lower-level limit of noise, over some period of time, that can cause damage to the auditory system. The reference to ‘damage’ also exists on a spectrum, whereby the impact may be reversible (or to a degree), such as in temporal shifts, or irreversible, such as permanent hearing loss. This threshold may be calculated for a typical workweek or extended to a full week (24 hours of exposure for seven days).

11.2.1 Occupational Health and Safety: Noise Exposure. For hearing health and general safety associated with communication in loud environments, the sound level within a work environment that exceeds 70 dBA needs to be assessed with respect to the increased risk of auditory health, perception of speech and alarm sounds. Health risks need to consider both the sound exposure level and the duration of exposure. Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ISO 1999:2013 Acoustics – Estimation of noise-induced hearing loss.
b. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ISO 1996-1:2016 Acoustics – Description, measurement, and assessment of environmental noise – Part 1: Basic quantities and assessment procedures.
c. Benchmarking:
    1. Use findings to implement control measures based on the hierarchy of controls: elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE).

Level 2

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ISO 9612:2009, Acoustics – Determination of occupational noise exposure – Engineering method.
b. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ISO 5349-1:2001 Mechanical Vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 1: General requirements.
c. Benchmarking:
    1. Evaluate exposure patterns over time to understand cumulative effects on occupants using statistical metrics (i.e., Ln).
    2. Use findings to implement control measures based on the hierarchy of controls: elimination, substitution, engineering controls, administrative controls, and personal protective equipment (PPE).
    3. Implement findings from surveys of operators, maintenance staff, operations engineers, and safety professionals associated with facility operations. Quantify and correlate occupant feedback with perceived safety risks, work quality, and satisfaction.

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:

    1. Stakeholders may evaluate exposure patterns continuously to understand cumulative effects on occupants using statistical metrics (i.e., Ln).
    2. ISO 5349-1:2001, Mechanical Vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 1: General requirements
    3. ISO 9612:2009, Acoustics – Determination of occupational noise exposure – Engineering method
    4. ISO 3744:2010, Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Engineering methods in an essentially free field over a reflecting plane.

b. Use advanced engineering tools to test and evaluate root causes of elevated levels of airborne noise and/or vibration and options for engineering controls.
    1. Sound intensity or acoustical cameras.
    2. Continuous noise monitoring systems to capture long-term noise data, incorporating advanced analytics to detect patterns and anomalies. May apply machine learning algorithms for predictive modeling of noise exposure risks.
    3. Correlation with measurement by collecting occupant feedback to capture subjective experiences of noise levels and disturbances.

c. Benchmarking:
    1. Integrate data from various sources, such as personal dosimeters, environmental noise monitors, and building management systems, to develop comprehensive noise management strategies.

Additional applicable and/or relevant standards:

a. Align with ISO 45001:2018 (Occupational health and safety management systems – Requirements with guidance for use.
b. ISO 9612:2009 Acoustics -- Determination of occupational noise exposure—Engineering method
c. ISO 1999:2013, Acoustics — Estimation of noise-induced hearing loss
d. ISO 11904-1:2002, Acoustics — Determination of sound immission from sound sources placed close to the ear — Part 1: Technique using a microphone in a real ear (MIRE technique)
e. ISO 11904-2:2021, Acoustics — Determination of sound immission from sound sources placed close to the ear — Part 2: Technique using a manikin
f. ISO 11202:2010, Noise emitted by machinery and equipment

11.2.2 Hearing Protection and Conservation. Hearing protection strategies are necessary to mitigate risks from high noise levels in the workplace. Develop and implement a hearing conservation program that includes regular noise exposure monitoring, periodic audiometric testing, training, and provision of suitable hearing protectors. Follow guidelines from ISO 4869-2:2018 (Acoustics – Hearing protectors – Part 2: Estimation of effective A-weighted sound pressure levels when hearing protectors are worn). Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Identify high-risk areas and activities through surveys and simple measurements.
b. Benchmarking: (To be completed)

Level 2

a. Use detailed noise mapping and personal dosimetry to evaluate exposure in various settings.
b. Benchmarking: (To be completed)

Level 3

a. Apply comprehensive noise reduction strategies, including engineering controls and continuous monitoring
b. Benchmarking: (To be completed)

Additional applicable and/or relevant standards:

a. ISO 9612:2009 Acoustics -- Determination of occupational noise exposure—Engineering method
b. ISO 1999:2013, Acoustics — Estimation of noise-induced hearing loss

c. ISO 11904-1:2002, Acoustics — Determination of sound immission from sound sources placed close to the ear — Part 1: Technique using a microphone in a real ear (MIRE technique)
d. ISO 11904-2:2021, Acoustics — Determination of sound immission from sound sources placed close to the ear — Part 2: Technique using a manikin
e. ISO 11202:2010, Noise emitted by machinery and equipment

11.2.3 Noise Sensitivity. Noise sensitivity can vary significantly among individuals, influencing their response to the acoustic environment.

Auditory health effects are directly related to hearing damage caused by excessive noise exposure, including temporary or permanent threshold shifts, tinnitus, and noise-induced hearing loss (NIHL). These effects primarily result from prolonged exposure to high sound levels that exceed physiological tolerance. In contrast, non-auditory health effects refer to systemic impacts of noise that do not involve direct damage to the auditory system. These include sleep disturbances, cognitive impairment, cardiovascular stress, increased risk of hypertension, and psychological effects such as anxiety or decreased concentration. While auditory effects are typically associated with sound intensity, non-auditory effects can result from chronic exposure to lower-level but persistent noise that affects overall well-being. For sound levels lower than a threshold, generally between 70 and 80 dB, we can investigate the non-auditory health risks associated with noise.

The objective of this section is to assess noise sensitivity through both environmental measurements and occupant feedback. Use detailed surveys to evaluate sensitivity levels and correlate them with specific frequencies or types of noise.

Note 1: While there are non-auditory health effects associated with noise above the threshold, regulations exist to protect auditory health.

Note 2: Noise sensitivity research shows that non-auditory health effects are more strongly correlated with spatial, spectral and/or temporal properties of sound.

11.2.3.1 Indoor Noise from Building Systems, Services and/or Utilities. Thresholds for interior background sound levels are defined within building standards by sound level based on room occupancy and sensitivity.

Acoustical professionals may be able to identify rooms that exceed performance goals without the need for instrumentation. However, most users and designers would only recognize significantly poor performance using an observation-only method I'm not sure I understand this sentence. If an acoustician goes into a room and hears that it is noncompliant without instrumentation, isn't that an observation-only method? What point are you trying to make?

When an observation-only study is conducted, an occupant survey should be completed within the first 3 to 6 months of occupancy to assess satisfaction with the acoustics. Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Complete observation walk-through of all spaces to identify any rooms that may not be meeting expectations.
b. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ASA/ANSI S12.72-2015, American National Standard Procedure for Measuring the Ambient Noise Level in a Room
c. Benchmarking:
    1. Correlate with measurement by collecting occupant feedback to capture subjective experiences of noise levels and disturbances.

Level 2

a. Complete observation walk-through of all spaces to identify any rooms that may not be meeting expectations.

b. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ASA/ANSI S12.72-2015, American National Standard Procedure for Measuring the Ambient Noise Level in a Room
c. Use advanced engineering tools to test and evaluate root causes and options for engineering controls of indoor noise.
d. Benchmarking:
    1. Assess any sources of noise that exceed project expectations, include audio and video recordings.
    2. Document any sound sources or conditions that could negatively impact building occupants (e.g. tonal, pulsing, fluctuations, incidental).
    3. Correlate with measurement by collecting occupant feedback to capture subjective experiences of noise levels and disturbances.

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ASA/ANSI S12.2-2019, American National Standard Criteria for Evaluating Room Noise
    2. ASA/ANSI S12.72-2015, American National Standard Procedure for Measuring the Ambient Noise Level in a Room
b. Use advanced engineering tools to test and evaluate root cause and options for engineering controls of sources of elevated levels of airborne noise and/or vibration.
    1. Conduct continuous noise monitoring to capture long-term noise data, incorporating advanced analytics to detect patterns and anomalies. May apply machine learning algorithms for predictive modeling of noise exposure risks.
c. Benchmarking:
    1. Correlate with measurement by collecting occupant feedback to capture subjective experiences of noise levels and disturbances.

Additional applicable and/or relevant standards:

a. ASTM E966-18a, Standard Guide for Field Measurements of Airborne Sound Attenuation of Building Facades and Facade Elements
b. ISO 12354-3:2017, Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 3: Airborne sound insulation against outdoor sound

11.2.3.2 Environmental Noise: Intrusion from Outside the Building. Environmental noise intrusion refers to unwanted external sounds penetrating a building's envelope, thereby impacting its interior acoustical environment. These sounds originate from different sources, including traffic, railways, aircraft, and industrial activities, and are often perceived as disturbing, distracting, or annoying. The building envelope serves as the primary barrier to reduce such noise, with its requirements varying across jurisdictions, depending on the assessed risk.

Transportation systems and building systems are the most common sources of environmental noise in urban areas, while suburban and rural communities may experience a mix of these with natural sounds. Human perception of noise depends on factors such as location, activity, and individual sensitivity. The World Health Organization (WHO) provides recommendations for noise exposure from sources like road traffic, railways, aircraft, wind turbines, and leisure activities, linking these to potential long-term health effects. Although these recommendations focus on residential settings, they are also relevant to workplaces, schools, and other occupied spaces, although residential settings often have low background noise conditions with an expectation for adequate sleeping conditions.

Noise assessments in communities are often case-specific, focusing on emissions from particular sources or their impacts on individual locations, residences, or facilities. Major airports and some international regions have conducted extensive studies over decades to evaluate noise impacts from transportation and industrial activities.

Common sources of environmental noise intrusion include:

a. Roadway noise primarily results from the interaction between vehicle wheels and the road surface, with vehicle speed and surface type being the dominant factors. Secondary sources include engine noise, braking systems, and acceleration from stops. Metrics such as day-night average sound level (Lden), hourly average (Leq), and hourly maximum (Lmax) are commonly used to characterize roadway noise.
b. Rail noise originates from train engines and wheel-rail interactions. Engine noise, typically low-frequency, correlates with train speed and engine RPM. Wheel-rail interactions, such as wheel squeal, are particularly noticeable on curved tracks. Ground-borne vibrations can also transfer structure-borne noise into nearby buildings. Like roadway noise, rail noise is commonly measured using Lden, Leq, and Lmax.
c. Aircraft noise primarily stems from engine operations during flyovers at varying altitudes. Noise characteristics depend on aircraft orientation and engine thrust, with take-offs generating the loudest noise due to maximum thrust. Descents introduce additional noise from landing gear and flap turbulence. Standard metrics for aircraft noise commonly include Lden, Leq, and Lmax.
d. Industrial noise involves sound from nearby manufacturing facilities, data centers, or other commercial operations. Sources include ventilation systems, transportation activities, and operational machinery. Noise characteristics vary based on equipment type, building design, and operational conditions. Assessments commonly document Lden, Leq, and Lmax. When exterior systems, such as HVAC units, contribute to noise, property-line noise impacts are often a focus, particularly near sensitive occupancies.
e. Entertainment noise, could include music venues (regardless of whether they are indoor or outdoor venues), athletic facilities like pickleball courts or stadia, etc.

Exterior sound level limits for industrial noise are typically defined by local Authorities Having Jurisdiction (AHJs). Transportation-related noise is often regulated by transit agencies, although personal vehicles may have specific sound limits. Interior noise limits, on the other hand, address noise intrusion through building facades and focus on creating acceptable indoor acoustic conditions. Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Conduct simple exterior noise measurements using portable sound level meters to identify primary noise sources and approximate their impact on the building envelope.
b. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ASA/ANSI S12.72-2015, American National Standard Procedure for Measuring the Ambient Noise Level in a Room
    2. ISO 1996-2:2017, Acoustics – Description, measurement, and assessment of environmental noise – Part 2: Determination of environmental noise levels
c. Benchmarking:
    1. Correlate with measurements by collecting occupant feedback to capture subjective experiences of noise levels and disturbances.
    2. Exterior sound level limits are defined by local AHJs when the source of noise is from industrial sources. Documentation for noise impacts from transportation-based sound sources is often prescribed by transit agencies, but usually only vehicles owned by an individual have specific sound level limits. The interior noise limits are applied to exterior noise intrusion through exterior facades.

Level 2

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ASA/ANSI S12.72-2015, American National Standard Procedure for Measuring the Ambient Noise Level in a Room
    2. ISO 1996-2:2017, Acoustics – Description, measurement, and assessment of environmental noise – Part 2: Determination of environmental noise levels.
b. Use advanced engineering tools to test and evaluate root causes and options for engineering control of indoor noise intrusion.
    1. Compare the assessed performance to predictions, calculations, and 3D models.
    2. Consider testing areas posing greater risk of breakout noise (e.g., fenestrations).
    3. Consider testing and monitoring for prolonged periods, spectral content and varying positions and/or locations.
    4. ISO 16283-3:2016, Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 3: Façade sound insulation.
c. Benchmarking:
    1. Survey building users to assess their perception of exterior noise on this site with respect to expectations and exterior building use.
    2. Detail an acoustical remediation plan for any assemblies, details, or conditions that do not meet project expectations.

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ASA/ANSI S12.72-2015, American National Standard Procedure for Measuring the Ambient Noise Level in a Room
    2. ISO 1996-2:2017, Acoustics – Description, measurement, and assessment of environmental noise – Part 2: Determination of environmental noise levels.
b. Use advanced engineering tools to test and evaluate root causes and options for engineering control of indoor noise intrusion.
    1. Consider testing areas posing greater risk of breakout noise (e.g., fenestrations).
    2. Consider testing and monitoring for prolonged periods the spectral content and varying positions and/or locations.
    3. Employ advanced simulations and predictive modeling techniques to evaluate noise intrusion under various conditions. Use software tools to simulate the impact of design interventions (e.g., barrier placement, façade materials).
    4. ISO 16283-3:2016, Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 3: Façade sound insulation
    5. ISO 12354-3:2017, Building acoustics – Estimation of acoustic performance of buildings from the performance of elements – Part 3: Airborne sound insulation against outdoor sound.
c. Benchmarking:
    1. Detail an acoustical remediation plan for any assemblies, details, or conditions that do not meet project expectations.

Additional applicable and/or relevant standards:

a. ANSI S1.13 Measuring Sound Pressure Levels in Air
b. ASA/ANSI S12.9-2013/Part 1 (R2018), American National Standard Quantities and Procedures for Description and Measurement of Environmental Sound, Part 1: Basic Quantities and Definitions.
c. ASA/ANSI S12.9-1992/Part 2 (R2018), American National Standard Quantities and Procedures for Description and Measurement of Environmental Sound, Part 2: Measurement of Long-Term, Wide-Area Sound.

d. ASA/ANSI S12.9-2005/Part 4 (R2020), American National Standard Quantities and Procedures for Description and Measurement of Environmental Sound, Part 4: Noise Assessment and Prediction of Long-Term Community Response.
e. ASA/ANSI S12.17-1996 (R2020), American National Standard Impulse Sound Propagation for Environmental Noise Assessment.
f. ASTM E1014-12, Guide for Measurement of Outdoor A-Weighted Sound Levels
g. ASTM E1503-14, Standard Test Method for Conducting Outdoor Sound Measurements Using a Digital Statistical Sound Analysis System
h. ASTM E1686-16, Standard Guide for Applying Environmental Noise Measurement Methods and Criteria
i. ASTM E1780-12, Standard Guide for Measuring Outdoor Sound Received from a Nearby Fixed Source
j. ISO 1996-1:2016, Acoustics — Description, measurement and assessment of environmental noise — Part 1: Basic quantities and assessment procedures
k. ISO 1996-2:2017, Acoustics — Description, measurement and assessment of environmental noise — Part 2: Determination of sound pressure levels
l. ISO/PAS 1996-3:2022, Acoustics — Description, measurement and assessment of environmental noise — Part 3: Objective method for the measurement of prominence of impulsive sounds and for adjustment of LAeq
m. ISO 12354-4:2017, Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 4: Transmission of indoor sound to the outside

11.2.3.3 Environmental Noise Emitted to Surroundings. Operational requirements for buildings are defined by occupant needs, which are provided by occupant surveys. Perhaps mention that you need to meet the noise emission standards for the equipment and systems on your property (e.g. does your generator meet the property line noise code?). The noise emitted from the equipment and systems need to be managed—within the building, within the property and at and beyond the property's boundary. Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Walkthrough with reporting of noise that may be deemed to be distracting, disturbing, annoying and/or painful. Indicate location of the noise source, with descriptive qualifiers.
b. Benchmarking:
    1. Use findings to implement control measures based on the hierarchy of controls: elimination, substitution, engineering controls, and administrative controls.

Level 2

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ISO 12354-4:2017, Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 4: Transmission of indoor sound to the outside
b. Use advanced engineering tools to test and evaluate root causes and options for engineering control of indoor noise.
    1. Consider testing and monitoring for prolonged periods, spectral content and varying positions and/or locations.
    2. Apply certified or approved computational modelling software.
    3. Spectral (and overall) measurement of noise sources.
    4. Measurements of noise sources using statistical metrics.
    5. Octave band/One-third octave band measurement.
    6. Statistical levels.
    7. OINR testing.
    8. Vibration measurement.
c. Benchmarking:

      1. Use findings to implement control measures, based on the hierarchy of controls: elimination, substitution, engineering controls, and administrative controls.

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. ISO 12354-4:2017, Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 4: Transmission of indoor sound to the outside
b. Use advanced engineering tools to test and evaluate root causes and options for engineering control of indoor noise.
    1. Consider testing and monitoring for prolonged periods, spectral content and varying positions and/or locations.
c. Qualification and quantification of the impact of the site on the ambient environment of adjacent sites and/or community.
    1. ISO 12913-1:2014: Acoustics — Soundscape — Part 1: Definition and conceptual framework.
    2. ISO/TS 12913-2:2018: Acoustics — Soundscape — Part 2: Data collection and reporting requirements.
    3. ISO/TS 12913-3:2019: Acoustics — Soundscape — Part 3: Data analysis.
d. Benchmarking:
    1. Use findings to implement control measures, based on the hierarchy of controls: Elimination, substitution, engineering controls, and administrative controls.

11.3 Acoustical Comfort. Acoustical comfort in buildings is achieved by managing sound levels and acoustic properties to minimize annoyance, distraction, and discomfort. This section provides methodologies for evaluating acoustical comfort across different levels of resolution.

11.3.1 Room Acoustics: Absorption, Reflection, and Diffusion. Acoustical perception and comfort are often associated with the behavior of sound within enclosed spaces, commonly noted with respect to reverberation time. The performance is based on the room size and finishes, which affects the overall sound level, based on the number of occupants and room use. Reflected sound can affect the perception of acoustical quality, comfort, and the overall perception of sound in spaces. Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. Stakeholders should prioritize testing of spaces having a primary function for meeting, or learning and/or communication. They may choose to focus on identifying rooms with excessively long or short reverberation times.
    2. ASTM E2235-04(2020), Standard Test Method for Determination of Decay Rates for Use in Sound Insulation Test Methods.
    3. ISO 3382-2:2008, Acoustics – Measurement of room acoustic parameters – Part 2: Reverberation time in ordinary rooms.
b. Benchmarking: (To be completed)

Level 2

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:
    1. For critical spaces for intelligibility, it is common to also assess Early Decay Time (EDT), Clarity, and Definition.
    2. ASTM E2235-04(2020), Standard Test Method for Determination of Decay Rates for Use in Sound Insulation Test Methods.

3. ISO 3382-1:2009 (Acoustics – Measurement of room acoustic parameters – Part 1: Performance spaces).

b. Benchmarking:

1. Document measurement procedures and results compared to the performance criteria. Identify any rooms that did not meet the criteria, with observations about the potential causes and options for remediation.

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by industry standards:

1. ASTM E2235-04(2020), Standard Test Method for Determination of Decay Rates for Use in Sound Insulation Test Methods.

b. ISO 3382-2:2008, Acoustics – Measurement of room acoustic parameters – Part 2: Reverberation time in ordinary rooms. Use advanced engineering tools to test and simulate the acoustic performance of spaces.

1. Conduct comprehensive room acoustic analyses using advanced tools, like 3D modeling and simulation software, to predict reverberation times and optimize room design.

c. Benchmarking:

1. Detail the performance, including how the measured results compared to predictions, calculations, and 3D models. Identify any rooms, conditions, finishes, or assemblies that do not meet the project expectations, and provide a detailed acoustical remediation plan. Include 3D Sound Intensity Vectors where possible.

Additional applicable and/or relevant standards:

a. ISO 3382-1 standard for performance spaces
b. ISO 3382-2 standard for ordinary rooms,
c. ASTM E2235 standard

11.3.2 Electronically Generated Masking Sound. The purpose of introducing electronically generated masking sound is to manage ambient acoustic conditions that contribute to poor satisfaction (i.e., inadequate acoustical comfort). Effective incorporation of masking sound requires minimizing the variance of the following properties:

a. Temporal (time-related consistency)
b. Spectral (frequency-related consistency)
c. Spatial (location-related consistency)

Electronically generated masking sound can be introduced for the following purposes:

a. To improve acoustical privacy (e.g., speech privacy) between two positions in open-plan and/or enclosed spaces.
b. To enhance acoustical comfort in various environments.

Note 1: The quality of the "noise" parameter in the Signal-to-Noise Ratio (SNR) equation is a critical determinant of acoustical comfort.

Note 2: The introduction of electronically generated masking sound, when aligned with general best practices, does not explicitly reduce the quality of communication. Instead, it should be understood as a reduction in the intelligibility scoring (correlated with communication) of speech at greater distances (i.e., beyond 2–4 meters or 6.5–13 feet). This reduction relates to the typical speech levels of men or women and the rate of sound decay (with distance doubling). This effect is demonstrated in accordance with calculations describing the Lombard effect, as outlined in ISO 9921: Ergonomics – Assessment of Speech Communication.

The evaluation of the performance of sound masking systems is addressed in ASTM E1573-22, Standard Test Method For Measurement And Reporting Of Masking Sound Levels Using A-Weighted And One-Third-Octave-Band Sound Pressure Levels. It is important to recognize the following distinction.

The performance of a sound masking system depends on:

a. design of the system and the sound masking control zones, and

b. commissioning of the system.

The commissioning must be such that every masking control zone is individually calibrated (or 'tuned') to the respective masking sound spectrum, otherwise the output of loudspeakers is not known because of many factors, which include hardware, software, and, notably, architectural features of the environment.

The design and specification of control zones should be congruent with the guidelines of ASTM E1573, otherwise there will likely be failures in the effective commissioning of sound masking systems.

Level 1

a. The sound masking system is commissioned to meet the performance requirements for the overall sound pressure level and the one-third octave bands (for the range between 100 Hz and 10,000 Hz) defined in the project documents.
    1. The design and specifications of the system should be compliant with those requirements.
    2. The design and specifications of the system should be compliant with the requirements for testing of "Test Areas" as per the ASTM E1573-22 standard.
    3. ASTM E1573-22, Standard Test Method For Measurement And Reporting Of Masking Sound Levels Using A-Weighted And One-Third-Octave-Band Sound Pressure Levels.

b. Benchmarking:
    1. Correlate with measurement by collecting occupant feedback to capture subjective experiences of reduced perception of noises and the quality of the masking spectrum.
    2. Note: Occupant surveys should be formal and standardized to avoid the introduction of bias (e.g., by drawing attention to the introduction of electronically generated masking sound).

Level 2

a. There is a commissioning report documenting the calibration of each sound masking control zone.
    1. ASTM E1573-22, Standard Test Method For Measurement And Reporting Of Masking Sound Levels Using A-Weighted And One-Third-Octave-Band Sound Pressure Levels.

b. Benchmarking:
    1. Correlate with measurement by collecting occupant feedback to capture subjective experiences of reduced perception of noises and quality of the masking spectrum.
    2. Note: Occupant surveys should be formal and standardized to avoid the introduction of bias (e.g., by drawing attention to the introduction of electronically generated masking sound).
    3. Integrate data from various sources to identify sources of noise, and employ additional noise management strategies.

Level 3

a. There is a commissioning report and/or third-party testing (testing similar locations) documenting the calibration of each sound masking control zone.
    1. ASTM E1573-22, Standard Test Method For Measurement And Reporting Of Masking Sound Levels Using A-Weighted And One-Third-Octave-Band Sound Pressure Levels.

b. Use advanced engineering tools to test and simulate the ambient acoustic environment.
    1. Use comprehensive techniques, including binaural recordings and computational modeling, to predict ambient acoustic conditions. Use advanced software tools for simulating scenarios and testing the effectiveness of proposed sound masking design.
    2. Conduct continuous monitoring to capture the cadence of disruptive acoustic events, incorporating advanced analytics to detect patterns and anomalies. Machine learning algorithms may be applied for predictive modeling of noise exposure risks.

c. Benchmarking:
    1. Correlate with measurement by collecting occupant feedback to capture subjective experiences of reduced perception of noises, quality of the masking spectrum.
    2. Note: Occupant surveys should be formal and standardized to avoid the introduction of bias (e.g., by drawing attention to the introduction of electronically generated masking sound).
    3. Integrate data from various sources to identify sources of noise and employ additional noise management strategies.

11.3.3 Occupant-Generated Noise. Occupant-generated noise represents a complex and often sensitive aspect of a building's acoustic environment, as it directly impacts the perceptions, satisfaction, and well-being of its users. Unlike mechanical or environmental noise, occupant-generated noise arises from human activities and interactions, making it inherently variable and context-dependent.

Currently, there are no widely accepted standards for evaluating occupant-generated noise, posing challenges for consistent benchmarking. This section provides a framework for addressing this issue by introducing a tiered approach—Levels 1, 2, and 3—that progressively evaluates the performance of buildings in managing occupant-generated noise. Each level builds upon the preceding one, offering increasing resolution and sophistication in measurement and analysis.

By establishing a systematic approach, this section aims to support designers, engineers, and building operators in identifying practical strategies for mitigating occupant-generated noise, ultimately contributing to improved acoustical environments and occupant satisfaction. Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1:

a. Assess occupant noise levels through simple observational surveys and measurements using handheld sound level meters.
    1. See Section 11.2.3.1 Indoor Noise from Building Systems, Services and/or **Utilities**.
b. Benchmarking: (To be completed)

Level 2

a. Use advanced engineering tools to test and evaluate root causes and options for engineering controls of the transmission of occupant-generated noise within and between spaces.
    1. Consider testing and monitoring for prolonged periods spectral content and varying positions and/or locations.
    2. Employ intermediate methods to quantify and analyze noise transmission through floors and walls.
    3. See Section 0 Indoor Noise from Building Systems, Services and/or **Utilities**.
b. Measure impact noise (e.g., footfall noise) using standard test methods
    1. See Section 0 Footfall Noise below.
    2. Reference: (To be completed)
c. Benchmarking:
    1. Assess common sources of noise and document the sound emission with details about testing methods and sources (e.g. footfalls on hard-flooring, chair feet on flooring, appliances, unoccupied background for a baseline.)
    2. Correlate with measurements by collecting occupant feedback to capture subjective experiences of reduced perception of noises, quality of the masking spectrum, and other relevant topics.

Level 3

a. Use advanced engineering tools to test and evaluate root cause and options for engineering controls of the transmission of occupant-generated noise within and between spaces.
    1. Consider testing and monitoring for prolonged periods spectral content and varying positions and/or locations.
    2. Use advanced modeling tools to predict and manage noise levels resulting from occupant activity. Implement noise control strategies such as flooring treatments, acoustic ceilings, and movable partitions.
    3. See 0 Indoor Noise from Building Systems, Services and/or **Utilities**.
    4. See 0 Footfall Noise below.
b. Benchmarking:
    1. Assess common sources of noise and document the sound emission with details about testing methods and sources (e.g. footfalls on hard-flooring, chair feet on flooring, appliances, unoccupied background for a baseline.)

2. Correlate with measurement by collecting occupant feedback to capture subjective experiences of reduced perception of noises, quality of the masking spectrum, and other relevant topics.

Additional applicable and/or relevant standards:

1. ASTM E1374, E1130, E1414

11.4 Acoustical Privacy. Acoustical privacy is essential for maintaining control and supporting occupant behavior in the built environment. Privacy encompasses multiple dimensions, including physical, social, psychological, and informational aspects. This section outlines methodologies for assessing and enhancing acoustical privacy at varying levels of resolution. Currently, no published standards exist for evaluating "acoustic privacy" (commonly referred to as acoustical privacy).

A lack of speech privacy is the most common source of acoustical dissatisfaction in the built environment. Not all spaces require the same degree of speech privacy, as expectations vary depending on the purpose and function of the space. While not explicitly defined in standards, speech privacy is generally understood as the degree to which speech is unintelligible, whereas speech security refers to the degree to which speech is inaudible.

11.4.1 Sound Insulation from Exterior. Effective sound insulation from exterior sources is a critical factor in ensuring the acoustic quality and functionality of indoor environments. Exterior noise—originating from traffic, industrial activities, and environmental sources—can significantly impact occupant satisfaction, productivity, and well-being. Managing sound insulation is particularly important in urban and high-density areas where exposure to external noise is frequent and persistent.

This section provides methodologies for evaluating and enhancing the performance of building envelopes in mitigating exterior noise. By addressing varying levels of resolution, the framework aims to equip designers, engineers, and building operators with practical tools to assess and optimize sound insulation strategies. The goal is to balance regulatory compliance, building performance, and occupant comfort while accounting for site-specific conditions and use cases. Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Review the design and construction details of the building's façade ensuring the use of acoustic materials and adherence to laboratory-tested solutions.
    1. ISO 10140-2:2010 (Acoustics – Laboratory measurement of sound insulation of building elements – Part 2: Measurement of airborne sound insulation).
b. Benchmarking: (To be completed)

Level 2

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. ISO 16283-1
    2. ISO 16283-2:2018, Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 2: Impact sound insulation.
b. Benchmarking:
    1. Analyze results to determine the need for additional insulation or structural modifications.

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. Use comprehensive techniques, including computational modeling, to predict sound transmission and identify potential weaknesses in building design. Use advanced software tools to simulate scenarios to test the effectiveness of proposed insulation solutions.
    2. ISO 10848-1:2017, Acoustics – Laboratory and field measurement of flanking transmission for airborne, impact and building service equipment sound between adjoining rooms).
b. Benchmarking: (To be completed)

11.4.2 Speech Privacy and Speech Security. Speech privacy refers to the ability to conduct confidential conversations without the risk of being overheard or distracted by other conversations. It is a critical consideration in environments such as open-plan offices, healthcare facilities, and meeting rooms.

Speech privacy is assessed by evaluating the intelligibility of spoken words and sentences between a talker and an unintended listener. These evaluations take into account sound insulation, the presence of background noise, and the resulting signal-to-noise ratio that affects the perception of speech. At its highest level—referred to as speech security—speech privacy is achieved when the signal-to-noise ratio prevents the listener from hearing any intelligible words from the nearby talker. Speech privacy is often quantified by the number of words or sentences perceived over time and the degree to which this aligns with the desired level of confidentiality. Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Non-instrumented or observation-only assessments are possible, but only as a baseline check of performance.
b. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. ASTM E1130 Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index
    2. ASTM E2638 Standard Test Method for Objective Measurement of the Speech Privacy Provided by a Closed Room
    3. ISO 3382-3 Acoustics — Measurement of room acoustic parameters, Open plan offices
    4. ASTM E1573-22, Standard Test Method for Measurement and Reporting of Masking Sound Levels Using A-Weighted and One-Third-Octave-Band Sound Pressure Levels
c. Benchmarking:
    1. Evaluate basic speech privacy assessments using simple tools like sound level meters to measure ambient noise levels and background speech levels. Use the Articulation Index (AI) to assess basic speech privacy conditions.
    2. Speech privacy is not widely adopted in building codes or guidelines but is the strongest indicator of acoustical satisfaction (of performance between spaces).

Level 2

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. Stakeholders are encouraged to test additional spaces that have expectations for acoustical privacy (e.g., speech security, privacy from distractions), that may or may not be included in the above testing.
    2. ASTM E1130 Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index
    3. ASTM E2638 Standard Test Method for Objective Measurement of the Speech Privacy Provided by a Closed Room
    4. ISO 3382-3 Acoustics — Measurement of room acoustic parameters, Open plan offices
    5. ASTM E1573-22, Standard Test Method For Measurement And Reporting Of Masking Sound Levels Using A-Weighted And One-Third-Octave-Band Sound Pressure Levels
    6. ANSI/ASA S12.70:2016 (Criteria for Evaluating Speech Privacy in Healthcare Facilities.
b. Benchmarking:
    1. Survey building occupants to assess their perception of privacy and distraction with respect to expectations and room/space use.
    2. Evaluate basic speech privacy assessments using simple tools like sound level meters to measure ambient noise levels and background speech levels. Use the Articulation Index (AI) to assess basic speech privacy conditions.

3. Speech privacy is not widely adopted in building codes or guidelines but is the strongest indicator of acoustical satisfaction (of performance between spaces).

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
   1. Stakeholders are encouraged to test a greater number of spaces than in Level 2 that have expectations for acoustical privacy (e.g., speech security, privacy from distractions), that may or may not be included in the above testing.
   2. ASTM E1130 Standard Test Method for Objective Measurement of Speech Privacy in Open Plan Spaces Using Articulation Index
   3. ASTM E2638 Standard Test Method for Objective Measurement of the Speech Privacy Provided by a Closed Room
   4. ISO 3382-3 Acoustics — Measurement of room acoustic parameters, Open plan offices
   5. ASTM E1573-22, Standard Test Method For Measurement And Reporting Of Masking Sound Levels Using A-Weighted And One-Third-Octave-Band Sound Pressure Levels
   6. ANSI/ASA S12.70:2016 (Criteria for Evaluating Speech Privacy in Healthcare Facilities.

b. Use advanced engineering tools to test and evaluate the performance spaces.
   1. Apply advanced tools, such as binaural recordings and acoustic modeling software, to predict speech transmission paths and optimize room acoustics for expected levels of privacy.

c. Benchmarking:
   1. Survey building occupants to assess their perception of privacy and distraction with respect to expectations and room/space use.
   2. Implement targeted solutions, such as sound masking, partitioning, or absorption materials, to improve privacy.

11.4.3 Sound Insulation between Interior Spaces. Sound isolation, a term used in North America, qualitatively describes the degree of separation between two spaces. Sound insulation, a term used more consistently internationally, is a more specific term used to describe a structure's capacity to attenuate acoustic energy. The performance of the building envelope and internal separating structures contributes to acoustical comfort by reducing the level of noise between adjacent spaces, thereby improving acoustical privacy. Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Review and confirm that assemblies match laboratory-tested sound isolation rating, STC, in accordance with ASTM E90 / ISO 10140

b. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
   1. Stakeholders are encouraged to test a variety of separating assemblies within the building, with special attention to spaces where there is a specific priority (e.g., privacy, noise-sensitive space):
   2. ASTM E336
   3. ISO 12354-1:2017, Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 1: Airborne sound insulation between rooms
   4. ISO 12354-2:2017, Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 2: Impact sound insulation between rooms

c. Noise Reduction (NR) is the one-third octave band sound reduction between enclosed spaces; source level minus receiver level, using the test methods noted.

d. Benchmarking: (To be completed)

Sound Isolation is included in building codes associated with multi-family construction, and in standards and guidelines for most buildings with interior sound isolation expectations for privacy and acoustic comfort. Non-instrumented or observation-only assessments are not recommended for sound isolation due to the variabilities associated with these methods.

For example: International Building Code (IBC) section 1206.2 Airborne Sound notes sound isolation requirements based on laboratory (STC) or field-tested (NNIC) sound isolation performance.

Level 2: Sound Isolation Testing of Representative Partitions

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. ISO 16283-1
    2. ISO 16283-2:2018, Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 2: Impact sound insulation.

b. Apply procedures outlined in ISO 10140-2:2010 (Acoustics – Laboratory measurement of sound insulation of building elements – Part 2: Measurement of airborne sound insulation).
    1. Stakeholders are encouraged to test a variety of separating assemblies within the building, with special attention to spaces where there is a specific priority (e.g., privacy, noise-sensitive space):
    2. ASTM E336, Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings
    3. ASTM E336
    4. ISO 12354
    5. When conducting testing per these standards, practitioners should direct special attention to the collective assembly (i.e., floor-to-ceiling)

c. Benchmarking:
    1. Complete thorough documentation of tested sound isolation performance. These results should be compared to design and construction standards, based on building type and applicable performance building certification (e.g. LEED, WELL, FGI, etc.). These results should be summarized along with the Speech Privacy and Speech Security testing. For rooms to assess interior sound isolation expectations for privacy and acoustic comfort.

Level 3

a. Use comprehensive techniques, including binaural recordings and computational modeling, to predict sound transmission and identify potential weaknesses in building design. Use advanced software tools for simulating scenarios and testing the effectiveness of proposed insulation solutions.

b. Incorporate methodologies from ISO 10848-1:2017 (Acoustics – Laboratory and field measurement of flanking transmission for airborne, impact and building service equipment sound between adjoining rooms).

c. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. Stakeholders are encouraged to test a variety of separating assemblies within the buildings, with special attention to spaces where there is a specific priority (e.g., privacy, noise-sensitive space):
    2. ASTM E336, Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings
    3. ASTM E336
    4. ISO 12354

d. In the documentation of testing and results, references to Speech Privacy and Speech Security should be made.

e. Benchmarking:
    1. Complete thorough documentation of tested sound isolation performance. These results should be compared to design and construction standards based on building type and applicable performance building certification (e.g. LEED, WELL, FGI, etc.). These results should be

summarized along with the Speech Privacy and Speech Security testing. For rooms to assess interior sound isolation expectations for privacy and acoustic comfort.

Additional applicable and/or relevant standards:

a. ASTM E90, Standard Test Method for Laboratory Measurement of Airborne Sound Transmission Loss of Building Partitions and Elements
b. ASTM E336, Standard Test Method for Measurement of Airborne Sound Attenuation between Rooms in Buildings
c. ISO 12354-1:2017, Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 1: Airborne sound insulation between rooms
d. ISO 10140-2:2021, Acoustics — Laboratory measurement of sound insulation of building elements

11.4.4 Structure-Borne Noise: Vibration and Impacts. Vibration propagating through building structures can generate noise that impacts privacy and comfort. Assessing and mitigating structure-borne noise from vibrations is essential for ensuring a high-quality indoor acoustic environment.

Structure-borne noise refers to background noise originating from vibrating equipment, systems, or activities. Common sources include footfall impacts, fitness activities, noise from elevators, plumbing systems, and vibrating equipment such as pumps and air-handling units. While the source of noise is tied to structural or vibrational impacts, the resulting sound perception arises from the vibration of building materials, such as gypsum board, glass, metal, wood, or concrete.

The energy associated with these sources is typically measured in terms of vibrational metrics (e.g., acceleration, velocity, displacement), while the noise impact on occupants is documented using acoustic metrics such as average sound level (Leq) and maximum sound level (Lmax). These measurements consider the type of sound, its duration, and the frequency of occurrence.

Background sound levels for constant operation of building systems should align with the criteria defined in the interior noise section (11.5.3). High-impact or incidental activities and systems, such as those related to fitness, plumbing, or elevator usage, should be observed and evaluated qualitatively through non-instrumented testing.

Use occupant surveys to identify noise sources contributing to complaints, particularly in the context of MEP (Mechanical, Electrical, and Plumbing) systems, HVAC operations, or activities such as fitness.

Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. Conduct preliminary assessments by measuring vibration levels using portable accelerometers in areas where vibrations are noticeable or where complaints have been reported. Identify primary sources of vibration, such as mechanical equipment or foot traffic.
    2. ISO 4866:201, Mechanical vibration and shock – Vibration of fixed structures – Guidelines for the measurement of vibrations and evaluation of their effects on structures.
b. Benchmarking action: (To be completed)

Level 2

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. For occupant-induced or mechanical system vibration-borne sound, measure the average (Leq) and instantaneous (Lmax) sound pressure levels on an octave, one-third octave, A-weighted, and C-weighted basis.
    2. ISO 10848-1:2017, Acoustics — Laboratory and field measurement of flanking transmission for airborne, impact and building service equipment sound between adjoining rooms — Part 1: Frame document

    3. ISO 2631-2:2003, Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 2: Vibration in buildings (1 Hz to 80 Hz)) for comprehensive assessments.
b. Use more sophisticated vibration analysis techniques, including frequency analysis and impact testing, to evaluate the transmission of vibrations through building elements.

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. For occupant-induced or mechanical system vibration-borne sound measure the average (Leq) and instantaneous (Lmax) sound pressure levels on an octave, one-third octave, A-weighted, C-weighted, and FFT basis.
    2. ISO 14837-1:2005, Mechanical vibration – Ground-borne noise and vibration arising from rail systems – Part 1: General guidance.
b. Benchmarking:
    1. Complete detailed assessment for any conditions that are deemed to exceed project expectations. Investigate to determine the root cause of the exceedance.
c. Use advanced modeling tools to simulate the propagation of vibrations and structure-borne noise throughout the building. Implement vibration isolation strategies, such as floating floors, resilient mounts, and dampening materials, to mitigate transmission.

Additional applicable and/or relevant standards:

a. ISO 4866:2010 (Mechanical vibration and shock – Vibration of fixed structures – Guidelines for the measurement of vibrations and evaluation of their effects on structures
b. ISO 10848-1:2017 to quantify structure-borne sound transmission.
c. ISO 2631-2:2003 (Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 2: Vibration in buildings (1 Hz to 80 Hz)) for comprehensive assessments.
d. ISO 14837-1:2005 (Mechanical vibration – Ground-borne noise and vibration arising from rail systems – Part 1: General guidance).

11.4.4.1 Footfall Noise. Impact sound is commonly associated with footfall and other human occupant vibration-borne sources from normal living activities. While the source of noise is associated with structural or vibration impacts, the perception of sound is associated with the vibration of building materials such as gypsum board, glass, metal, wood, or concrete, which generates airborne noise in the occupied space.

Footfall insulation is used in building codes associated with multi-family construction and in standards and guidelines for some building types with footfall noise reduction for acoustical privacy and comfort. Non-instrumented or observation-only assessments are not recommended for footfall insulation due to the variabilities associated with different walkers (e.g. weight, shoe-type, walking style, etc.). The background sound levels defined in the interior noise section (11.5.3) applies for the constant operation building systems. High-impact or incidental activities or systems that building occupants engage (e.g. fitness, plumbing, elevator, etc.) should be observed and non-instrumented tested.

Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Confirm assembly is constructed per the intended the design, and the system is tested per laboratory standards
    1. ASTM E492, Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine
    2. ISO 12354, Building acoustics — Estimation of acoustic performance of buildings from the performance of elements

    AND/OR

b. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. ASTM E1007, Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission Through Floor-Ceiling Assemblies and Associated Support Structures
    2. ISO 16283, Acoustics — Field measurement of sound insulation in buildings and of building elements

c. Benchmarking: (To be completed)

Level 2

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. Stakeholders are encouraged to individually analyze low-frequency and high-frequency impact noise metrics.
    2. ASTM E1007, Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission Through Floor-Ceiling Assemblies and Associated Support Structures
    3. ISO 16283, Acoustics — Field measurement of sound insulation in buildings and of building elements
    4. For occupant induced vibration-borne sound stakeholders are encouraged to measure the average (Leq) and instantaneous (Lmax) sound pressure levels on an octave, one-third octave, A-weighted, and C-weighted basis.
    5. ASTM E3207-21, Standard Classification for Determination of Low-Frequency Impact Noise Ratings. This standard provides methods for calculating single-number ratings of low-frequency impact noise transmission, focusing on the "thudding" sounds often generated by footfall on lightweight structures.
    6. ASTM E3222-20a, Standard Classification for Determination of High-Frequency Impact Sound Ratings. This standard offers procedures for assessing high-frequency impact noise transmission, such as the "clicking" sounds produced by hard-soled shoes on hard surfaces.
    7. ASTM E492-22, Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine. This test method evaluates the overall impact sound transmission performance of floor-ceiling assemblies.
    8. ASTM E989-21, Standard Classification for Determination of Single-Number Metrics for Impact Noise. This classification defines the Impact Insulation Class (IIC), a single-number rating for impact sound insulation.

b. Benchmarking:
    1. Complete survey for building occupants to provide experiential opinions of acoustical performance associated with structure-borne noise (e.g. footfall, chairs, etc.) to correlate with measured performance.
    2. Identify construction conditions and/or causes for structure-borne noise that exceed the building code, design guidelines, or community standards.

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. Assess the field-tested footfall noise impact, ISR and NISR, for 100% of the floor-ceiling assemblies and flooring finishes.
    2. ASTM E1007, Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission Through Floor-Ceiling Assemblies and Associated Support Structures
    3. ISO 16283, Acoustics — Field measurement of sound insulation in buildings and of building elements

b. This should include reporting on enhanced metrics for low- and high-frequency impacts.

1. ASTM E3207-21, Standard Classification for Determination of Low-Frequency Impact Noise Ratings. This standard provides methods for calculating single-number ratings of low-frequency impact noise transmission, focusing on the "thudding" sounds often generated by footfall on lightweight structures.
2. ASTM E3222-20a, Standard Classification for Determination of High-Frequency Impact Sound Ratings. This standard offers procedures for assessing high-frequency impact noise transmission, such as the "clicking" sounds produced by hard-soled shoes on hard surfaces.
3. ASTM E492-22, Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine. This test method evaluates the overall impact sound transmission performance of floor-ceiling assemblies.
4. ASTM E989-21, Standard Classification for Determination of Single-Number Metrics for Impact Noise. This classification defines the Impact Insulation Class (IIC), a single-number rating for impact sound insulation performance.

c. Benchmarking: (To be completed)

Applicable and/or Relevant Standards

a. ASTM E492 Standard Test Method for Laboratory Measurement of Impact Sound Transmission Through Floor-Ceiling Assemblies Using the Tapping Machine
b. ASTM E 1007, Standard Test Method for Field Measurement of Tapping Machine Impact Sound Transmission through Floor-Ceiling Assemblies and Associated Support Structures
c. ISO 12354-2:2017, Building acoustics — Estimation of acoustic performance of buildings from the performance of elements — Part 2: Impact sound insulation between rooms
d. ISO 16283-2:2020, Acoustics — Field measurement of sound insulation in buildings and of building elements, Part 2: Impact sound insulation
e. International Building Code (IBC) section 1206.3 Structure-borne sound requirements based on laboratory (IIC) or field-tested (NISR) footfall insulation performance.

11.5 Communication. Speech communication is a complex field of study. The adoption of principles relevant in the architectural community, like that for speech privacy, is focused around ‘intelligibility,’ ‘cadence’ and ‘audibility.’

The qualification of the quality of communication should be centered on calculations of intelligibility, which are possible using several international testing standards. However, it is imperative to identify and acknowledge the assumptions of the different test standards in the interpretation of the results.

Perhaps most significant, is the correlation between acoustic measurements of the environment and human performance. More specifically, relationships are developed by simulating acoustic conditions in a controlled environment, and by calculating the intelligibility scores of subjects. These ‘listening tests’ use different ‘word lists’ that vary in complexity, such as phonetically balanced (PB) words, consonant-vowel-consonant (CVC) words, “first-presentation sentences” (FPS) and “Harvard Sentences”. The importance of selecting the correct testing standard depends on the type of space. For instance, one may choose to use CVC or PB intelligibility relationships in a waiting room, but FPS or Harvard Sentences in meeting rooms.

11.5.1 Intelligibility and Good Listening Conditions. Speech communication and intelligibility are associated with the clear perception of words and sentences within the listening environment. The performance is associated with the signal-to-noise ratio from the talker to the listener with respect to room conditions (e.g. sound reflections, background sound, and distance). Speech privacy is often defined by the percentage of words or sentences that are accurately understood by listeners.

Note:Measuring speech intelligibility using a compatible system is highly recommended for rooms using speech amplification.

Speech intelligibility is used in public address and system amplification design but is not currently adopted in building standards or guidelines.

Consider Table 11.1 in the determination of the proportion of spaces or areas, or number of rooms to test.

Level 1

a. Non-instrumented or observation-only assessments provide a good baseline check for performance from amplified and unamplified speakers within large speech sensitive rooms.
b. Fire protection and warning systems should be evaluated per AHJ regulations.
    1. PA requirements (e.g., STI) Possible NFPA 72 reference (To be completed)
c. Benchmarking: (To be completed)

Level 2

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. What is the standard? (To be completed)
b. Benchmarking: (To be completed)

Level 3

a. Conduct testing in accordance with the applicable standard(s), using the most stringent methodology where multiple standards apply, as defined by the AHJ or, where not specified, as recommended by recognized industry standards:
    1. What is the standard? (To be completed)
b. Benchmarking: (To be completed)

Additional applicable and/or relevant standards:

a. IEC 60268-16
b. ASTM E1130

12. EVALUATING THE IMPACT OF INTERDEPENDENT IEQ FACTORS ON OCCUPANTS

12.1 Introduction – Managing IEQ for Human Occupants. Human physiology is remarkably resilient and able to adapt to exposure to challenging environmental conditions when necessary. Nevertheless, we have a finite amount of metabolic energy that must be allocated to support functions ranging from physical movement to cognitive activity. When our environment is optimized, occupants have greater ability to maintain overall health and cognitive functioning. As humans spend more time indoors, (Klepeis et al. 2001) optimizing IEQ for occupants has both immediate and long-term health benefits, such as relieving eye irritation, fatigue, and headaches, as well as minimizing long-term conditions like respiratory diseases and cognitive decline (Frontczak and Wargocki 2011). Furthermore, there are powerful downstream economic benefits, such as decreased absenteeism, improved productivity, and lower healthcare costs – factors that can significantly affect the profitability of businesses within buildings (Al Horr et al. 2016; Allen et al. 2016). Understandably, implementing strategies to improve IEQ has become a high priority for building designers, managers and users.

12.2 Data Collection. Managing IEQ for occupants requires defining the optimal occupant experience and identifying the key indoor parameters that support this experience.

The factors affecting occupants can be separated into two categories. The first includes environmental influences perceived subjectively, and which can be captured by questionnaires on "comfort" or "satisfaction". Examples are sensations of being overheated or cold, distractions from light glare or noise, and unpleasant odors. Subjective reports of comfort, however, are influenced by occupant mood, job satisfaction and other experiential factors that change over time. (Yetton 2019). Comfort, therefore, is considered highly subjective. The assumption that physical health is correlated with comfort is also not supported by studies on long-term health conditions, such as the likeness of developing obesity or susceptibility to developing type 2 diabetes.

The second category of environmental influences includes exposures that impact health but may not be perceived, for example, excessively dry air that dehydrates mucus membranes that protect airways from infections, fatigue-inducing carbon dioxide concentrations, and ozone emissions that cannot be smelled but are nonetheless inflammatory when inhaled. Acute IAQ impacts include asthma, throat irritation, shortness of breath, and heart disease (Heinsohn 2013; Davis 2007). Chronic impacts include, but are not limited to, cancer, chronic lung diseases and bronchitis (Sofuoglu 2011). Measuring indoor exposure to imperceptible

IEQ components requires a “sixth sense” provided by technology, such as IAQ sensors, that capture data for comparison to published safety and wellness standards. Physiologic measurements such as vital signs (temperature, heart rate, blood pressure, respiratory rate), blood levels of oxygen, cortisol, inflammatory biomarkers, etc. and cognitive tests such as memory, hand-eye coordination, and attention to tasks, are measures of environmental influences.

12.2.1 IEQ: Identifying Indoor Influences on Occupants: Visual, Acoustics, IAQ, Thermal Comfort. The majority of IEQ evaluations encompass building factors known to impact occupants. These include temperature and humidity, sound amplitude and frequency, light intensity and color, and IAQ (Mujan 2019).

a. Thermal (temperature and humidity) deviation from an indoor climate that achieves a state of physical and psychological comfort leads to heightened negative emotions and greater effort needed to maintain performance levels.
b. Visual environment relates to conditions necessary for performing visual tasks efficiently and comfortably, and promotes circadian rhythms. Sources include natural daylight, artificial lighting, glare control, and color rendering. Optimal lighting conditions can reduce eye strain, improve mood, and increase productivity among building occupants.
c. Acoustic quality refers to controlling sound to allow communication and concentration, avoiding distracting or annoying conditions identified as “noisy”. Factors influencing acoustic comfort include building design, construction materials, interior space layouts that reduce distractions such as talking, telephone and other equipment beeps and alarms.
d. IAQ to support short- and long-term health outcomes. A perceived 10% decrease in IAQ was associated with a 1.1% reduction in productivity performance. Deviations from published norms, determined by indoor air monitoring, directly affect occupants’ respiratory and mental health (Torresin 2018).

12.3 Analysis of Relationships between Occupant Health and Environmental Exposures. To develop a holistic model to assess the impact of IEQ on occupant health, data is needed to quantify multi-modal IEQ exposures using questionnaires to assess the subjective occupant experience, as are objective measurements using sensors to measure imperceptible conditions (Ncube 2012). Research studies have included data on occupant physiology collected by wearable technology and biomarkers, however, this is outside the norm for ASHRAE PMP categories discussed in this guideline.

The following are findings from studies that correlate subjective, survey-based results, with indoor conditions listed above.

a. Occupant studies on subjective impacts of IEQ: A study (Tang et al. 2020) on perceived IEQ influences used questionnaires to benchmark participant satisfaction with each of the four factors – thermal comfort, illuminance, sound pressure and carbon dioxide as a surrogate for IAQ. Regression analysis revealed multiple interactions, including illuminance and acoustic satisfaction, thermal comfort and IAQ satisfaction, and to a lesser degree sound pressure on IAQ satisfaction.
b. Perceived relationships between categories reported by occupants include:
    1. Thermal Environment – Visual Environment
    2. Thermal Environment – Indoor Air Quality
    3. Thermal Environment – Acoustical Quality
    4. Visual Environment – Indoor Air Quality
    5. Visual Environment – Acoustical Quality
    6. Indoor Air Quality – Acoustical Quality
c. Occupant assessment of subjective IEQ factors varied according to building use. For example, IAQ was weighed the most heavily in commercial office buildings, whereas in schools, thermal comfort was prioritized. Personality factors have also been found to influence occupant satisfaction. For example, employees with job satisfaction are more likely to be happy with their IEQ (Cheung et al. 2000).
d. Studies on perceived impacts of the four IEQ components (see Section 12.2.1) report independent, additive, subtractive, synergistic, or antagonistic effects, depending on occupant activities in the

building (Bluyssen 2008 and 2010; ASHRAE 2010; Torresin 2018; Bonnefoy 2004 and 2007; Lewtas 2007; Babisch 2008; Houtman 2008).

e. While methods of investigating IEQ often focus on single variables, temperature, humidity, visual, acoustics, and IAQ clearly coexist and in combination impact human health and comfort. A comprehensive model, however, would also include both perceived and measured data that is aggregated to identify the dominant factors and secondary influencers (See Figure 12.1).

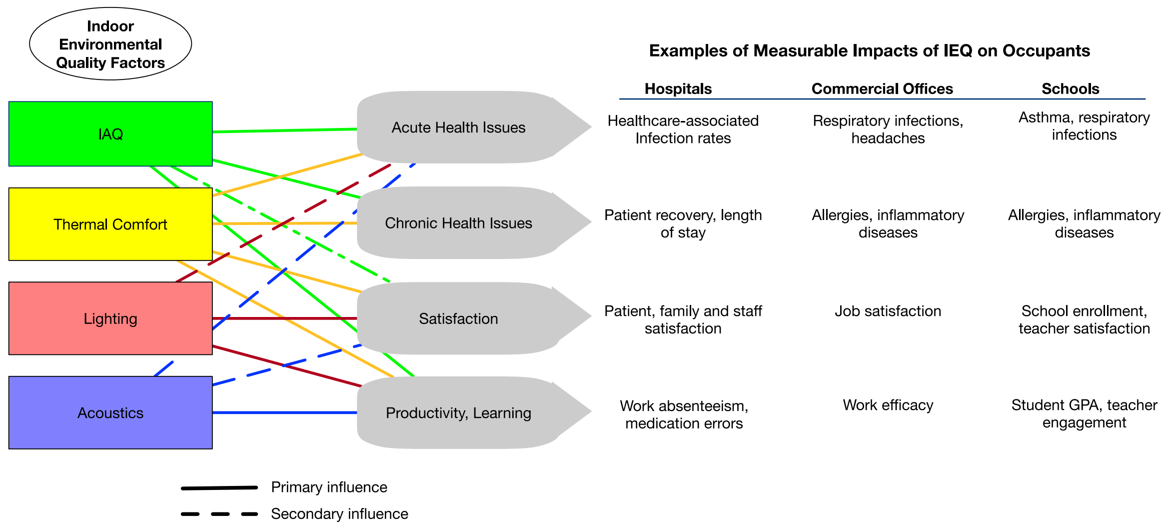


Figure 12.1 Schematic Showing Interrelationships between IEQ Components, Occupant Health Impacts and Consequences According to Building Use.

12.4 Data Analysis. Individual IEQ factors coexist and interact in complex ways, often producing additive, synergistic, or even antagonistic effects on occupant health and comfort. While traditional approaches examine these factors in isolation, an integrated model considers their interdependence to prioritize the most impactful adjustments. (Bluyssen 2008; ASHRAE 2010; Torresin 2018; Bonnefoy 2004; Fisk 2007; Lewtas 2007; Babisch 2008; Houtman, Douwes, de Jong 2008).

12.4.1 Moving Forward: Physiologic Impacts of IEQ. Demonstrating a link between IEQ metrics and health outcomes requires correlating exposure data to occupant physiological measurements such as vital signs (heart rate, blood pressure, respiratory rate, body temperature), biomarkers, and cognitive tests. Health metrics, however, are not currently captured for these correlations; the data missing from most studies includes physiological metrics or biomarkers to quantify non-perceived impacts of indoor exposures. Mathematical modelling strategies include Analytic Hierarchy Process (Saaty and Vargas: 2000), Multivariate Linear Regression, and structural equation modeling (SEM). These approaches have varying strengths, and analysis of these strengths is outside the scope of this chapter.

With aggregation and analysis of multi-faceted data, comprehensive IEQ scores could be validated by correlation with subjective feedback from satisfaction and comfort questionnaires, as well as with data on physiological metrics, inflammatory biomarkers, and health and productivity outcomes.

a. Proposed Framework for Integration:
   1. Holistic Data Aggregation: Combine occupant data from both subjective feedback and physiologic metrics with environmental sensor data into a centralized framework.
   2. Dynamic Modeling Tools: Employ methods like Multivariate Linear Regression and Structural Equation Modeling to analyze interactions, overarching trendsand predict outcomes.
   3. Validation Through Outcomes: Link above IEQ scores to tangible results, such as occupant satisfaction, physiological health markers, and productivity metrics.

b. Examples of IEQ Integration Approaches:

1. Use continuous monitoring systems that combine occupant metrics with environmental data on sensible and latent heat, visual, acoustical, and IAQ data.
2. Identify potential conflicts with predictive tools (e.g., thermal adjustments that affect acoustic quality).
3. Visualize and enable dynamic building management with dashboards and real-time IEQ adjustments.

12.5 Discussion and Conclusions. A shift towards integrated, interdisciplinary evaluation is essential for advancing IEQ management to transform buildings into spaces that promote health, happiness, and prosperity. Key recommendations include:

a. Identify actionable solutions, challenges and research needs
b. Encourage multi-disciplinary collaboration among building engineers, health professionals, and data scientists
c. Differentiate between subjective and objective occupant and environmental measurements
d. Leverage biomarkers for precise occupant feedback while balancing invasiveness with effectiveness
e. Develop adaptive systems that respond to occupant needs in real time
f. Clarify goals of testing: building performance, human performance, business output, education success

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(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX A
CARBON CALCULATION METHODOLOGY

A1. Background

ASHRAE has stated that building decarbonization is imperative for global climate stability, energy security, and the general well-being of communities. As the building sector accounts for significant global greenhouse gas (GHG) emissions, prioritizing decarbonization action serves the public interest. Addressing this issue has the potential not only to help mitigate climate change in the short term, but also to provide a stable environment for future generations. The benefits of building decarbonization include improved indoor air quality, energy efficiency, community health, and social equity.

Building decarbonization encompasses a building's entire life cycle, including building design, construction, operation, occupancy, and end of life. Building construction, energy use, methane, and refrigerants are the primary sources of GHG emissions. Building life-cycle assessment involves consideration of operational and embodied emissions. Operational emissions are generally from energy use. Embodied emissions include GHG emissions associated with building construction, including extracting, manufacturing, transporting, and installing building materials, as well as the emissions generated from maintenance, repair, replacement, refurbishment, and end-of-life activities. Embodied emissions also include refrigerant releases across the building life cycle.

ASHRAE has multiple standards that seek to make buildings more efficient (see Table A.1), and has now included procedures for reporting carbon emissions in Standard 105-2021 (ASHRAE 2021). Standard 105-2021 provides consistent methods for determining and reporting energy performance of buildings to facilitate: (a) the comparison of design and operation strategies in new and existing buildings, (b) the development of building energy performance standards, and (c) the reporting of greenhouse gas emissions associated with building operation.

ASHRAE is preparing a new Standard 240P – Evaluating Greenhouse Gas (GHG) and Carbon Emissions in Building Design, Construction and Operation. This standard establishes how to measure and verify the GHG and carbon emissions of a building or group of buildings, over the entire life-cycle. This standard provides consistent procedures and data to be referenced by other standards that address new and existing building performance.

Standard 204P covers: 1. existing buildings, new buildings, groups of buildings, or portions of buildings; 2. determination, including calculation methodology, and expression of the building(s) zero net GHG and zero net carbon status for building operation; 3. GHG and carbon emissions associated with flows across the site boundary and off-site credited flows; and 4. embodied GHG and carbon emissions of building materials and systems.

A2. ASHRAE Standard 105-2021

ASHRAE Standard 105-2021 provides consistent methods for determining, expressing, and reporting energy performance of buildings to facilitate: (a) the comparison of design and operation strategies in new and existing buildings, (b) the development of building energy performance standards, and (c) the reporting of greenhouse gas emissions associated with building operation. ASHRAE Standard 105-2021 also provides consistent methods for determining, expressing, and comparing the greenhouse gas emissions associated with the design of new buildings and with improvements to, or changes in, the operation of existing buildings.

ASHRAE Standard 105-2021 covers: a. new buildings and existing buildings or portions thereof; b. the determination and expression of building energy performance and the estimate of greenhouse gas emissions associated with that energy use; and c. techniques for the comparison of the energy performance and associated greenhouse gas emissions between different buildings or between alternative designs or operation strategies for the same building.

A3. ASHRAE Standard 240P

A draft of the proposed ASHRAE Standard 240 was released for public review (Feb. 2nd, 2024 to March 18th, 2024). Currently SPC 240P is reviewing comments and preparing the Standard for public release.

Table A.1 ASHRAE Standards Addressing Energy Efficiency, GHG and Refrigerant Emissions, and Renewables (Table 1, ASHRAE 2024).

	Topic				
Standard/Code	**Energy Efficiency**	**Operational GHG Emissions**	**Embodied GHG Emissions**	**Refrigerant Emissions**	**Renewables**
ANSI/ASHRAE Standard 105-2021, *Standard Methods of Determining, Expressing, and Comparing Building Energy Performance and Greenhouse Gas Emissions*	●	○			●
ANSI/ASHRAE Standard 147-2019, *Reducing the Release of Halogenated Refrigerants from Refrigerating and Air-Conditioning Equipment and Systems*				●	
International Green Construction Code® and **ANSI/ASHRAE/ICC/USGBC/IES Standard 189.1-2020,** *Standard for the Design of High-Performance Green Buildings*	●	●	●		●
ANSI/ASHRAE/ASHE Standard 189.3-2021, *Design, Construction, and Operation of Sustainable High-Performance Health Care Facilities*	●	●	●	○	●
Proposed ASHRAE Standard 227P, *Passive Building Design Standard*	■			■	
Proposed ASHRAE Standard 228P, *Standard Method of Evaluating Zero Net Energy and Zero Net Carbon Building Performance*		□		□	□
Proposed ASHRAE Standard 240P, *Evaluating Greenhouse Gas (GHG) and Carbon Emissions in Building Design, Construction and Operation*	■	■	■	■	■

Legend:
- ● Included in standard
- ○ Carbon calculation methodology included in standard
- ◌ Under consideration for inclusion in next update of standard
- ■ Included in proposed standard
- □ Carbon calculation methodology included in proposed standard

Note: Energy efficiency directly contributes to operational GHG emission reductions.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX B
COST ESTIMATION

B1. Background

Guideline 45P does not address the cost of conducting the performance measurements that are the subject of this guideline. While these costs are substantial and need to be considered, they are not addressed in the guideline because they change over fairly short time periods so that costs evaluated today would not be applicable during the 5-yr applicability of Guideline 45. This became quite apparent when the document Performance Measurement Protocols for Commercial Buildings, published by ASHRAE in 2010, was reviewed. Table 2-1 in the PMP document listed a range of costs (in US dollars) for staff time and instrumentation for each of the six levels (energy, water, thermal comfort, IAQ, lighting, and acoustics); these estimated ranges were quite broad, were not based on any detailed analysis, and were deemed not very useful for practitioners.

Nonetheless, one approach that was developed for the U.S. Army by the Energy Systems Laboratory at Texas A&M University: Development of a Measurement and Verification (M&V) Costing Toolkit (ESL-HH-04-05-30) may be a useful resource or starting point for users of Guideline 45P. This toolkit provides a standardized labor and equipment costing procedure for measuring and verifying energy savings for commercial building retrofit projects. It includes pricing for a wide-variety of sensors, data loggers, portable data loggers and transducers used for retrofits to buildings. The costing toolkit also contains a framework for pricing the installation, maintaining the equipment, and the removal of instrumentation associated with these measurements. The toolkit also includes costing procedures for collecting the data from remote sites, archiving the data, QC procedures, data analysis, savings reporting, and project closeout costs. Several examples are provided that illustrate the procedures.

The toolkit includes spreadsheets containing a database of data acquisition equipment and costs associated with the measurements (equipment, installation, calibration, maintenance, removal, etc.). Labor cost information is given as rates ($/hr), fringe benefits (% of rate), and total cost for various personnel categories. Labor and equipment costs can change significantly over time and by geographic region. Users of Guideline 45 may find the U.S. Army's spreadsheet useful, or may develop their own spreadsheets, customized for their projects, which may include other performance measurement categories (e.g., water, IAQ, thermal comfort, acoustics, etc.). However it is used, the procedure provides a checklist of cost items/elements that need to be considered in any performance measurement project.

B2. U.S. Army M&V Costing Toolkit

The U.S. Army M&V Costing Toolkit was developed for use by the Federal government or third party planners to design a M&V plan and to estimate the M&V costs associated with the verification of savings from the implementation of energy conservation measures in a building, or group of buildings. The M&V Costing Toolkit report (Haberl et al. 2003) presents a general overview of the M&V costing process (see Figure B.1), various methods for monitoring and verifying savings, and a description of the M&V Costing Toolkit.

Three M&V methods have been developed for this toolkit, including: a) monthly utility billing analysis, b) hourly or daily data analysis, and c) calibrated simulation. With the exception of the monthly utility billing analysis, each method has several data collection options, including: a) using data loggers, b) using EMCS data and c) using utility interval data recorded by the utility supplier and transferred to the data analyst.

Additional references have been included that provide detailed descriptions of some of the M&V methods intended to be used with the report, as well as vendors of data acquisition equipment referred to in this report.

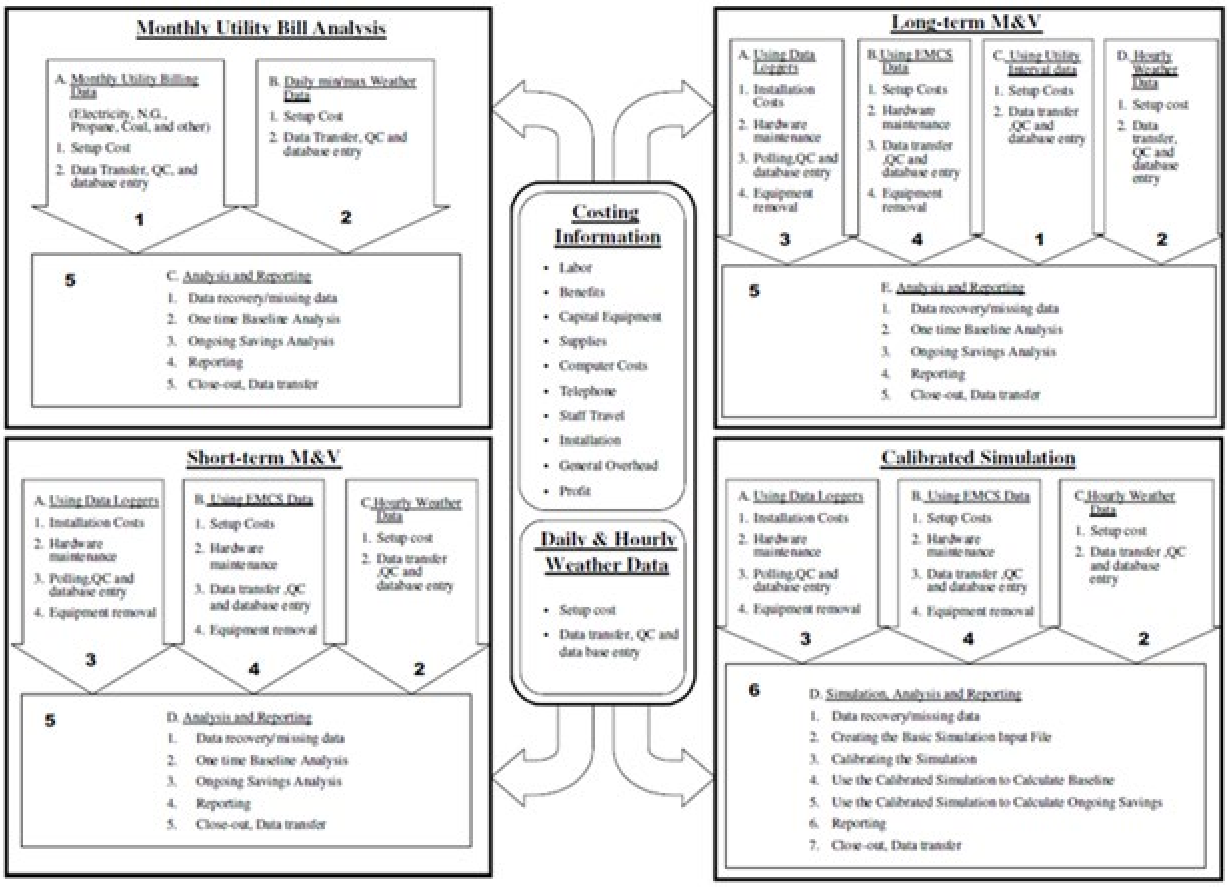


Figure B.1 U.S. Army Measurement and Verification (M&V) Costing Toolkit: Overview Diagram (Haberl et al. 2003).

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX C
ASHRAE RESEARCH PROJECT 1702

In 2016, ASHRAE Technical Committee 7.6 sponsored a research project, 1702-RP Case Studies to Test Performance Measurement Protocols, to assess the validity, reliability, and practicality of ASHRAE's Performance Measurement Protocols (PMP) for Commercial Buildings. The PMP defines a standardized method of measuring and analyzing building performance in six categories: energy, water, thermal comfort, indoor air quality, lighting, and acoustics.

The research was conducted by the University of Wyoming, working with Iowa Energy Center, and the University of Alabama. The objective of this study was to provide a basis for future updates to the 2010 ASHRAE PMP through case studies. Case studies were conducted for five buildings following the PMP. Based on experiences applying the protocol in this wide range of buildings, the researchers assessed the validity, reliability, and practicality of the PMP and provided comments and recommendations for future revisions, as reported in the final report (Wang et al. 2018) and the journal article published in ASHRAE's Science and Technology for the Built Environment (Wang et al. 2019).

The following are the principal findings of the study:

a. At the basic level, most of the performance measurement protocols are reliable, practical, and valid, even though some of the suggested metrics and benchmarking criteria may need clarifications and/or additional information.
b. At the intermediate level, the required measurement protocols are only somewhat reliable and some of them are impractical. The benchmarking criteria for some categories at this level are not clearly defined.
c. At the advanced level, most measurement protocols are complex and need to be performed by qualified or specially trained personnel, and thus should be used only in specialized applications and/or for selected building types. The benchmarking criteria are often missing for the required measurements. Because many of the measurement protocols at this level were based on ongoing research, some tools and software used were not widely available within, or fully supported by, the industry. These factors made protocols at this level very difficult to be implemented by industry practitioners in real buildings; thus, they should be used only in specialized applications.

The project determined that future work is needed to create an updated, more consistent version of the ASHRAE PMP; this work is addressed in this new Guideline 45. Many of the challenges in validity, reliability, and practicality should be addressed. More research on building performance evaluation should be conducted. Moreover, the focus of future work should shift from challenging intermediate- and advanced-level protocols to methods and resources that are more accessible and practical for typical building managers, energy auditors, and commissioning agents, and that are more widely accepted within industry. In addition to necessary clarifications in all PMP sections to ensure the ease of understanding for various procedures, the protocol should be accompanied with accessible and practical measurement methods. For example, efforts should be made so that both a facility manager for a single small building or a large campus or network of buildings, can understand and implement PMP measurement methods. Outdated resources and software should be replaced with newer, more user-friendly alternatives. For example, a new program for generating inverse models should be developed to replace the current IMT software.

In addition, research on alternative methods of measurements that are not mentioned in the current PMP should be explored. Many methods mentioned in the 2010 PMP were innovative but are now outdated or not widely used in industry. There are also additional widely accepted metrics for some of the categories that should be explored for possible inclusion in future editions of the PMP. There are also alternative methods for evaluating performance and acceptability of some acoustic parameters that should be further explored.

Table C.1 is representative of a Summary of Findings (Table 11, Wang et al. 2019). Of the six categories considered, only the energy category is illustrated as an example.

Table C.1 Summary of Findings for Energy Category (Table 11, Wang et al. 2019).

Evaluation Level	Key Issues	Recommendations	Assessment Score*
Basic			
Measurement Methods	No details given on how data should be collected.	Add more specific methods on how to collect data.	2
Metrics	Need a few classifications on maintenance log analyses, walk-through checklist, annual building energy use.		1
Performance Evaluation/Benchmarking	Does not cover some building types.	Update benchmarking tables.	2
Intermediate			
Measurement Methods	Conducting end-use analysis for facilities without submeters already installed is challenging.	Define meter calibration requirements. Move end-use analysis to advanced level if submeters are not available.	2
Metrics	Occupancy schedule needs to be assumed for OLF calculation. End-use analysis can be cost prohibitive.	Move end-use analysis to advanced level is submeters are not available.	2
Performance Evaluation/Benchmarking	The description of inverse model needs more detailed instructions for readers to understand and use the model. No benchmarking is provided for end-use analysis.	Move inverse model description from advanced to intermediate level. Providerecommendations on how to use the information in the end-use breakdown for energy efficiency.	3
Advanced			
Measurement Methods	Require modeling experts to perform the task.	Define meter calibration requirements.	3
Metrics	Whole-building calibrated simulation approach presents challenges.	Proved recommendations for the whole-building calibrated simulation approach.	3
Performance Evaluation/Benchmarking			1

*Assessment Scores defined:

1. The measurement does what it is intended to do at this level and was readily implemented.
2. The measurement does what it is intended to do at this level to a large extent and was nearly readily implemented.
3. The measurement needs some significant revision, but most of the issues can be addressed and clarified. The measurement can be implemented after the revision.
4. The measurement does not adequately indicate performance at this level, was difficult if not impossible to implement, and/or can be done but is of insignificant value.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX D
SENSOR QUALITY AND CALIBRATION

D1. Occupants

While occupancy and occupant behavior sensing are relatively new compared to IEQ and energy sensing/metering, key references on sensor selection and accuracy include:

a. Azimi and O'Brien (2022). This paper provides a comprehensive review of occupancy-sensing applications, occupancy sensor technologies, and sensor properties. It then provides a method to select the most appropriate sensor technologies, depending on the application(s). One of the key considerations of sensor technology selection is not only the accuracy, but false positives and false negatives. For some applications, false negatives could have safety implications (e.g., occupancy-triggered lighting), while false positives may have negative energy implications (e.g., over-ventilation for demand-controlled ventilation systems). There is also a distinction made between technologies that detect occupancy (as a binary) vs. estimation of number of occupants.
b. Chu et al. (2022). This paper presents and tests performance metrics for occupancy sensing. While the paper is aimed at residential buildings, it is generally applicable to commercial buildings as well. The authors found that the location of occupants, lighting, and doorway locations were most impactful on sensor performance.
c. Hobson et al. (2019). This paper used a case study to systematically evaluate occupancy sensing technologies and techniques against a ground truth (i.e., manual measurements by the researcher). They used the following proxies to estimate occupancy: Wi-Fi device count, lighting load, electrical load, and CO_2. They also used sensor fusion to combine pairs of these technologies. They concluded that the highest accuracy was obtained using Wi-Fi + lighting load, followed by just Wi-Fi, and then Wi-Fi + electrical load.
d. Chen et al. (2018). This paper, similar to Hobson et al. (2019), compares a wide variety occupancy sensing technologies and their fusion. It extends to other proxies for occupancy, such as temperature, relativity humidity, and lighting level. It provides key characteristics of cost, accuracy, and privacy of each configuration.
e. Wagner et al. (2018). This paper provides a comprehensive resource on occupant sensing technologies, with other related topics covered, such as sensor placement, validation, ethics, and survey methods.

D2. Energy Use

The measurement of whole-building performance of an existing building requires in-situ field measurements and testing of a whole-building and various equipment. Sensor selection depends on the quality (accuracy, precision, drift, rate of response, range, and output), quantity, installation restrictions, and method of measurement required, and the resources available to purchase and support the sensor. This appendix summarizes the techniques that described in ASHRAE Guideline 14-2023 (ASHRAE 2023), Appendix A – Physical Measurements, which are applicable for the measurement of energy and demand, including: run time; electric demand and energy use; temperature; liquid, air, and steam flow; thermal energy; psychometric properties (humidity); pressure; and outside weather conditions. Appendix A of Guideline 14-2023 is presented in three sections: A1-Introduction; A2-Metering Devices; and A3-Equipment Testing Standards. Appendix A contains seventeen tables that present information across a broad range of measurement:

a. Table A-1: Minimum Instrumentation Requirements

b. Table A-2: Typical (Electrical) Meter Capabilities by Type
c. Table A-3: Measurement Methods for Electrical use
d. Table A-4: Natural Gas Flowmeter Comparison
e. Table A-5: Measurement Methods for Natural Gas Use
f. Table A-6: Water Properties as a Function of Temperature
g. Table A-7: Measurement Methods for Btu Meters
h. Table A-8: Hot Water and Chilled Water Flowmeter Comparisons
i. Table A-9: Measurement Methods for Flow Meters
j. Table A-10: Measurement Methods for Liquid Flow for Nonthermal Applications
k. Table A-11: Measurement Methods for Temperature
l. Table A-12: Measurement Methods for Psychrometric Measurement
m. Table A-13: Measurement Methods for Airflow Measurements
n. Table A-14: Measurement Methods for Pressure Measurements
o. Table A-15: Measurement Methods for Run-time Measurements
p. Table A-16: Measurement Methods for Mechanical Ventilation
q. Table A-17: Measurement Methods for Additional Weather Data

A brief summary of these seventeen tables is provided below:

Table A-1 Minimum Instrumentation Requirements (I-P): This table contains minimum instrumentation requirements for 18 instruments, which include: range, accuracy, resolution and calibration interval. The 18 instruments include those for measurement of: rotation, temperature, electrical quantities, air pressure, air velocity, humidity, flow hood characteristics, hydronic pressure, hydronic differential pressure, data loggers (seven types: temperature, humidity, CO_2, CO, lighting, electrical, static pressure, and water pressure), and thermal (infrared) characteristics.

Table A-2 Typical (Electrical) Meter Capabilities by Type: This table provides information about electricity meters, including revenue grade meters, advanced energy meters and electrical submeters. For each type of meter the table lists: if the meter is considered "revenue accuracy", which refers to whether or not the meter is accurate enough for financial transactions; if the meter can conduct electricity energy use and electric demand measurements; if the meter can analyze electric power quality (i.e., power factor); if the meter has data logging capabilities; and how the data from the meter can be transferred to another device (i.e., data output and communication), for example, the type of data (pulse, or analog, communication (RS-232/485), fiber optic, wireless, modem, ethernet, etc.; the table indicates whether the meter had alarm and control capabilities; if it is programmable; if it has display capabilities; the electrical connection required (i.e., CTs, accuracy of the CTs, if a potential transformer is required); and finally, the table includes the meter cost.

Table A-3 Measurement Methods for Electrical use: This table describes seven characteristics of electrical measurement equipment, including: existing electrical energy use meters; existing electric demand meters; portable Watthour meters; ability of the meter to use infrared pulse technology; whether or not the meter requires Current Transformers (CTs); if the meter can be used for portable metering; and finally if the metering allows for pulse splitting (i.e., sharing an existing pulse). For each of the measurement devices the following is listed: accuracy; measurement procedures; and a place for comments about the particular meter.

Table A-4: Natural Gas Flowmeter Comparison: This table provides information about four different types of natural gas flow meters: diaphragm, rotary, turbine, thermal gas mass flow. For each meter type the maximum gas pressure (psig)a the maximum gas flow capacity (SCF/h); accuracy; and comments about the advantages and disadvantages is provided.

Table A-5: Measurement Methods for Natural Gas Use: This table contains information regarding the measurement of natural gas, including: existing natural gas meters; combustion efficiency meters; pulse initiators for natural gas meters; and run-time sensors for natural gas meters. For each measurement device the table describes the meter accuracy, the estimated time for the installation and maintenance; the procedure used for measurement and comments about the methods.

Table A-6: Water Properties as a Function of Temperature: This table shows water properties at varying temperatures, including: specific heat (Btu/lbm-F or kJ/kg-C), density (lbm/ft^3 or kg/m^3), conversion constant (Btu-min/gal-F-hr or kJ-min/C-hr).

Table A-7: Measurement Methods for Btu Meters: This table lists two measurement methods for Btu meters, including: electronic Btu meter and data loggers with real-time math. For each device the accuracy, information about installation and maintenance, measurement procedures and additional comments is provided.

Table A-8: Hot Water and Chilled Water Flowmeter Comparisons: This table contains a comparison of information regarding hot-water and chilled water flow meters, including the type of meter, configuration, accuracy, advantages and disadvantages. Types of meters include: turbine (full diameter and insertion type); full bore magnetic, single-point magnetic, vortex shedding and transit type ultrasonic meters.

Table A-9: Measurement Methods for Flow Meters: This table contains information about liquid flowmeters, including: ultrasonic; in-line or insertion; accumulating; and pulse flowmeters. For each meter type the accuracy, sensor installation and maintenance, and related comments are given.

Table A-10: Measurement Methods for Liquid Flow for Nonthermal Applications: This table compliments Table A-9 and includes information about three measurement types and nine different devices. For each measurement device the diameter of the device; range of flow rate; accuracy limits relative to the flowrate; and rangeability velocity is given. The measurement types include: displacement measurement methods (nutating disc, rotary piston), velocity measurement methods (multijet, single jet, turbine-vertical jet, turbine-inline) and electronic velocity measurements (fluidic-oscillator, ultrasonic, electromagnetic).

Table A-11: Measurement Methods for Temperature: Table A-11 provides information about measurement methods for temperature, including: four measurement devices (portable electronic thermometers, portable recording electronic thermometers, surface-mounted electronic temperature sensors, and electronic temperature sensor and a thermowell). For each measurement method the accuracy, sensor installation and maintenance, measurement procedure and related comment s are provided.

Table A-12: Methods for Psychrometric Measurement: Table A-12 provides information about the measurement of psychrometric properties, including: the measurement device (sling psychrometer, portable electronic RH meter, electronic RH sensor, and electronic dew-point sensor). For each measurement type the accuracy, sensor installation and maintenance, measurement procedure and related information is provided.

Table A-13: Measurement Methods for Airflow: Table A-13 provides information about methods for measuring air flow, including: flow hoods and pressurization and depressurization tests. For each measurement device the information is provided about the accuracy; sensor installation and maintenance; measurement procedures; and related comments.

Table A-14: Measurement Methods for Pressure: Table A-14 provides information about measurement methods for pressure measurement, including: pressure transmitters and pressure transducers. The information provided includes: the accuracy of the device; sensor installation and maintenance; measurement procedures; and related comments.

Table A-15: Measurement Methods for Run-time: Table A-15 provides information about one run-time measurement device (i.e., status sensor), including: accuracy; sensor installation and maintenance; and related comments.

Table A-16: Measurement Methods for Mechanical Ventilation: Table A-16 provides information about methods used to measure mechanical ventilation tracer gas, perfluorocarbon tracer tests (PFT), and blower doors. For each measurement method the accuracy; sensor installation and maintenance; measurement procedures; and related comments are provided.

T**able A-17: Measurement Methods for Additional Weather Data:** Table A-17 provides information about additional weather data measurements, which include pyrheliometer solar radiation (solar beam data); pyranometer solar radiation (global, horizontal solar radiation); and wind speed (recording anemometer, and meteorological grade recording anemometer). Items addressed include: accuracy; sensor installation and maintenance; measurement procedures; and related comments.

Guideline 14-2023 also contains:

a. **Appendix E – Retrofit Isolation Approach Techniques**, which includes guidance for in-situ measurement of pumps, blowers or fans, chillers, boilers, furnaces, interior lighting, and HVAC unitary equipment.
b. **Appendix F – Cost Estimation for Measurement and Verification**, which contains guidance on estimating the costs of monitoring and verification over the life of the retrofit and reference to the U.S. Army's M&V Costing Toolkit.
c. **Appendix H – Long-term Data Storage**, which provides advice on the long-term planning for archiving and storage of data over multiyear periods, including: long-term data storage medium, data collection methodology, data integrity, data recovery, and documentation of methods/equations used for the calculation of secondary variables.
d. **Appendix I – Informative References and Bibliography** contains references to the sources of information contained in the guideline, especially the test and measurement procedures of:
    1. American Gas Association (AGA)
    2. Air-Conditioning, Heating, and Refrigeration Institute (AHRI)
    3. American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE)
    4. American National Standards Institute (ANSI)
    5. American Refrigeration Institute (ARI)
    6. American Society of Mechanical Engineers (ASME)
    7. American Water Works Association (AWWA)
    8. International Performance Measurement and Verification Protocol (IPMVP)
    9. International Organization for Standardization (ISO)
    10. Institute of Electrical and Electronics Engineering (IEEE)
    11. National Centers for Environmental Information (NCEI)
    12. National Institute of Standards and Technology (NIST)
    13. National Oceanic and Atmospheric Administration (NOAA)

D3. Water Use

Water measurement uses instruments for various tasks to determine existing conditions or to determine water use. These measurements are used to diagnose water flow issues and to log water use to determine how to reduce it. Basic instruments include:

a. **Water Instrument Types**

1. **Totalizing Water Meters:** These are positive displacement meters that measure a fixed amount of water passing through the meter over time, where flow is not dependent on velocity, time or pressure. These are normally Nutating Disc, Oscillating Piston, or Oval Gear meters. These meters are best for recording total flow over time becaause zero flow or low flow does not affect the total reading. Totalizing water meters do not provide instantaneous flow values so they cannot measure peak and minimum flows .
2. **Instantaneous Water Meters:** These are flow meters that measure velocity of the water in the pipe where flow is dependent on velocity at a specific moment in time. For plumbing systems these are normally Multijet Flow Meters, Turbine Flow Meters, Electromagnetic Water Meters, or Ultrasonic Water Meters; for these meters accuracy is affected by zero or low flow. These meters record instantaneous flow and can be used to determine peak and minimum flow values at a point in time; they should not be used for totalizing flow over time for systems that have periods of zero or flow below the meter accuracy range.
3. **Water Temperature Thermometer:** These thermometers, sensors or meters are used to test and record water temperature for diagnostic and data logging purposes.
4. **Pressure Instrument or Gauge:** Pressure gauges or pressure instruments are used to test and record water pressure for diagnostic and data logging purposes. Gauge range should fit the application.
5. **TDS Meter:** TDS meters are used to test the total dissolved solids of the water and its electrical conductivity, which indicates water hardness. Hard water is usually defined as water that contains a high concentration of calcium and magnesium ions. However, hardness can also be caused by dissolved metals, such as aluminum, barium, strontium, iron, zinc, and manganese.
6. **PH Meter:** PH Meters measure the level of acidity of the water on a scale from 0 to 12 ph, where 0 is extremely acidic and 12 is very alkaline and 6 ph is considered neutral. The level of acidity determines the corrosiveness of the water.

b. **Water Instrument Specifications**

1. **Totalizing Water Meters:** These meters are available from 12 mm to 152 mm or (½” to 6”) and can read from 0.23 m^3/hr. to 136 m^3/hr. or (1 to 600 GPM). Meters are provided with odometer readouts that read from 0.1 m^3 to 99,999 m^3 or (.01 Gallons to 9,999,999 Gallons). Meters can be purchased with pulse heads that can feed into an Energy Management system or a SCADA system for monitoring. Required meter accuracy is ±1.5% or better.
2. **Instantaneous Water Meters:**
   i. Multijet meters for domestic water are available for 12 mm to 203 mm or (1/2” to 8”) and can read from 0.23 to 298 m^3/hr. or (1 to 1,320 GPM). Multijet Instantaneous water meters are available with odometer readouts that read from 0.1 m^3 to 99,999 m^3. or (.01 Gallons to 9,999,999 Gallons) with an accuracy of ±1.5%. They can be purchased with pulse heads that can feed into an Energy Management system or a SCADA system for monitoring.
   ii. Turbine meters for domestic water are available for 19 mm to 600 mm or (¾” to 24”) pipe size and can read from 1.13 m^3/hr. to 1,136 m^3/hr. or (5 GPM to 5,000 GPM) with an accuracy of ±2%. Turbine meters will not read accurately at zero flow or very low flows, so they should not be used for systems that have periods of zero flow or flow below the accuracy range of the meter. These meters are electronic sensors that need to be connected to a controller that has a local readout, or connected into an EMS or SCADA system for data collection.
   iii. Electromagnetic Water Meters for domestic water are available for 50 mm to 600 mm or (1.5” to 24”) and can read from 0.27 m^3/hr. to 1,136 m^3/hr. or (12 GPM to 5,000 GPM) with an accuracy of ±1%. Electromagnetic meters will not read accurately at zero flow or very low flows, so should not be used for systems that have periods at zero flow or flow below the accuracy range of the meter. These meters are electronic sensors that need to be

connected to a controller that has a local readout, or connected to an EMS or SCADA system for data collection.

iv. Ultrasonic Water Meters for domestic water are available for 12 mm to 1,800 mm or (0.5" to 24") and can read from 0.013 m^3/hr. to 6,020 m^3/hr. or (0.06 GPM to 26,500 GPM) with an accuracy of ±1%. Ultrasonic Meters will not read accurately at zero flow or very low flows, so should not be used for systems that have periods at zero flow or flow below the accuracy range of the meter. These meters are electronic sensors that need to be connected to a controller that has a local readout or connected to an EMS or SCADA system for data collection.

3. **Water Temperature Thermometer:** Sensor range for domestic water should be -20°C to 100°C or (0°F to 200°F), with an accuracy of ±0.5° of reading + 1°C or (±0.5° of reading + 2°F) and a resolution of 0.1°F.
4. **Pressure Instrument or gauge:** Gauge range should fit the application with an accuracy of +/–0.50% of span and a resolution of 5 kpa or (1 psi).
5. **TDS Meters:** TDS meters should have a measurement range of 0-9990 µs/cm or (0-9990 ppm) with a temperature range of 0.1°C to 50°C or (32°F to 122°F). Accuracy should be ±2% of full scale.
6. **PH Meter:** PH meters should have a range of 0.00 to 14.00 ph with an accuracy of 0.1 ph and a resolution of 0.01 ph. Meter should be capable of reading water in a temperature range of –5.0 to 60.0°C or (23.0 to 140.0°F).

c. Water Instrument Required Calibrations:

1. **Totalizing Water Meters:** These meters do not normally require calibration unless the meter is damaged or clogged with debris. To calibrate a positive displacement meter, flow volume is measured with a portable Ultrasonic meter and compared to the meter reading over time, or the volume of water can be captured and measured and compared to the meter reading over time.
2. **Instantaneous Water Meters**

i. Multijet meters do not normally require calibration unless the meter is damaged or clogged with debris. To calibrate a multijet meter, flow volume is measured with a factory calibrated portable Ultrasonic flow meter and compared to the meter reading. If the readings are off by more than the stated accuracy of the meter, clean and repair or replace the meter. The recommended calibration verification interval is every 5 years.

ii. Turbine meters are calibrated by measuring flow with a factory calibrated portable Ultrasonic Flow meter and comparing the instantaneous flow to the Turbine meter reading. If the readings are off by more than the meter accuracy, adjust the turbine meter output for correct calibration. The recommended calibration interval is every 5 years.

iii. Electromagnetic Water meters are calibrated by measuring flow with a factory calibrated portable Ultrasonic Flow meter, and comparing the instantaneous flow of the ultrasonic meter to the electromagnetic meter reading. If the readings are off by more than the stated meter accuracy, adjust the electromagnetic meter output for correct calibration. The recommended calibration interval is every 5 years.

iv. Ultrasonic Water Meters are calibrated by measuring flow with a factory calibrated portable Ultrasonic Flow meter and comparing the portable calibrated test instrument reading to the tested meter reading. If the readings are off by more than the stated meter accuracy adjust the tested ultrasonic meter output for correct calibration. The recommended calibration interval is every 5 years.

3. **Water Temperature Thermometers** do not require calibration but temperature instruments do. To calibrate a temperature instrument, the sensing element is immersed in a temperature probe salt bath that produces a calibrated temperature. If the meter reading varies from the calibrated bath by more than 15%, the instrument range the instrument must be repaired and recalibrated by a calibration center. If the variance is less, then the instrument reading can be

offset by the variance amount to produce calibrated readings. Recommended calibration verification is every 2 years.

4. **Pressure Instruments or Gauges** are calibrated by using a certified calibrated gauge or test stand to verify that the gauge or instrument reads the same as the calibrated gauge. If the gauge reading varies from the calibrated gauge by more than 15% of the gauge range, the gauge should be replaced or repaired. If the variance is less, the instrument reading can be offset by the variance amount to produce calibrated readings. Recommended calibration verification is every 2 years.
5. **TDS Meters** are calibrated using a calibration fluid that is laboratory created for a certain TDS level. The meter is tested to verify it is within the accuracy range of the calibration fluid. If it is off substantially the meter should be replaced or repaired, if the reading is off by less than 50 TDS use an offset on future readings to ensure proper readings. Recommended calibration verification is every 5 years.
6. **PH Meters** are calibrated using a calibration fluid that is laboratory created for a certain ph. The meter is tested to verify it is within the accuracy range of the calibration fluid. If it is off substantially the meter should be replaced or repaired, if the reading is off by less than 5 ph you can use an offset on future readings to ensure proper readings. Recommended calibration verification is every 5 years.

D4. Thermal Comfort

For accurate thermal comfort assessment in existing buildings, both occupant surveys and environmental measurements are essential. Section 4.5 provides sample survey questions for evaluating occupant thermal comfort, which can be administered via paper or online surveys. For environmental measurements, it is recommended to adhere to the specified measurement range and accuracy requirements outlined in ASHRAE Standard 55-2023 (ASHRAE 2023), particularly in Table 7-1, as shown in Table D.1 below. Additionally, ensure that air temperature sensors are properly shielded to prevent radiation exchange with surrounding surfaces.

Table D.1. ASHRAE Standard 55-2023, Table 7-1 Instrumentation Measurement Range and Accuracy.

Quantity	Measurement Range	Accuracy
Air temperature	10°C to 40°C (50°F to 104°F)	±0.2°C (0.4°F)
Mean radiant temperature	10°C to 40°C (50°F to 104°F)	±1°C (2°F)
Plane radiant temperature	0°C to 50°C (32°F to 122°F)	±0.5°C (1°F)
Surface temperature	0°C to 50°C (32°F to 122°F)	±1°C (2°F)
Humidity, relative	25% to 95% rh	±5% rh
Air speed	0.05 to 2 m/s (10 to 400 fpm)	±0.05 m/s (±10 fpm)
Directional radiation	-35 W/m^2 to +35 W/m^2 (-11 Btu/ h·ft^2 to +11 Btu/ h·ft^2)	±5 W/m^2 (±1.6 Btu/h·ft^2)

D5. Indoor Air Quality

The reliability and accuracy of sensors used for continuous and targeted monitoring may differ. It is often the case that a continuous monitoring sensor will prioritize spatial coverage, temporal variation and affordability over reliability and accuracy. This does not necessarily degrade the usefulness of continuous monitoring sensors, but it is important for an engineer or facility manager to set realistic expectations with users. A certain amount of downtime and data loss is to be expected with continuous monitoring sensors. This could be due to any of several factors – power loss, connection loss, signal issues, etc. Offline sensors/monitors used for targeted measurements can also fail to measure or store data; this is why for those instruments it is recommended to save data frequently.

Sensors should be factory calibrated. Additionally for CO_2 sensors: Certified by the manufacturer to require calibration not more frequently than once every 5 years. We recommend referring to ASHRAE Standard 62.1-2022 (ASHRAE 2022 addendum AB) that refers to Automatic Background Calibration (ABC) logic, which is commonly used with commercial CO_2 sensors to automatically maintain calibration. It uses 400 ppm as the ambient concentration targeted by the logic, so ambient concentration is effectively indicated as 400 ppm regardless of actual ambient concentration. Therefore, when CO_2 sensors with ABC logic are used, ambient concentration should always be assumed to be 400 ppm.

Additional sources of information can be found in the RESET Air Test Procedure for Accredited Monitors (2023) which specifies the test methodology and protocols for sensor evaluation via standardized test protocol. Table D.2 provides minimum recommended technical specifications of the air quality sensors.

Table D.2 Minimum Recommended Technical Specifications of the Air Quality Sensors. (Sources: ASHRAE 62.1-2022, ASHRAE 55-2023, RESET Air 2023).

Parameter	Range	Sensor type	Accuracy (±)	Resolution (±)
Carbon dioxide, CO_2	400-4000 ppm	Non-dispersive infrared	75 ppm at conc. of 600 and 1000 ppm	1 ppm
Air temperature	10-40°C [50-104°F]	Metal oxide semiconductor	0.2°C (0.4°F)	0.1°C
Relative humidity	10-85% (non-condensing)	Metal oxide semiconductor	5%	1%
Carbon monoxide, CO	0.1-25 ppm	Electrochemical, Non-dispersive infrared, photometry	Greater of 3 ppm or 20% of reading	1 ppm
Nitrogen dioxide, NO_2	1-200 ppb	Electrochemical, chemiluminescence	10 ppb below 100 ppb	1 ppb
Particulate matter, $PM_{2.5}$	1-500 µg/m^3	Photometer, optical particle counter	5 µg/m^3 at 5-100 µg/m^3 or 20% of reading	1 µg/m^3
Particulate matter, PM_{10}	1-1000 µg/m^3	Photometer, optical particle counter	10 µg/m^3 at 5-200 µg/m^3	1 µg/m^3
Total volatile organic compounds, TVOC	1-2500 µg/m^3	Photo-ionization detectors, electrochemical, metal oxide semiconductor	20 µg/m^3 +20%	10 µg/m^3
Ozone, O_3	5-500 ppb	Electrochemical	5 ppb	5 ppb

D6. Visual Environment

The following summarizes the lighting sensors and related devices that measure visual environment. Each sensor should be calibrated at the factory before deploying them at the site. This process ensures each unit meets specified accuracy and performance standards, guaranteeing reliable and consistent data.

a. Illuminance Meters

Illuminance meters are used to measure the total amount of light falling on a surface, in units of footcandles (fc) or lux (lx). These meters can be rack mountable, bench top, or portable with varying levels of precision and accuracy. Illuminance meters commonly used in field evaluations consist of a photodiode detector connected to an amplifier and display. Light reaching the meter detector is filtered to mimic the spectral sensitivity (V(λ)) of the human visual system.

ISO/CIE 19476, Characterization of the Performance of Illuminance Meters and Luminance Meters (ISO/CIE, 2014), summarizes typical errors for common commercially available illuminance meters. In particular, most illuminance meters should have some means of correcting measurements to a true cosine response; however, inaccuracies may result in measurements of light incoming at large angles from normal. Additionally, the meter detectors have varying spectral responsivity and it is important to select a meter with the best match to the human visual system (V(λ) function). The meter spectral responsivity may also influence measurements from LED or saturated light sources, which may have relatively narrow-wavelength bands.

When capturing field measurements using illuminance meters, it is recommended that the meter detector be level or parallel to the intended measurement plane – horizontal, vertical, or inclined. The meter detector should have a field of view free of any shadows or obstructions that are not typically in the scene (people or measurement equipment). Some meters may have communication ports for remote operation and measurement.

b. Luminance Meters

Luminance meters are used to measure the amount of light emitted from a source or reflected from a surface, falling within a known solid angle. Luminance is often used to describe perceived brightness and uses the units of candelas per square meter (cd/m^2). Luminance meters are essentially illuminance meters with the addition of suitable optics to image the target area onto the detector. Typically, the target and surrounding areas can be viewed through an eyepiece. Types of luminance meters include beam splitter spot meters, aperture mirror photometers, and digital luminance meters, which can produce luminance values for every pixel of the imaged scene.

Luminance meters are susceptible to the same errors as illuminance meters. Additionally, the optical elements are sensitive to dust and must be properly focused to produce accurate measurements. ISO/CIE 19476, Characterization of the Performance of Illuminance Meters and Luminance Meters (ISO/CIE, 2014), contains a summary of typical errors for luminance meters for the best commercially available meters. It is important to consider the dynamic range of the luminance meter, given that these meters may be used to measure scenes with instances of high brightness.

Luminance measurements used to understand occupant perceived brightness should be representative of actual working lighting conditions at realistic occupant locations and view directions within the space. Daylight should be included in measurements of daytime luminance, considering weather and time of day, and minimized for measurements of nighttime luminance. Task, general, and supplementary electric lighting should be in use.

c. Spectroradiometers

Spectroradiometers are used to measure the spectral (color) characteristics of light like relative spectral power distribution (SPD), spectral radiance and irradiance, spectral reflectance and transmittance, and spectral scattering. Within the meter, a dispersing element is used to separate the various wavelengths of incoming light before it reaches the detector. Unlike for an illuminance meter, incoming light is not filtered and the resulting radiometric measurements can be used to calculate illuminance or circadian lighting metrics, using the appropriate spectral weighting functions (typically, this illuminance calculation is done electronically as provided in the meter data). Additional metrics that can be calculated from spectroradiometer measurements include correlated color temperature (CCT), color rendering index (CRI), and chromaticity.

CIE 202, Spectral Responsivity Measurement of Detectors, Radiometers and Photometers (CIE, 2011), contains a summary of typical errors for spectrophotometers for the best commercially available meters.

When using spectroradiometers to measure illuminance, it is recommended that the meter detector be level to the intended measurement plane – horizontal, vertical, or inclined. This is particularly important for measurements for estimating circadian lighting metrics, which are meant to reflect the amount and spectrum of light reaching the eye of occupants. Spectroradiometers can also be used to estimate the relative SPD of luminaires by capturing a measurement with the meter relatively close to the emitting surface of the luminaire. Relative SPD measurements should be normalized to a peak power value of 100.

d. Flicker Meters

Handheld flicker meters vary in capabilities and level of accuracy. Generally, more advanced handheld meters are capable of measuring flicker at higher frequencies (3000 Hz or greater) and can characterize the time-based waveform of the light source, needed for calculating existing flicker metrics. Higher frequency measurements provide more confidence for detecting the phantom array effect. Note that there are no approved methods for calibrating handheld flicker meters.

e. High Dynamic Range Imaging

For the hardware, the following components are required:

1. a dSLR (Digital Single Lens Reflex) camera is recommended, either based on CCD or CMOS sensors. Measurements using lower-cost cameras, e.g., based on Raspberry Pi cameras (Kim et al., 2020) are possible, however require more involvement in the process.
2. A circular fisheye lens, essential to approximate the human visual field that extends to a span that conventional perspective lenses cannot accommodate. Fisheye lenses can be classified based on their visual span (typically measured in degrees) and their distortion type (equidistant vs equi-solidangle), with this information being necessary inputs in the glare evaluation algorithms.
3. A tripod that will ensure the images to be merged will be capturing the exact same frame, avoiding 'shaky' or blurred images.
4. A calibrated spot luminance meter and a gray target, which will be used to extract the calibration function for that particular setup. The gray target is preferred to demonstrate lambertian behavior to avoid specular reflections.
5. A calibrated illuminance meter that will be used to evaluate the accuracy of the method.
6. An optional neutral density (ND) filter that is necessary for instances of extreme luminances (e.g., the sun in the field of view). As the physical characteristics of fisheye lenses prevents traditional ND filters from being mounted on the lens, gelatine filters should be preferred and be mounted between the lens and the sensor.
7. For increased accuracy, additional components including a color checker chart, a sliding plate and panoramic rotation unit, and a stable bright light source are also required.

Once the calibration is completed, the given combination of camera and lens can be used for measurements without further repeated calibrations

The software to be used for the process ranges from open-source tools to costly dedicated commercial solutions. For the needs of this guideline we will discuss free-to-access tools that cover different steps of the procedure.

1. qDSLR dashboard, a freeware tool that allows the computer to operate the dSLR camera, automating multiple exposures shooting
2. Radiance (Ward, 2024), a command-line tool that can handle different steps including image manipulation
3. hdrgen (Ward, 1998), a command-line tool that can generate HDR images from single exposures
4. Evalglare (Wienold, 2006), a command-line that is included in the Radiance suite that can calculate glare metrics and other luminance statistics over the HDR images.

The complete process workflow is discussed by Pierson et al. (2021), which is to-date the most comprehensive guide available.

The pipeline begins by capturing low dynamic range, single-exposure photos and merging them into HDR. The latter are then manipulated through Radiance towards resizing and cropping to appropriate dimensions. After that, corrections are implemented to account for the distortion of the circular fisheye lens, as well as the vignetting effect (gradual decrease of resulting luminance at increasing distances from the center of the lens). Then, the response function of the combination of camera and lens is applied on the image, effectively producing a luminance map that can be an input to Evalglare. The latter can perform a series of calculations on the HDR images, including vertical illuminance, average luminance, and all major glare metrics. Inanici and Galvin's (2004) report measured average error rates under a variety of light sources, including daylight under different sky conditions. These error rates ranged from 2.6% (a dark room under high-pressure sodium lights) to 11.1% (a dark room under T-5 fluorescent lights) with a correlation factor (R^2) of 98.8%.

D7. Acoustical Quality

(To be completed)

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX E
EXAMPLE OCCUPANT SURVEY

This appendix presents an example survey (E1) and report (E2) from the CBE Occupant Satisfaction Survey. It presents both the types of questions that are asked in a generic survey, as well as shows how the survey results may be analyzed and presented.

E1. Occupant Survey: Office Example Questions

Table of Contents

Personal Workspace Location

On which floor number is your workspace located?

____

In which area of the building is your workspace located?

- North
- East
- South
- West
- No windows
- I don't know

In which direction do the windows closest to your workspace face?

- North
- East
- South
- West
- No windows
- I don't know

Are you near (within about 15 feet/5 meters)...

	Yes	No
An exterior wall	◯	◯
A window	◯	◯

Which of the following best describes your personal workspace?

◯ Enclosed office, private

◯ Enclosed office, shared with other people

◯ Cubicle with high partitions

◯ Cubicle with low partitions

◯ Workspace in open office with no partitions (just desks)

◯ Flexible or hot desking

◯ Other ____

Thermal Comfort

How satisfied are you with the temperature in your workspace?

	Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied
	◯	◯	◯	◯	◯	◯	◯

Display This Question:

If How satisfied are you with the temperature in your workspace? = Very dissatisfied

Or How satisfied are you with the temperature in your workspace? = Dissatisfied

Or How satisfied are you with the temperature in your workspace? = Somewhat dissatisfied

You have expressed dissatisfaction with the thermal environment in your workspace. How would you best describe the source of this discomfort? (Check all that apply)

▢ Humidity too high (damp)

▢ Humidity too low (dry)

▢ Air movement too high

▢ Air movement too low

▢ Incoming sun

☐ Drafts from windows or vents

☐ My area is hotter than other areas

☐ My area is cooler than other areas

☐ Thermostat is inaccessible/controlled by others

☐ Heating/cooling system doesn't respond quickly enough

☐ Clothing policy is not flexible

☐ I can't open or close the windows

☐ Other ____

Please describe any other aspects related to the thermal environment of your workspace that are important to you.

____

Air Quality

How satisfied are you with the air quality (i.e., stuffy/ stale air, cleanliness, odors) in your workspace?

	Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied
	○	○	○	○	○	○	○

Display This Question:

If How satisfied are you with the air quality (i.e., stuffy/ stale air, cleanliness, odors) in your... = Very dissatisfied
Or How satisfied are you with the air quality (i.e., stuffy/ stale air, cleanliness, odors) in your... = Dissatisfied
Or How satisfied are you with the air quality (i.e., stuffy/ stale air, cleanliness, odors) in your... = Somewhat dissatisfied

You have expressed dissatisfaction with the air quality in your workspace. Which of the following contribute to your dissatisfaction? (Check all that apply)

- ☐ Food smells
- ☐ Odors from carpet or furniture
- ☐ Odors of other people
- ☐ Perfume smells
- ☐ Cleaning products
- ☐ Outside scents (car exhaust, smog)
- ☐ The space smells musty/stale
- ☐ The air does not feel clean
- ☐ There is not enough air movement in the space
- ☐ There is no ability to let in outdoor air
- ☐ Other ______________________________

Please describe any other aspects related to the air quality of your workspace that are important to you.

____

Lighting and Views

How satisfied are you with...

	Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied
The amount of electric light in your workspace	○	○	○	○	○	○	○
The amount of daylight in your workspace	○	○	○	○	○	○	○
Glare and reflections on screens and surfaces	○	○	○	○	○	○	○
The window view from your workspace	○	○	○	○	○	○	○

Display This Question If

If How satisfied are you with... = The amount of electric light in your workspace [Very dissatisfied]
Or How satisfied are you with... = The amount of electric light in your workspace [Dissatisfied]
Or How satisfied are you with... = The amount of electric light in your workspace [Somewhat dissatisfied]
Or How satisfied are you with... = The amount of daylight in your workspace [Very dissatisfied]
Or How satisfied are you with... = The amount of daylight in your workspace [Dissatisfied]
Or How satisfied are you with... = The amount of daylight in your workspace [Somewhat dissatisfied]

You have expressed dissatisfaction with the lighting in your workspace. Which of the following contribute to your dissatisfaction? (Check all that apply)

☐ I don't have enough control over the lighting

☐ Not enough daylight

☐ Too much daylight

☐ Not enough electric lighting

☐ Too much electric lighting

☐ Electric lighting flickers

☐ Electric lighting is an undesirable color

☐ No task lighting

☐ Reflections on the computer screen

☐ Shadows on the workspace

☐ Too much glare within the space

☐ Other ____

Display This Question:
If How satisfied are you with... = Glare and reflections on screens and surfaces [Very dissatisfied]
Or How satisfied are you with... = Glare and reflections on screens and surfaces [Dissatisfied]
Or How satisfied are you with... = Glare and reflections on screens and surfaces [Somewhat dissatisfied]

You have expressed dissatisfaction with glare in your workspace. Which of the following contribute to your dissatisfaction? (Check all that apply)

☐ My screens

☐ The space overall

☐ When looking at others

☐ Desk surfaces

☐ Building surfaces (e.g., walls, floors, ceilings)

☐ Other ____

Display This Question:
If How satisfied are you with... = The window view from your workspace [Somewhat dissatisfied]
Or How satisfied are you with... = The window view from your workspace [Dissatisfied]
Or How satisfied are you with... = The window view from your workspace [Very dissatisfied]

You have expressed dissatisfaction with the window(s) view in your workspace. Which of the following contribute to your dissatisfaction? (Check all that apply)

- My workspace is not near a window
- The view from my window is unappealing
- The view from my window is distracting
- I have no way of controlling the light/sun coming in from the windows
- There are no blinds/shading on the windows
- The view from my window is frequently blocked by blinds/shading
- I cannot open or close the windows
- Other ____

Please describe any other aspects related to the lighting within and views from your workspace that are important to you.

____

Acoustic Quality

How satisfied are you with the...

	Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied
Noise level in your workspace	○	○	○	○	○	○	○
Ability to communicate without your neighbors overhearing and vice versa	○	○	○	○	○	○	○

Display This Question:

If How satisfied are you with the... = Noise level in your workspace [Very dissatisfied]
Or How satisfied are you with the... = Noise level in your workspace [Dissatisfied]
Or How satisfied are you with the... = Noise level in your workspace [Somewhat dissatisfied]
Or How satisfied are you with the... = Ability to communicate without your neighbors overhearing and vice versa [Very dissatisfied]
Or How satisfied are you with the... = Ability to communicate without your neighbors overhearing and vice versa [Dissatisfied]
Or How satisfied are you with the... = Ability to communicate without your neighbors overhearing and vice versa [Somewhat dissatisfied]

You have said you are dissatisfied with the acoustics in your workspace. Which of the following contributes to this problem? (Check all that apply)

- ☐ People talking on the phone or video call
- ☐ People talking in neighboring areas
- ☐ People overhearing my private conversations
- ☐ Electronic alerts (texts, emails, etc.)
- ☐ Office equipment noise
- ☐ Telephones ringing
- ☐ Mechanical (heating, cooling and ventilation system) noise
- ☐ Outdoor noise
- ☐ Other ____

Please describe any other aspects of the acoustics in your workspace that are important to you.

____

General Comments

Please briefly describe the ways in which your workspace influences your ability to complete your job?

____

How do you feel about your ability to control your workspace...

	Very dissatisfied	Dissatisfied	Somewhat dissatisfied	Neither satisfied nor dissatisfied	Somewhat satisfied	Satisfied	Very satisfied
Furnishings	○	○	○	○	○	○	○
Layout	○	○	○	○	○	○	○
Temperature	○	○	○	○	○	○	○
Air quality	○	○	○	○	○	○	○
Lighting	○	○	○	○	○	○	○
Views	○	○	○	○	○	○	○
Acoustics	○	○	○	○	○	○	○
Cleanliness	○	○	○	○	○	○	○
Maintenance	○	○	○	○	○	○	○
Aesthetics/overall look and feel	○	○	○	○	○	○	○

What do you like about your personal workspace?

____

What do you dislike about your personal workspace?

____

Any additional comments or recommendations about your personal workspace or building overall?

____

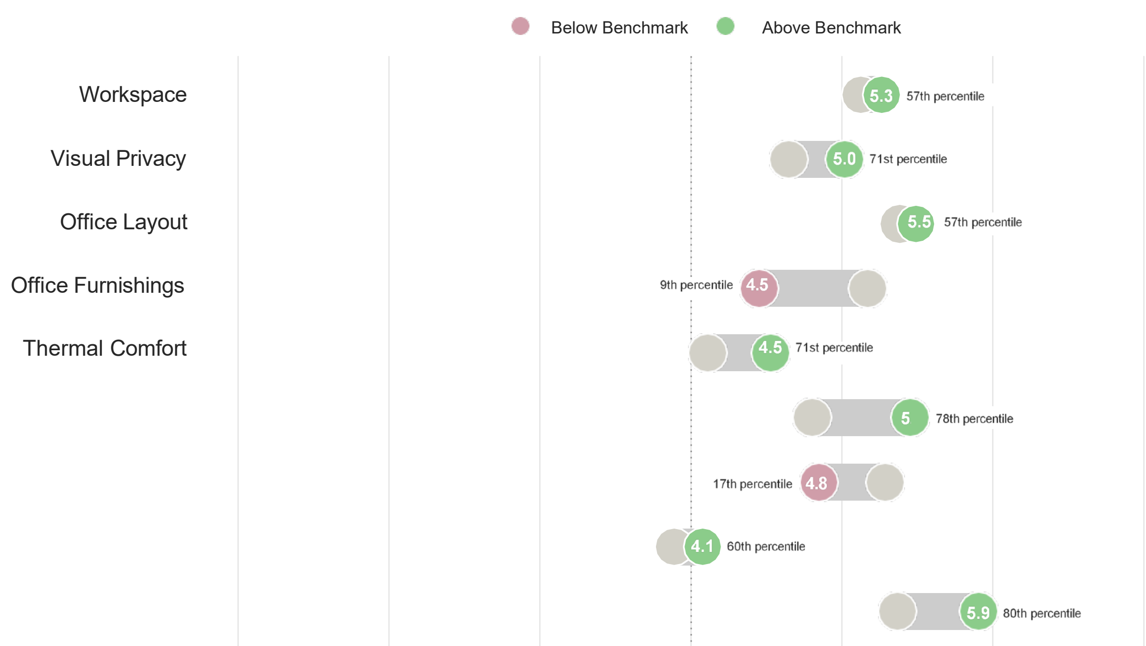
E2. Example Occupant Survey Report: CBE Occupant Survey

Benchmarking Your Building

Our research shows that spaces typically struggle with acoustical satisfaction. However, if you do not understand to what degree the average building struggles, you cannot know how large of an issue it is in your particular space.

Below you will see a comparison of your building to the broader CBE database. By comparing to our database, you can anchor your result to get a clearer picture of how well your building is actually preforming.

Use this information to pinpoint the strengths and weaknesses of the space, and make more informed decisions on where to invest to improve or maintain the quality of your environment.

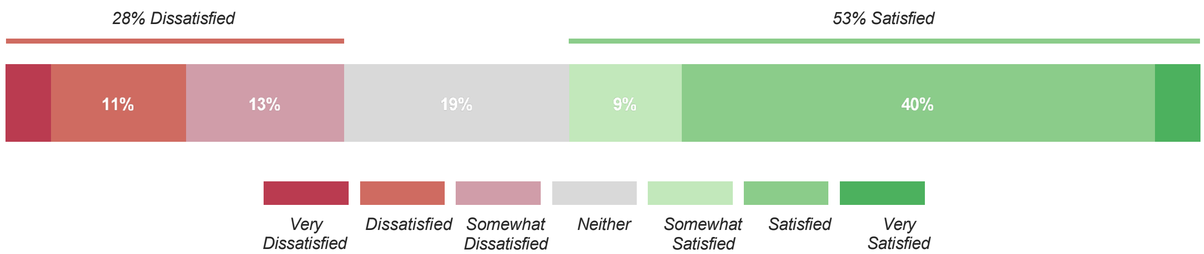


Thermal Comfort

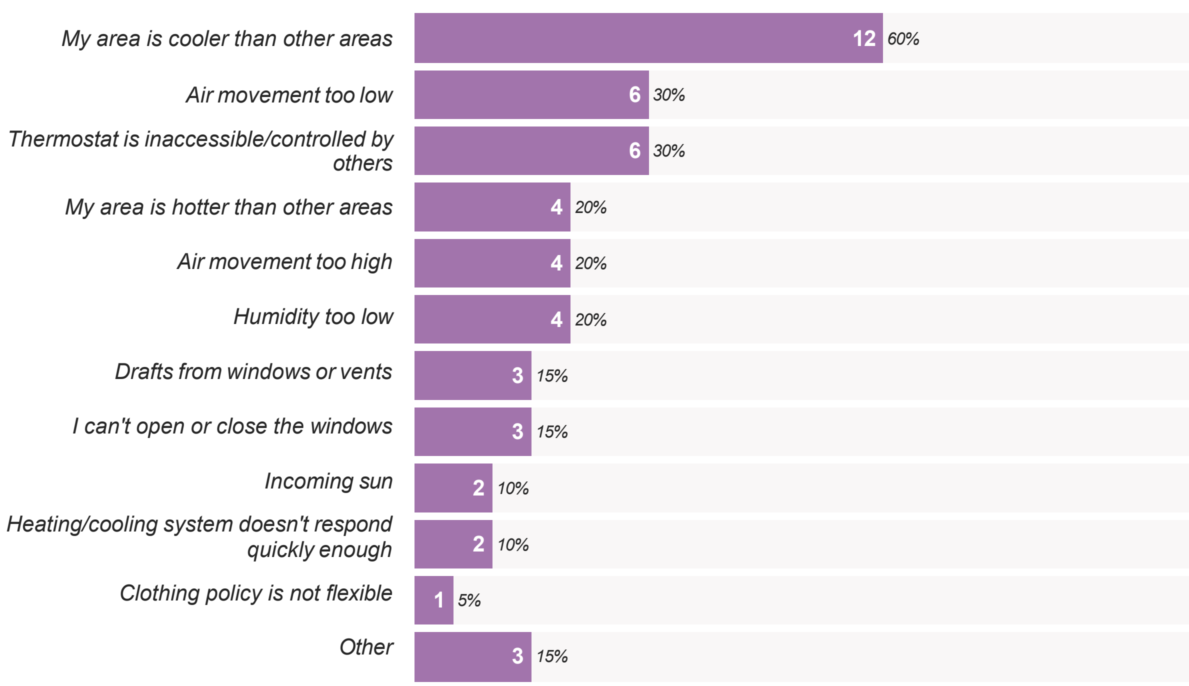
Next, this report highlights occupants' thermal experiences within the space. First, examine how satisfied the occupants are with their thermal comfort. Next, see which aspects of the environment that can influence thermal comfort are those occupants feel they have control over.

Whenever an occupant indicates dissatisfaction, they were prompted to identify why they are dissatisfied with the thermal environment. This question examines exactly which building features influence this thermal discomfort.

How satisfied are you with the temperature of your space?



*There were **20 participants** who indicated that they have some level of dissatisfaction with the temperature of the space. Below you will see the reasons for their dissatisfaction.*

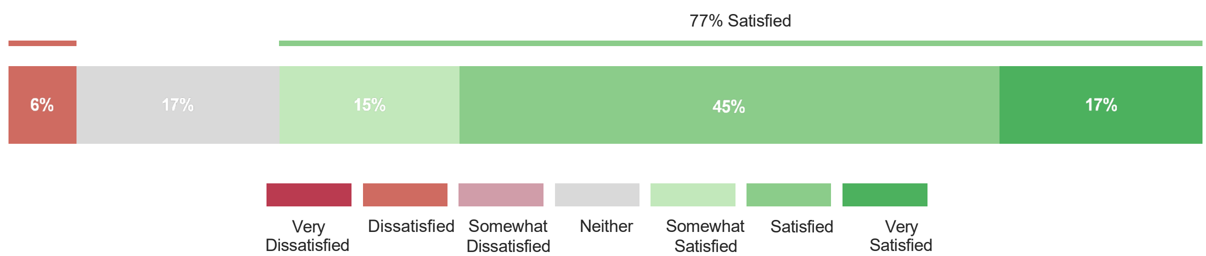


Participants were also asked to describe any specific issues related to thermal comfort that they feel are important to them. Please look to the raw data for these detailed text responses.

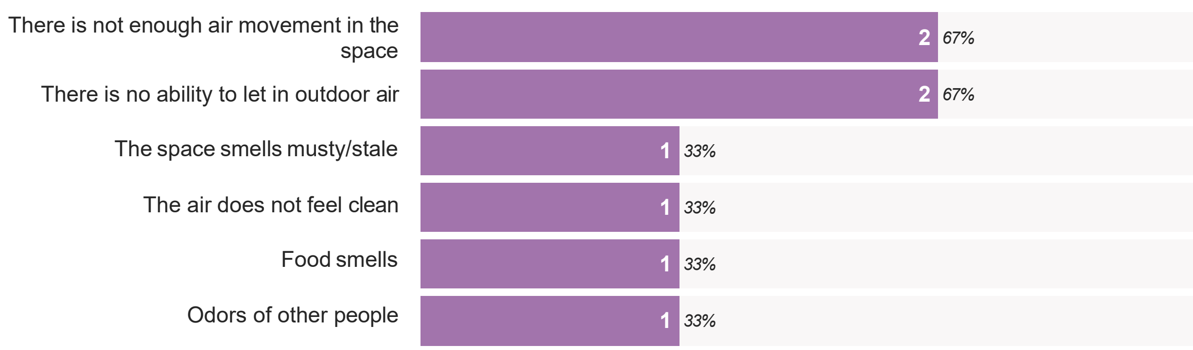
Air Quality

This section explores the ways in which occupants perceive the air quality of the space. Dissatisfied occupants are asked to identify the source of the issue within the space. These drill down questions will help you identify sources of dissatisfaction that you may be able to address.

How satisfied are you with the air quality in your space?



There were **3 participants** who indicated that they experience some level of dissatisfaction with the air quality of the space. The following are sources that contribute to issues within this space.



Participants were also asked to describe any specific issues related to air quality that they feel are important to them. Please look to the raw data for these detailed text responses.

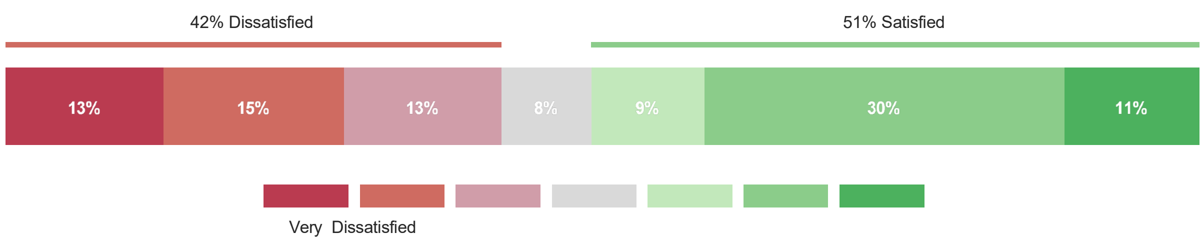
Lighting and Views

The next section examines the ways in which occupants perceive the lighting within and views from the space. Here you can see occupants' perceptions of the amount of light available to them, and their satisfaction with their own visual comfort and window(s) view.

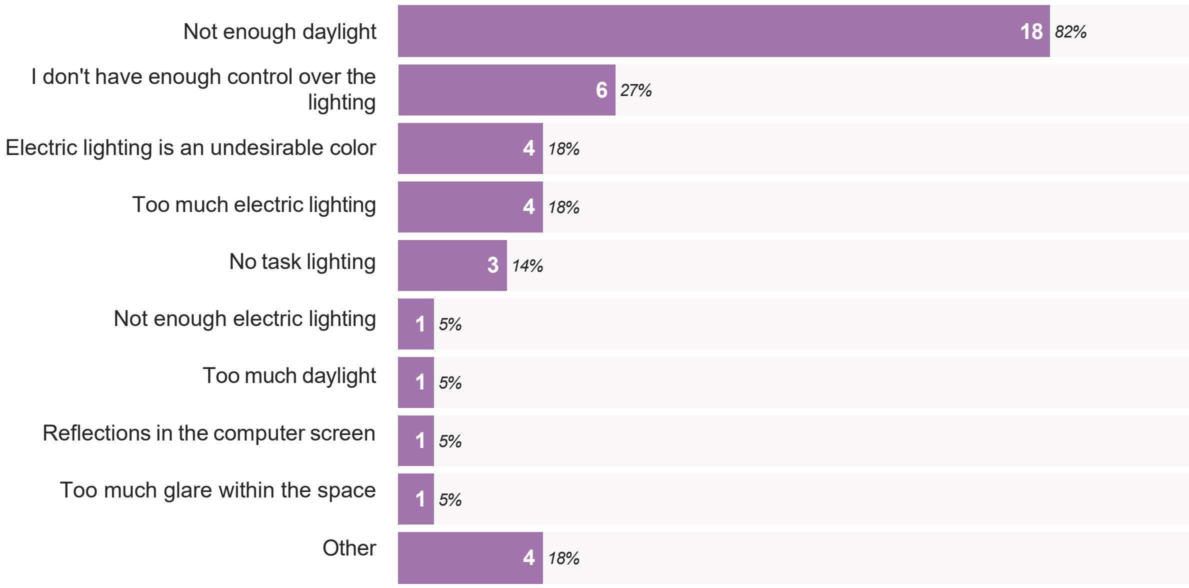
Again, whenever an occupant is dissatisfied they were asked to identify why they are dissatisfied with the lighting and/or views. These drill down questions will help you identify sources of dissatisfaction you may be able to address in the future to improve visual comfort and reduce environmental challenges like glare.

How satisfied are you with the amount of electric light in your space?

How satisfied are you with the amount of daylight in your space?



There were **22 participants** who indicated that they experience some level of dissatisfaction with the lighting in the space. The following contribute to lighting issues.



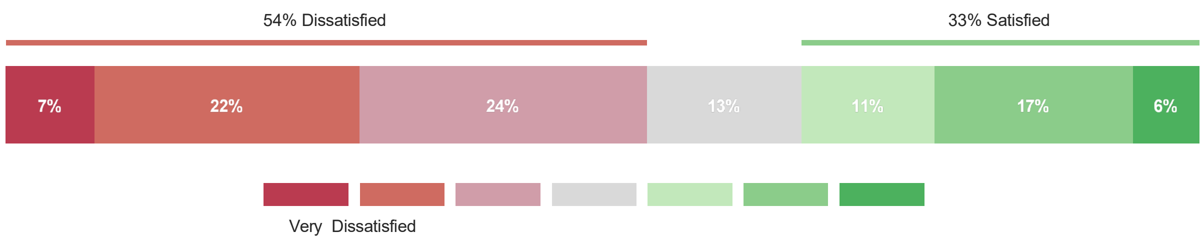
Participants were also asked to describe any specific issues related to lighting that they feel are important to them. Please look to the raw data for these detailed text responses.

Acoustic Quality

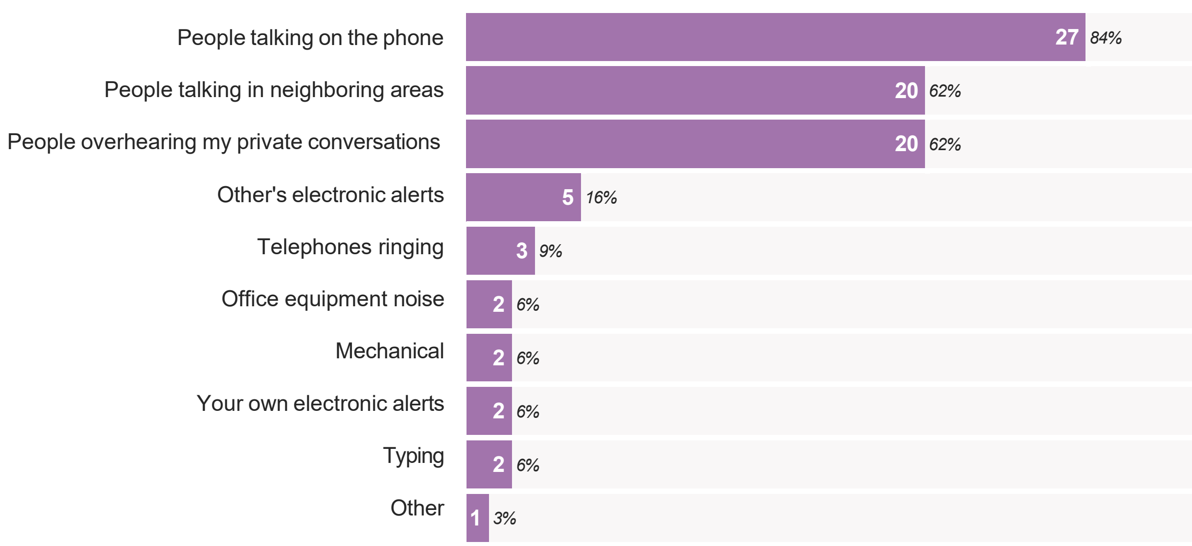
This section explores the ways in which occupants experience acoustics in the space. Specifically, occupants report their satisfaction with overall noise level and sound privacy. Further, whenever an occupant is dissatisfied they were asked to identify the sources of sound disturbances in the space. These drill down questions will help you identify sources of dissatisfaction you may be able to address in the future either with design or policy intervention.

How satisfied are you with the noise level of your space?

How satisfied are you with your ability to communication without your neighbor overhearing and vice versa



There were **32 participants** who indicated that they experience some level of dissatisfaction with the acoustics in the space. The following contribute to those acoustic issues.



Participants were also asked to describe any specific issues related to acoustics that they feel are important to them. Please look to the raw data for these detailed text responses.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX F
ENERGY USE APPLICATIONS

F1. Example of a Monthly Electricity Use Analysis

In this appendix, the whole-building inverse model is demonstrated with measured daily-average data, plotted for each month, from the former ASHRAE HQ building in Atlanta, Georgia (shown in Figure F.1 in its pre-renovation state, when the data here were applicable). Figure F.2 shows the monthly daily-average electricity use and monthly daily-average outdoor dry-bulb temperature for Atlanta for the period of September 2006 through August 2007 (NOAA 2008), together with the four-parameter (4-P) model result. The lines through the data points show the "model" of the two parts of the 4-P curve. Modeling tools such as the ASHRAE Inverse Modeling Toolkit (IMT) (Kissock et al. 2004) or other data analysis tools can be used to develop such modeling results. ASHRAE IMT is a toolkit developed in support of ASHRAE Guideline 14 for calculating linear, change-point linear, and multiple-linear inverse building energy models. The resulting IMT can be used as part of a procedure to measure and compare a building' weather-normalized energy performance.

Figure F.3 shows the linear and change-point linear models included in the IMT toolkit, which include: (a) mean, or one-parameter model; (b) two-parameter model; (c) three-parameter heating model (similar to a variable-base degree-day [VBDD] model for heating); (d) three-parameter cooling model (similar to a VBDD for cooling); (e) four-parameter heating model; (f) four-parameter cooling model; and (g) five-parameter model. The table below the model images describes and provides formulas for these models, along with examples of where to use the models. These models include: constant models, day-adjusted models, two-parameter models, three-parameter models, four-parameter models, five-parameter models, and multivariate models.

For the example in Figure F.2, the IMT was used, and whole-building electricity use model results show a "base" non-heating, non-cooling value of 1,590 kWh/day (lowest point of the model lines). The model outdoor temperature "change-point," is where the left-hand heating energy part of the curve stops and the right- hand cooling part begins, is 9.4°C (48.9°F). Cooling energy use is modeled as the slope of the right-hand part of the curve, at 41.9 kWh/day/Δ°C (23.3 kWh/day/Δ°F), where Δ°C (Δ°F) is the difference between the average daily outdoor temperature and the change-point, 9.4°C (48.9°F). If Δ°C (Δ°F) is negative, then cooling energy is zero. Heating energy is modeled as the left-hand part of the curve, at 144.5 kWh/day/ Δ°C (80.3 kWh/day/Δ°F), where Δ°C (Δ°F) is the difference between the average daily outdoor temperature and 9.4°C (48.9°F). If Δ°C (Δ°F) is negative, then heating energy is zero.

Data analysis tools also report "goodness-of-results" factors on modeling results, which are often important in aiding understanding of modeling results. One example model "goodness" factor is the linear regression least-squares R-square factor, which for this example building is 0.842 (a value of 1.00 means a perfect fit, and values above 0.80 are very good).

This type of analysis can be very important for a single-energy-source (all-electric) building like this example. The model serves as a self-reference whole-building energy use benchmark to compare against a later model of the same energy after any efficiency improvements are made. A subsequent model can show the efficiency improvements relative to the initial benchmark and can be used to calculate energy savings. Depending on the energy end uses involved, the efficiency improvement may show up as a lowering of the curve and/or reductions in slope of one or more parts of the curve. Similar to the whole-building energy use benchmark model presented in Figure F.2, and depending on the data available, similar model benchmarks might also be established for occupied and unoccupied periods, weekday and weekend energy, or possibly a major end use like heating energy. If data are available more often than monthly, model benchmarks can be more robust. However, for Figure F.2, only monthly data were available, and only for whole-building energy. An example that provides more extensive results for weekday and weekend daily energy use is shown in Appendix F2.

Figure F.1 The ASHRAE Headquarters Building (Photograph Courtesy of ASHRAE).

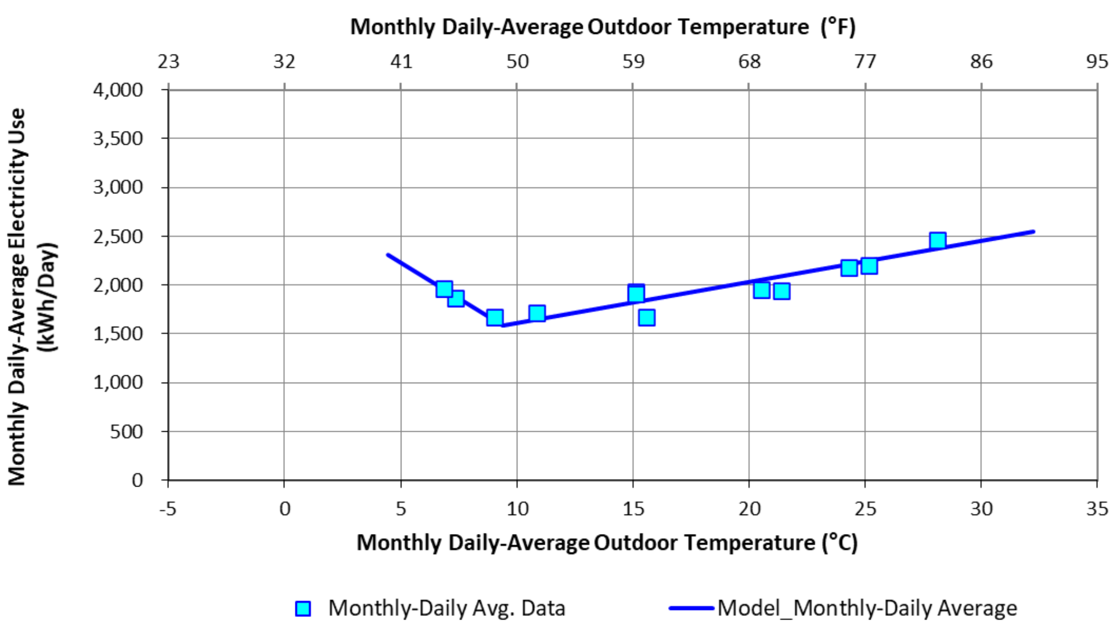
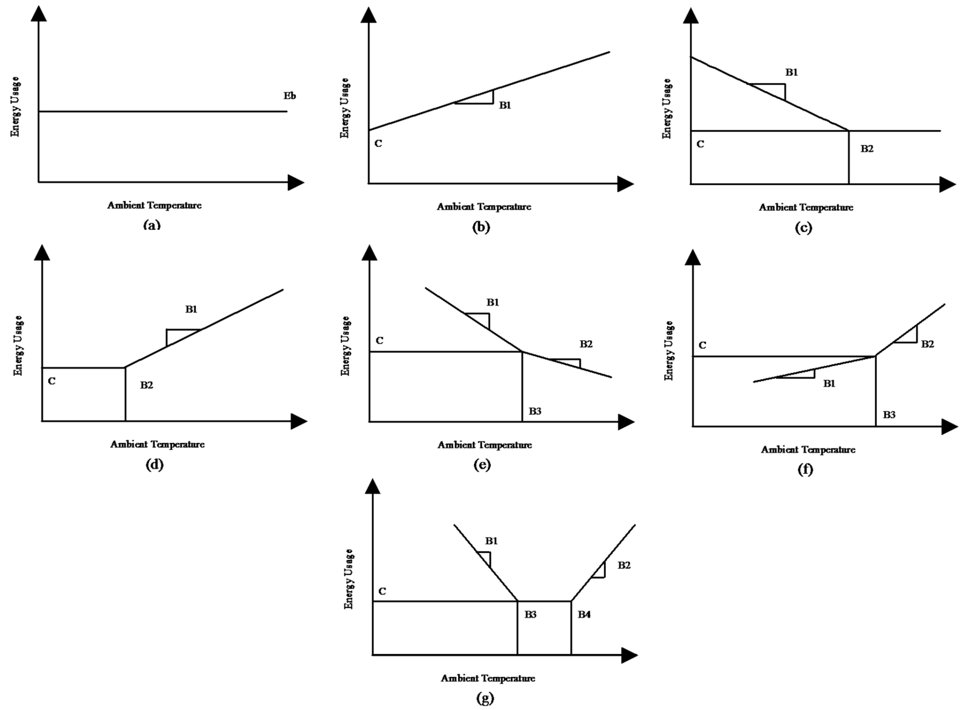


Figure F.2 Former ASHRAE HQ Building Whole-Building Electricity Use (Monthly) Versus Monthly Average Outdoor Dry-Bulb Temperature, Including the Inverse Model Toolkit 4-P Model.



Name	Independent Variables	Form	Examples
No adjustment/ constant model	None	$E = E_b$	Weather independent use
Day-adjusted model	None	$E = E_b \times day_b / day_c$	Weather independent use
Two-parameter model	Temperature	$E = C + B_1(T)$	Weather independent use
Three-parameter model	Temperature	$E = C + B_1(B_2 - T)^+$ $E = C + B_1(T - B_2)^+$	Weather dependent use (fuel or electric in winter, electricity in summer for cooling)
Three-parameter model	Degree-days	$E = C + B_1(\mathrm{DD}_{BT})$	Degree-days calculation to balance-point temperature
Four-parameter model	Temperature	$E = C + B_1(B_3 - T)^+ - B_2(T - B_3)^+$ $E = C - B_1(B_3 - T)^+ + B_2(T - B_3)^+$	Weather dependent use change-point model (fuel or electricity in winter, electricity in summer for cooling)
Five-parameter model	Temperature	$E = C + B_1(B_3 - T)^+ + B_2(T - B_4)^+$	Weather dependent use, heating and cooling supplied by same meter
Five-parameter model	Degree-days	$E = C + B_1(\mathrm{DD}_{TH}) + B_2(\mathrm{DD}_{TC})$	Weather dependent use, degree-days calculated to balance-point temperature, heating and cooling supplied by same meter.
Multivariate model	Degree-days, temperature, other independent variables	General form: $E = C_0 - C_1X_1 + C_2X_2 + \ldots C_nX_n$	Weather dependent use and other non-temperature-based variables (i.e. occupancy, production, etc.) Linear model shown

Figure F.3 Sample Models for the Whole-Building Approach: (a) Mean, or One-Parameter Model; (b) Two-Parameter Model; (c) Three-Parameter Heating Model (Similar to a Variable-Base Degree-Day [VBDD] Model for Heating); (d) Three-Parameter Cooling Model (Similar to a VBDD for Cooling); (e) Four-Parameter Heating Model; (f) Four-Parameter Cooling Model; and (g) Five-Parameter Model.

F2. Example of a Daily Electricity Use Analysis

In this appendix, the use of the ASHRAE IMT (Kissock et al. 2004) is demonstrated with measured daily whole-building electricity use data from the former ASHRAE HQ building in Atlanta. Figure F.4 shows the daily electricity use and daily-average outdoor dry-bulb temperature for Atlanta for the period

September 2006 through August 2007 (NOAA 2008). Both variables show the diurnal variation. While electricity use follows the outdoor temperature variation, the effect is damped, showing the thermal capacity of the building. Figure F.5 is a scatter plot of the daily electricity use versus average daily temperature, which includes separations for weekdays, Saturdays, Sundays, and holidays. Figure F.6 is a scatter plot of the daily electricity use, which includes separations for weekdays and weekends, and shows the 4-P model superimposed on the data. This establishes the baseline model against which future performance is to be compared.

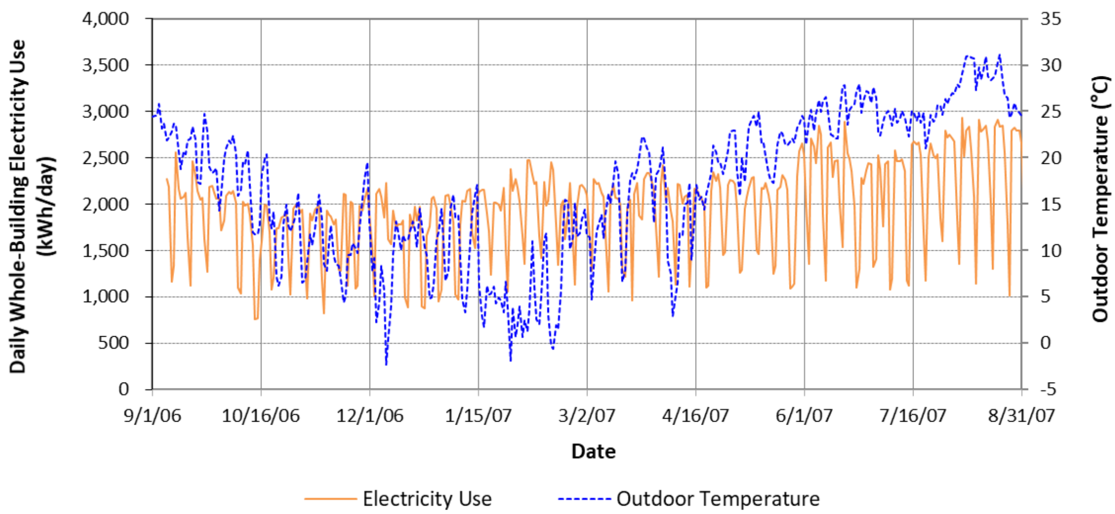


Figure F.4 Time Series Plots of the Former ASHRAE HQ Building Whole-Building Electricity Use (Daily) and Outdoor Dry-Bulb Temperature (Daily Hourly-Average, Atlanta, Georgia).

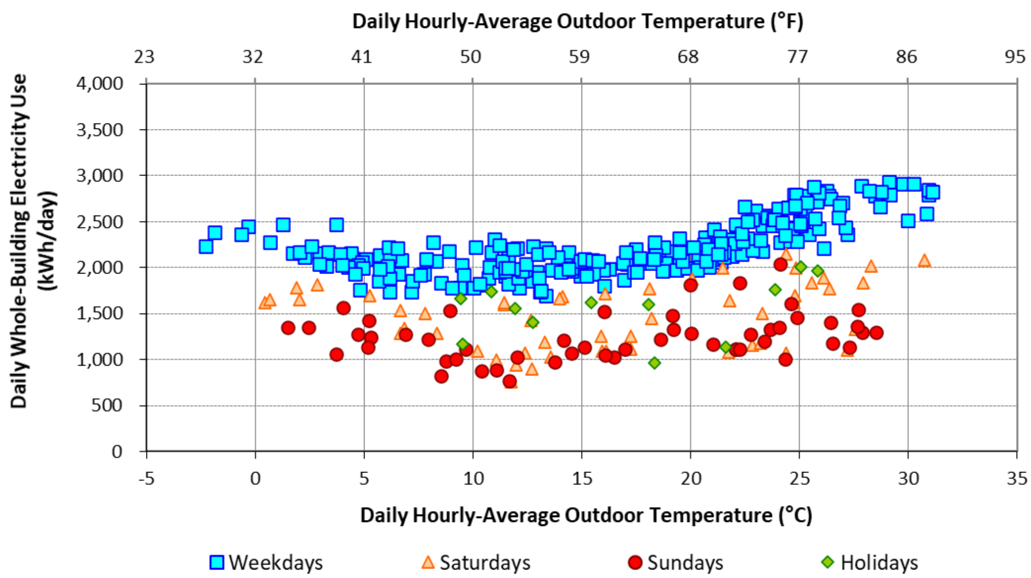


Figure F.5 Former ASHRAE HQ Building Whole-Building Electricity Use (Daily) for Weekdays, Saturdays, Sundays, and Holidays versus Daily Average Outdoor Dry-Bulb Temperature.

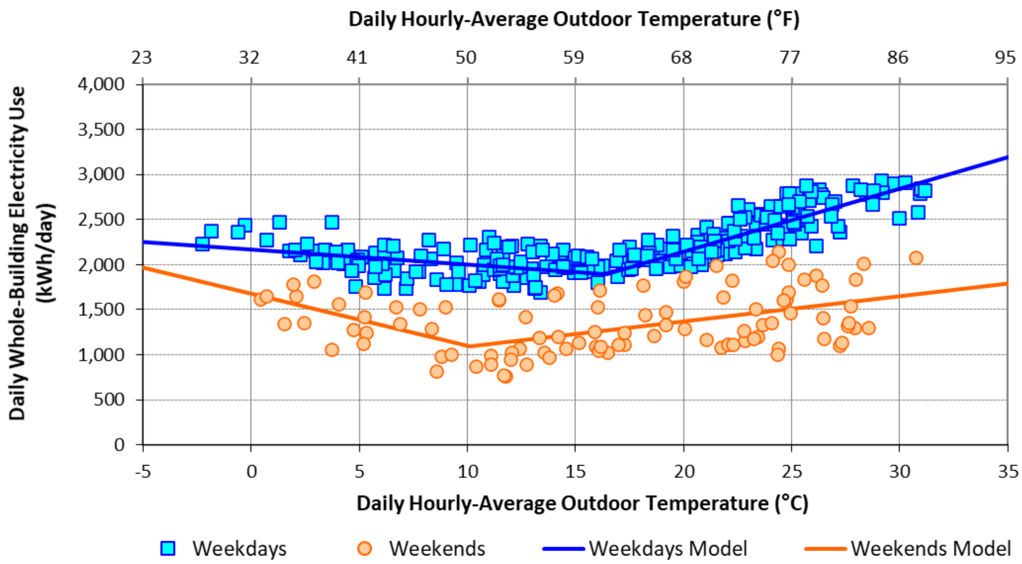


Figure F.6 Former ASHRAE HQ Building Whole-Building Electricity Use (Daily) for Weekdays and Weekends versus Daily Average Outdoor Dry-Bulb Temperature, Including the Inverse Model Toolkit 4-P Model.

F3. Example of a Demand Analysis with Hourly Load Profiles (Diversity Factors)

In this appendix, the ASHRAE Diversity Factors Toolkit (Abushakra et al. 2001) is demonstrated with measured hourly data from the former ASHRAE HQ building in Atlanta. Figure F.7 shows the hourly electric energy use for the building from September 2006 through August 2007. In this example, hourly load shapes, or diversity factors, are derived from the hourly data using percentiles, where the 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles are developed for each hour of the day-by-day type (i.e., weekday, weekend). The 50^{th} percentile values are recommended for use in modeling the hourly data and the 90^{th} percentile values are recommended for determining peak cooling load calculations.

To develop the diversity factors for the HQ building, six months of data were used from the Spring (March to May) and Fall (September to November) to represent those periods when the building was experiencing mild weather conditions to produce weather-independent diversity factor and load shapes. Figures F.8 and F.9 show the weekday and the weekend profiles, respectively, which include 10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles as well as minimum and maximum values.

These diversity factors are used to "capture" the actual light and receptacle loads so they can be entered into the calibrated simulation. The calibrated simulation is then used for the self-reference benchmark of the building that existed before the retrofit. In addition, the 90^{th} percentile of the diversity factor for a given month can be used to represent the monthly demand of the facility. The use of diversity factors is discussed in Abushakra et al. (2004) and Claridge et al. (2003).

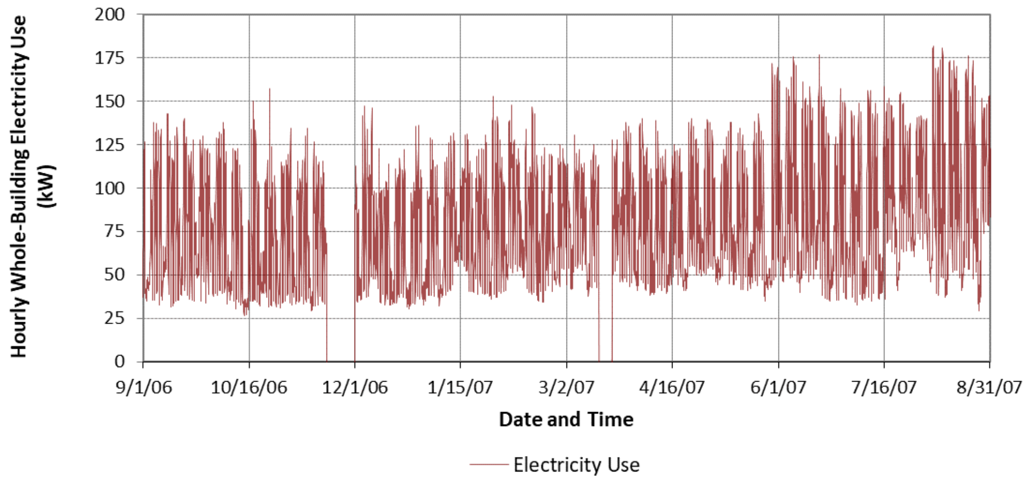


Figure F.7 Former ASHRAE HQ Building Hourly Whole-Building Electricity Use (September 2006 to August 2007).

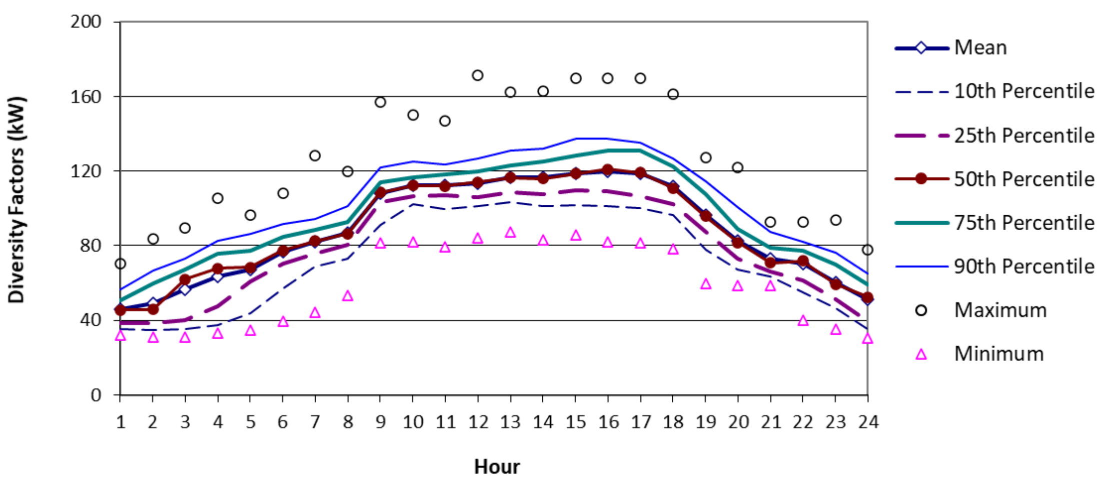


Figure F.8 Former ASHRAE HQ Building Weekdays Profile.

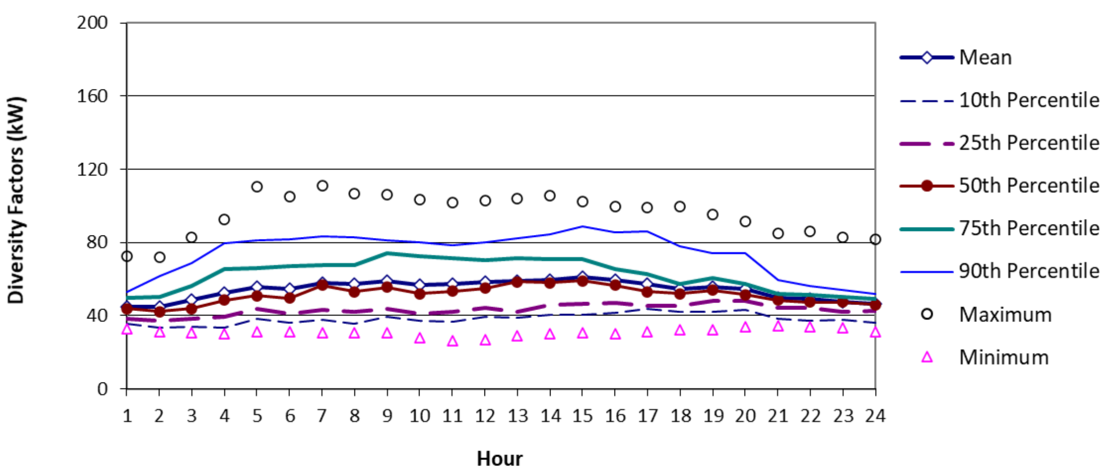


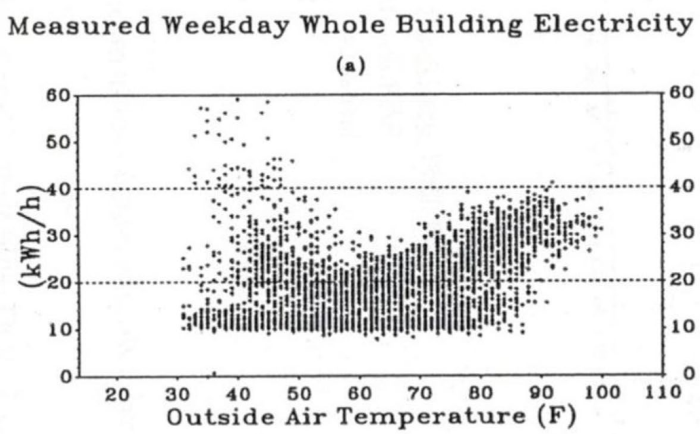
Figure F.9 Former ASHRAE HQ Building Weekends Profile.

F4. Example of an Hourly Electricity Use Analysis

In addition to the linear and change-point linear models included in the RP-1050 toolkit, other models have been developed for analyzing interval data (i.e., 15-minute or hourly data), including binned, pre-post retrofit models and weather-daytype models.

Figure F.10 shows an example of hourly whole-building electricity use for weekdays, binned into 5.6°C (10°F) bins. Figure F.10 (a) displays the hourly whole-building electricity use in the form of an x-y scatterplot versus the coincident hourly ambient temperature. Figure F.10 (b) presents the results of the 5.6°C (10°F) binned analysis for the same data. In this graph, box-whisker-mean symbols are used to represent the statistical properties of the data in each bin (i.e., max, 90th percentile, 75th percentile, 50th percentile, mean, 25th percentile, 10th percentile, and minimum values). Additionally, the mean from each bin can be connected with a line, which can be superimposed on other graphs to facilitate bin-by-bin data analysis.

In Figure F.11, the binning concept is applied to hourly whole-building electricity use data from the U.S. Department of Energy (USDOE) daycare center at the Forrestal building using three weather-daytypes (i.e., (a) less than 7°C (45°F), (b) 7°C (45°F) to 24°C (75°F), and (c) greater than 24°C (75°F)) only for weekdays as an example. Box-whisker-mean symbols are used for each hour of the day to display the statistical properties of the data in each bin.



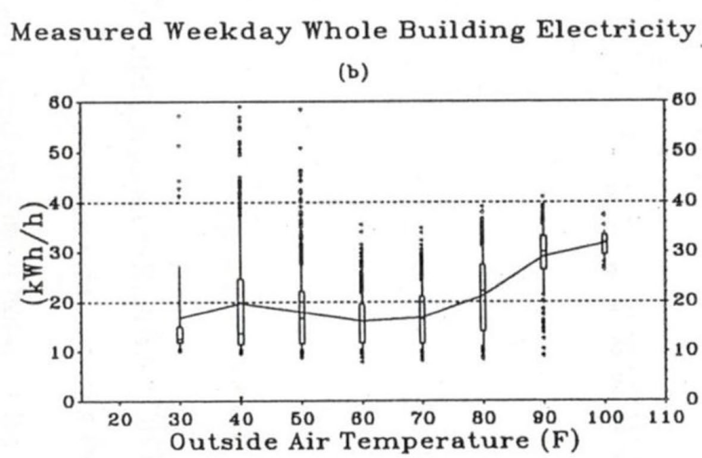


Figure F.10 Example of Binned, Hourly Weekday Whole-Building Electricity Use (Adopted from ASHRAE 2023).

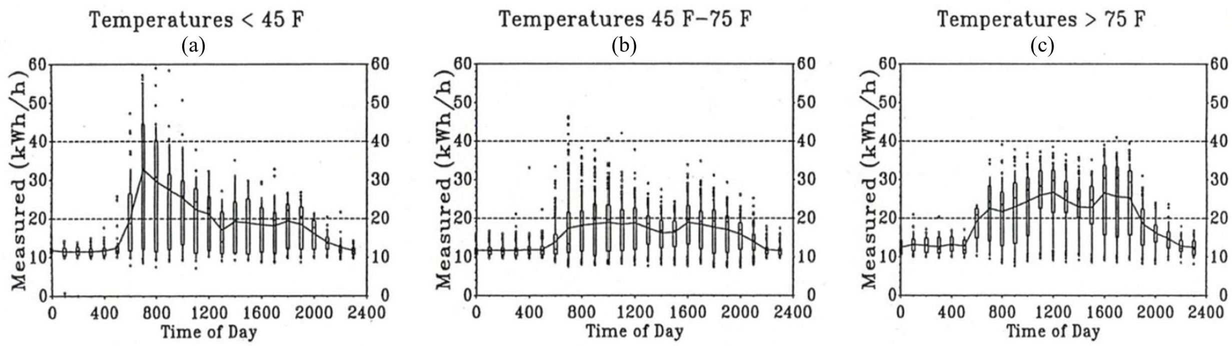


Figure F.11 Example of Weather-Daytype Plots for Hourly Weekday Whole-Building Electricity Use (Adopted from ASHRAE 2023).

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX G
WATER USE DESIGN GUIDES, BENCHMARKS, AND CALCULATIONS

G1. Water Design Guides

a. BSR/ASHRAE/USGBC/ASPE/AWWA/IAPMO Standard 191P Standard for the Efficient Use of Water in Building, Site, and Mechanical Systems
b. https://www.wbdg.org/design-disciplines/plumbing-engineering, Whole Building Design Guide, National Institute of Building Sciences
c. https://www.wbdg.org/FFC/VA/VADEMAN/dmPlbg.pdf, Department of Veterans Affairs, Design Manuals (PG-18-10)
d. Plumbing Engineering Design Handbook Vol 1 2021 https://www.aspe.org/product/plumbing-engineer-design-handbook-vol-1-2021 Fundamentals of Plumbing Engineering, American Society of Plumbing Engineers
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l. Hunter LEED Design Guide https://www.hunterindustries.com/sites/default/files/Hunter_LEED_Guide.pdf

G2. Water Use Benchmarks

Tables G.1 to G.6 present typical water use quantities by building type and fixture type.

Table G.1 Water Use Indices (DOE-FEMP 1996)[a].

Type of Building / Occupation	Gallons	Per Unit	Liters	Per Unit
Airports	3	Passenger	12	Passenger
Apartment Houses	100	Person/Day	379	Person/Day
Resort Apartment	60	Person/Day	228	Person/Day
Boarding Houses	40	Person/Day	152	Person/Day
Hotel	50	Guest/Day	190	Guest/Day
Lodging House	40	Guest/Day	152	Guest/Day
Motel	35	Guest/Day	133	Guest/Day

Motel with Kitchen	40	Guest/Day	152	Guest/Day
Laundry	550	Machine/Day	2082	Machine/Day
Office	15	Employee/Day	57	Employee/Day
Court Building	15	Employee/Day	57	Employee/Day
Data Centers	8	Ft^2/Day	2.74	m^2/Day
Public Lavatory	5	User/Day	19	User/Day
Restaurant-Conventional	9	Customer/Day	35	Customer/Day
Restaurant-Short Order	8	Customer/Day	31	Customer/Day
Shopping Center	8 - 13	Parking Space/Day	30 - 49	Parking Space/Day
Bowling Alley	200	Alley/Day	758	Alley/Day
Country Club	100	Member/Day	379	Member/Day
Camp Ground	30	Person/Day	114	Person/Day
Swimming Pool & Beach	10	Customer/Day	38	Customer/Day
Assembly Hall	3	Seat/Day	12	Seat/Day
Dormitory	35	Person/Day	133	Person/Day
Police Stations	42	Ft^2/Day	1712	m^2/Day
Prison	120	Inmate/Day	455	Inmate/Day
Medical Hospital	120	Bed/Day	455	Bed/Day
School	10	Student/Day	38	Student/Day
School with Cafeteria	15	Student/Day	57	Student/Day
School Cafeteria & Gym	25	Student/Day	95	Student/Day
University Buildings	15	Student/Day	57	Student/Day
Landscape non turf	785	Acre/Day	318	Hectare/Day
Landscape turf	1571	Acre/Day	636	Hectare/Day

a. Information taken from U.S. Department of Energy Federal Energy Management Program, Federal Water Use Indices which is based on American Water Works Association table 1996.
b. Information taken from Verein Deutscher Ingenieure VDI 3807 Blatt 3 (Association of German Engineers VDI 3807 Part 3).
c. Variances between data bases are due to major differences in the small sample of facilities used for the studies.

Table G.2 Water Use Indices (DOE-FEMP 2005, Association of German Engineers 2015)[a].

Annual Report to Congress on Federal Government Energy Management and Conservation Programs, Fiscal Year 2005			
Agency	**Annual Consumption (Million Gallons)**	**Gross Square Feet (Thou.)**	**Gallons per Gross (Square Foot)**
DOD	116,752.00	1,952,056.20	59.8
VA	9,337.30	144,836.10	64.5
Justice	8,731.00	72,917.60	119.7
DOE	6,455.20	111,942.50	57.7
USPS	5,455.90	312,962.70	17.4
Interior	3,624.30	61,724.90	58.7
GSA	2,651.20	176,414.50	15
USDA	2,150.90	57,480.90	37.4
NASA	2,036.50	38,896.20	52.4
HHS	1,799.70	31,338.40	57.4
DHS	1,522.80	45,556.70	33.4
Labor	1,029.00	20,335.80	50.6
TVA	733	27,969.80	26.2
DOT	464.1	25,722.10	18
Treasury	431.1	12,049.60	35.8
Commerce	352.1	13,627.90	25.8
State	169	4,476.70	37.8
EPA	168.1	3,723.30	45.2
SSA	125	9,262.00	13.5
Archives	107.9	4,062.00	26.6

HUD	21.8	1,432.00	15.2
RRB	5.5	346.9	15.9
Total Gov't	**164,123.60**	**3,129,134.90**	**52.5**

a. Information taken from Preliminary U.S. Department of Energy, Federal Energy Management Program Federal Water Use Indices for 2005.

Table G.3 Minimum Consumption for Total Water Usage (CIBSE 2014).

Type of building/occupation	Minimum Consumption[c]		
	Liters	Gallons	Per Unit
Hostel	90	23.78	Bed Space
Hotel[a.]	135	35.67	Bed Space
Office premises:[b.]			
— with canteen facilities	45	11.89	Employee
— without canteen facilities	40	10.57	Employee
Restaurant	7	1.85	Meal
Day school:			
— nursery	15	3.96	Pupil
— primary	15	3.96	Pupil
— secondary	20	5.28	Pupil
— technical	20	5.28	Pupil
Boarding school	90	23.78	Pupil
Children's home or residential nursery	135	35.67	Bed Space
Nurse's home	120	31.7	Bed Space
Nursing or convalescent home	135	35.67	Bed Space

a. There will be significantly greater demand in a luxury hotel than in a budget hotel.
b. Table lists recommended minimum consumption levels of cold water, for domestic applications, for hot and cold outlets. Note that if conservation measures are taken (e.g., installation of low-flow WCs), then the recommended consumption for offices of 40 liters per employee can be reduced.
c. The proportion of domestic consumption, other than dwelling accommodation, can be allocated as 67% cold and 33% hot.

Table G.4 Water Consumption Rates by Fixture (CIBSE 2014).[a,b]

Fixtures	Consumption			
	Liters/24 Hrs		Gallons/24 Hrs	
	Min	Max	Min	Max
Shower	140	230	36.99	60.77
Bath		900		237.78
WC		180		47.56
Basin		90		23.78
Sink	90	180	23.78	47.56
Urinal		110		29.06

a. Rates are for total water used for both hot and cold water.
b. Data taken from CIBSE Guide G Water Benchmarks.

Table G.5 Measured Daily Hot Water Consumption (CIBSE 2014).

Building Type		Total		Service		Catering	
		Liters / Person	Gallons / Person	Liters / Person	Gallons / Person	Liters / Meal	Gallons / Meal
Schools and	Max	13	3.43	7	1.85	18	4.76
Colleges	Avg	6	1.59	3	0.79	6	1.59
Hotels and	Max	464	122.59	303	80.05	62	16.38
Hostels	Avg	137	36.2	80	21.14	14	3.7
Restaurants	Max	17	4.49	10	2.64	73	19.29

Restaurants	Avg	7	1.85	3	0.79	8	2.11
Offices	Max	26	6.87	10	2.64	33	8.72
Offices	Avg	8	2.11	3	0.79	10	2.64
Large shops	Max	25	6.61	6	1.59	45	11.89
Large shops	Avg	10	2.64	4	1.06	8	2.11

Table G.6 Daily Hot Water Demands (CIBSE 2014)[b.].

Type of Building	Daily Demand		Storage per 24-h[a.]		Recovery
	Liter/Person	Gallon/Person	Demand/Liters	Demand/Gallons	Period/Hours
Colleges and schools:					
— boarding	115	30.38	23	6.08	2
— day	15	3.96	4.5	1.19	2
Dwelling houses:					
— economic, local authority	115	30.38	115	30.38	4
— medium, privately owned	115	30.38	45	11.89	2
— luxury, privately owned	136	35.93	45	11.89	2
Flats:					
— economic, local authority	68	17.97	23	6.08	4
— medium, privately owned	115	30.38	32	8.45	2
— luxury, privately owned	136	35.93	32	8.45	2
Factories	15	3.96	4.5	1.19	2
Hospitals†:					
— general	136	35.93	27	7.13	1
— infectious	225	59.45	45	11.89	1
— infirmaries	68	17.97	23	6.08	1.5
— infirmaries with laundry	90	23.78	27	7.13	1
— maternity	225	59.45	32	8.45	2
— mental	90	23.78	23	6.08	2
— nursing staff	136	35.93	45	11.89	2
Accommodation					
Hostels	115	30.38	32	8.45	2
Hotels:					
— 5 star rating	136	35.93	45	11.89	1
— 2 star rating	114	30.12	36	9.51	1.5
Offices	14	3.7	4.5	1.19	2
Sports pavilions	40	10.57	40	10.57	1
Restaurants (per meal) —	6	1.59	2	0.53	

a. The storage capacity can be reduced by using semi-instantaneous and instantaneous hot water boilers and generators.
b. Data taken from CIBSE Guide G Water Benchmarks.

G3. Water Use Calculations

The water calculations in Section 7.2 are used to determine water use for equipment or systems in isolation, whereas Section 7.3 is used for whole-building water use modeling. The sections below illustrate how these calculations are applied.

G3.1 Water Leaks

Water leak flow rates can be estimated by using Figure 7.2 Water losses due to leaks in fixtures or pipes, or Table 7.4, Water losses at 5 Bar pressure due to pipe leaks.

To find the leak rate of a dripping fixture, count the number of drops over a 10 second time period and use the Figure 7.2 to find the estimated flow rate.

SI Units
Example: A lavatory fixture is leaking 12 drops over a 10 second period. Table 7.4 indicates 12 drops equals 0.9 liters / Hour. Since the leak will flow 24 hours per day the total flow will be: 0.9 x 24 x 365 = **7,884 Liters Annually.**

(IP Units)
Example: A lavatory fixture is leaking 12 drops over a 10 second period. Table 7.4 indicates 12 drops equals 0.2 GPM / Hour. Since the leak will flow 24 hours per day the total flow will be: 0.2 x 24 x 365 = **1,752 Gallons Annually.**

To find the leak rate of a pipe under pressure, use Table 7.5. Measure or estimate the size of the hole in the pipe and measure the pipe pressure. Using the table find the leak rate for the hole size. Use the correction factors to find the flow at the measured pressure, if different than 5 bar.

SI Units
Example: A 25.4 mm diameter pipe is found to have a 6.5 mm hole with the pipe pressure at 3 Bar. Table indicates a 6.25 mm hole at 5 Bar = 2,041 liters/hr or 48.99 m^3/day. The table says to use a 0.77 multiplier to get to 3 bar. 48.99 x .77 = 37.72 m^3/day at 3 bar, so 37.72 x 365 = **13,768 m^3/year.**

(IP Units)
Example: A 1” diameter pipe is found to have a ¼” (6.5 mm) hole with the pipe pressure at 43.5 PSI or 3 Bar. Table indicates a 0.25” hole at 5 Bar = 8.987 GPM or 12,941 Gallons / Day. The table says to use a 0.77 multiplier to get to 3 bar. 12,941 x .77 = 9,964 gallons/day at 3 bar, so 9,964 x 365 or **3,636,860 Gallons annually.**

G3.2 Plumbing Fixtures
Water use of plumbing fixtures can be estimated using the water use formulas from Section 7.2.2.3 and Table 7.5 times the occupancy

The general formula for all plumbing fixtures is:
$$Gallons/Day = Number\ of\ Occuupants\ x\ Average\ Usage\ per\ day\ x\ Flow$$
The formula for trap primers is:
$$Gallons/Day = Number\ of\ Primers\ x\ Flow\ per\ day$$
The formula for general cleaning is:
$$Gallons/Day = Number\ of\ fixtures\ x\ Flow\ x\ times\ cleaned$$

Example:
A 5-story 10,869 m^2 (117,000 ft^2) university building with laboratory classrooms and lecture halls operates 5 days per week and has the following average design occupancy schedule daily. All fixtures are low flow. All WC & U have flush valves and all lavatories have auto valves that use tempered water control. Facility is occupied 5 days per week at 40 weeks per year.

Average Number of Male and Female Occupants							
Occupancy	**M**	**F**	**Oc. Factor**	**Hours**	**Eq Factor**	**Eq M**	**Eq F**
Full Time	30	50	1	8	1	30	50
Lectures	290	279	0.5	3	0.375	54	52
Classes	496	496	0.5	6	0.75	186	186
Total	**816**	**825**				**270**	**243**

Occupancy factor includes variance in class schedule differences for different days in the week and variance in attendance. Facility has the following plumbing fixtures:

Fixture Type	Quan
M WC	10
M U	10
M Lav	21
F WC	16
F Lav	16
Mop Sinks	6

Note that this fixture count is the legally required fixtures from the plumbing code, per the number of occupants. The number of fixtures actually installed was 25% greater, based on the architect's layout for symmetry between floors. Water use projections should always be from the required fixtures, so as to not overstate the water use from unused fixtures.

SI Units
From Table 7.5 select the water flow per use for both cold water and hot water.
Water closets M use, 270 x 3.5 lpf x 1 use/day = 945 lpd
Urinal M use, 270 x 1 lpf x 2 = 540 lpd
Lav. M cold water use, 270 x .9 lpv x 3 = 729 lpd
Lav. M hot water use, 270 x .5 lpv x 3 = 405 lpd
Water closets F use, 243 x 3.5 lpf x 3 = 2,552 lpd
Lav. F cold water use, 243 x .9 lpv x 3 = 656 lpd
Lav. F hot water use, 243 x .5 lpv x 3 = 364 lpd
Mop sinks cold water use, 6 x 3 uses x 6.5 lpm x 2 min = 234 lpd
Mop sinks hot water use, 6 x 3 uses x 6.5 lpm x 2 min = 234 lpd
Fixture cleaning water WC & U, 39 fixtures x 1 = 39 lpd
Fixture cleaning water Lav. 37 fixtures x 0.5 = 19 lpd
Total Cod water use = 5,480 lpd
Total Hot water use = 769 lpd
Total water uses = 6,249 lpd, x 5 days = 31,245 l/week, x 40 = **1,249,800 liters or 1,250 m^3**.

(IP Units)
From Table 7.6 select the water flow per use for both cold water and hot water.
Water closets M use, 270 x 1.28 gpf x 1 = 345 gpd
Urinal M use, 270 x 1 gpf x 2 = 540 gpd
Lav. M cold water use, 270 x .25 gpv x 3 = 202 gpd
Lav. M hot water use, 270 x .25 gpv x 3 = 202 gpd
Water closets F use, 243 x 1.28 gpf x 3 = 933 gpd
Lav. F cold water use, 243 x .25 gpv x 3 = 182 gpd
Lav. F hot water use, 243 x .25 gpv x 3 = 182 gpd
Mop sinks cold water use, 6 x 2 uses x 1 gpm x 2 min = 24 gpd
Mop sinks hot water use, 6 x 2 uses x 1 gpm x 2 min = 24 gpd
Fixture cleaning water WC & U, 39 fixtures x 1 = 39 gpd
Fixture cleaning water Lav. 37 fixtures x 0.5 = 19 gpd
Total Cod water use = 2,308 gpd
Total Hot water use = 384 gpd
Total water uses = 2,692 gpd, x 5 days = 13,460 g/week, x 40 = **538,400 gallons annually.**

G3.3 Cooling Tower Water Use Calculation (Delta Cooling Towers, 2021)
Using the formulas shown in 1 through 5 below, calculate the water use for the different aspects of cooling tower water use.

SI Units

1. Condenser water load Average annual load **(Q)**, not needed if average condenser flow is known.
2. Average Condenser Flow **(C),** If not known, C = (Average Chilled Water Load in Wh/((T1 – T2) x 1017.4)) x 1.3.
   Where 1152.1599 is the constant for standard water properties at 32.2°C for density and specific heat for ambient conditions of 35°C. Rule of thumb for HVAC applications.
3. Evaporation Loss **(E)** m^3/h = 0.0015179 x C x (T1 – T2)
   Where: C = Condenser flow m^3/h
   T1 – T2 = inlet water temperature minus outlet water temperature ºC,
   0.0015179 is evaporation constant (rule of thumb for 35ºC water). Evaporation rate varies based on the enthalpy of vaporization, which is dictated by the temperature of the water and the dry-bulb and wet-bulb temperatures of the air.
4. Drift Loss **(D)** = 0.02% of condenser water flow (rule of thumb)
   Drift loss is entrained water in the tower discharge vapor. Drift loss in cooling tower is a function of drift eliminator design and wind velocities.
5. Cycles of Concentration **(COC)** COC is best described as the ratio of chloride content in circulation water and in makeup water. Cycle of concentration for normal water treatment is 3-4 cycles. When using standard water treatment chemistry, where cycles of concentration are below 3, the quantity of blowdown water is increased; when cycles are over 4 scaling of the tower and piping may occur.
6. Blowdown **(BD)** = (E – (COC – 1) x D) / (COC – 1)
   Blowdown is the portion of circulating water that is discharged to lower solids concentration due to evaporation of the condenser water. The requirement of blowdown is related to the cycles of concentration (COC).
7. Total cooling water makeup m^3/h (MU) = evaporation loss (E) + drift loss (D) + blow down (BD).
8. Annual Cooling Tower Water use m^3 = MU x annual operating hours.

<u>**Example:**</u>
Given a cooling system with an <u>average</u> 527,549 W/hr cooling load (150 Tons), with an average 5.56ºC *Δ*T and an average cycle of concentration of 3.5 and total operating hours of 5,110 per year.

Unit ID	**Formula**	**Value**	**Unit**
Q	Annual Load Calculation if available	527,549.81	Wh
C	Measure or calculate Flow=Wh /((T1-T2) x* (017.4) x 1.3	107.0582	m^3/h
T1	Inlet Temp	35	ºC
T2	Outlet Temp	29.44	ºC
ΔT	Delta T	5.56	ºC
E	m^3/h = 0.0015179 x C x (T1-T2)	0.9035	m^3/h
D	0.02% of condenser flow	0.0214	m^3/h
COC	Cycles of Concentration	3.5	
BD	(BD) = (E – (COC – 1) x D) / (COC – 1)	0.3400	m^3/h
MU	(MU) = evaporation loss (E) + drift loss (D) + blow down (BD)	1.2649	m^3/h
		4380	Hours

	Annual Water used = MU x annual operating hours x 60	**5,540.38**	m^3

(IP Units)

1. Condenser water load Average annual load **(Q)**, not needed if average condenser flow is known.
2. Average Condenser Flow **(C)** = (Average Chilled Water Load Btu/hr / (500 x T1 – T2)) x 1.3
   Where 500 is the constant for standard water properties at 60°F, density: 8.33 lbs. per gallon for water with a specific heat of 1 Btu/lb °F and 1.3 is the heat of compression factor (rule of thumb).
3. Evaporation Loss **(E)** GPM = 0.00085 x C x (T1 – T2)
   Where: C = Condenser flow GPM
   T1 – T2 = inlet water temperature minus outlet water temperature ºF,
   0.00085 is evaporation constant (rule of thumb for 85º to 95º water). Evaporation rate varies based upon the enthalpy of vaporization which is dictated by the temperature of the water and the dry bulb and wet bulb temperatures of the air.
4. Drift Loss **(D)** = 0.02% of condenser water flow (rule of thumb)
   Drift loss is entrained water in the tower discharge vapor. Drift loss in cooling tower is a function of drift eliminator design and wind velocities.
5. Cycles of Concentration **(COC)** COC is best described as the ratio of chloride content in circulation water and in makeup water. Cycle of concentration for normal water treatment is 3-4 cycles. When using standard water treatment chemistry where cycles of concentration are below 3, the quantity of blowdown water is increased; when cycles are over 4, scaling of the tower and piping may occur.
6. Blowdown **(BD)** = (E – (COC – 1) x D) / (COC – 1)
   Blowdown is a portion of circulating water that is discharged to lower solids concentration due to evaporation of the condenser water. The requirement of blowdown is related to the cycles of concentration (COC).
7. Total cooling water makeup GPM **(MU)** = evaporation loss (E) + drift loss (D) + blow down (BD).
8. Annual Cooling Tower Water use Gallons = MU x annual operating hours x 60.

Example:

Given a cooling system with an average 1,800,000 Btu/h cooling load (150 Tons) with an average 10º ΔT and an average cycle of concentration of 3.5 and total operating hours of 5,110 per year.

Unit ID	Formula	Value	Unit
Q	Annual Load Calculation if available	1,800,000	Btu/h
C	Measure or calculate Flow = Btu/h / (500 x T1-T2)) x 1.3	468	GPM
T1	Inlet Temp	95	ºF
T2	Outlet Temp	85	ºF
ΔT	Delta T	10	ºF
E	GPM = 0.00085 x C x (T1-T2)	3.978	GPM
D	0.02% of condenser flow	0.0936	GPM
COC	Cycles of Concentration	3.5	
BD	(BD) = (E – (COC – 1) x D) / (COC – 1)	1.4976	GPM
MU	(MU) = evaporation loss (E) + drift loss (D) + blow down (BD).	5.5692	GPM
		4380	Hours
	Annual Water used = MU x annual operating hours x 60	**1,463,586**	Gallons

G3.4 Steam Boiler Water Use (Armstrong International, Inc. 2015)

Symbol	SI Unit	IP Unit	Description
P	kg/cm^2	PSI	Initial Steam Pressure
S	Kg/hr	lbs/hr	Steam Rate
r	%	%	Amount of condensate return
B	Kg/hr	lbs/hr	Boiler Blowdown
FS	Kg/hr	lbs/hr	Flash Steam
m	50 to 700		Anticipated TDS ppm of makeup water
b	2000 to 3500		Anticipated TDS ppm of water in the boiler
SH	kJ/kg	BTU	Sensible Heat of average condensate high pressure to Steam Traps
SL	kJ/kg	BTU	Sensible Heat of average condensate low pressure at discharge
H	kJ/kg	BTU	Latent Heat of average condensate low pressure at discharge

1. Estimating the percentage of condensate return

Total all steam rates for loads that do not return condensate to the boiler system, such as loads that inject the steam into the air or products or discharge condensate into plumbing drain systems. Convert the steam condensate return into a percentage of the total steam rate.

SI Units

Example:

For a 1.05 kg/cm^2 steam boiler system with a steam rate of 226.80 kg/hr that has 22.6 kg/hr of non-return condensate load the condensate return percentage will be **90%**.

2. Calculating the amount of blowdown water loss:

Using the following formula calculate the boiler blowdown loss:

$$B = \frac{S\,x\,m}{b - m}$$

Example:

S	Average Steam Rate	226.8 kg/hr
b	Boiler Water Maximum TDS	3000 ppm
m	Makeup Water TDS	150 ppm
r	Fraction of condensate return	0.9

$$B = \frac{226.8\,x\,150}{3000 - 150} = \mathbf{11.94\ kg/hr}$$

(IP Units)

Example:

For a 15lb steam boiler system with a steam rate of 500lbs/hr that has 50lbs/hr of non-return condensate load the condensate return percentage will be **90%**.

2. Calculating the amount of blowdown water loss:

Using the following formula calculate the boiler blowdown loss:

$$B = \frac{S\,x\,m}{b - m}$$

Example:

S	Average Steam Rate	500 lbs/hr
b	Boiler Water Maximum TDS	3000 ppm
m	Makeup Water TDS	150 ppm
r	Fraction of condensate return	0.9

$$B = \frac{500\ x\ 150}{3000 - 150} = \mathbf{26.32\ lb/hr}$$

3. Calculating the amount of flash steam water loss

Flash steam occurs any time live steam is discharged into an atmospheric tank for condensate return or into a flash tank for discharge into a sewer system; both losses are calculated the same. Using the following formula, calculate all flash steam losses:

SI Units

Table 7.2.6 Partial SI Steam Table				
Gauge P	**Temp**	**SH Liquid**	**LH of Evap.**	**Volume**
kPa	**^{0}C**	**kJ/kg**	**kJ/kg**	**m^3/kg**
0.0	101.3	419.1	2,257	1.67
28.6	107.1	449.2	2,238	1.33
118.7	123.3	517.6	2,193	0.81
178.7	131.2	551.4	2,170	0.65
448.7	155.5	655.8	2,096	0.34
698.7	170.4	720.9	2,047	0.24
848.7	177.7	752.8	2,021	0.20

$$FS = \left(\frac{SH - SL}{H}\right) x\ 45.645$$

<u>**Example:**</u>

P	1.05 kg/cm^2	
S	226.80 kg/hr.	
SH	507.4 kJ/kg	Sensible heat in the condensate at steam pressure
SL	419.1 kJ/kg	Sensible heat in the condensate at lower discharge pressure
H	2257 kJ/kg	Latent heat in the steam at lower discharge pressure

$$FS = \left(\frac{507.4 - 419.1}{2257}\right) x\ 45.645 = \mathbf{1.79\ kg/hr}$$

(IP Units)

Table 7.2.7 Partial IP Steam Table				
Gauge P	**Temp**	**SH Liquid**	**LH of Evap.**	**Volume**
PSI	**^{0}F**	**Btu/lb**	**Btu/lb**	**ft^3 / lb.**
0	212.0	180.0	970.0	26.8
5	227.0	195.0	960.0	20.1
14	248.0	216.0	947.0	14.3
24	265.0	233.0	934.0	10.8
65	312.0	282.0	901.0	5.5
100	338.0	309.0	880.0	3.9
125	353.0	325.0	868.0	3.2

$$FS = \left(\frac{SH - SL}{H}\right) x\ 100$$

Example:

P	15 lb	
S	500 lb/hr	
SH	218.9 Btu/hr	Sensible heat in the condensate at steam pressure
SL	180.7 Btu/hr	Sensible heat in the condensate at lower discharge pressure
H	970.3 Btu/hr	Latent heat in the steam at lower discharge pressure

$$FS = \left(\frac{218.9 - 180.7}{970.3}\right) x\ 100 = \mathbf{3.94\ lb/hr}$$

4. Calculating total makeup water to the steam system

To determine the total makeup water for the steam system, add the non-return condensate amount to the blowdown and flash steam loss.

$$Make\ Up = Non\ Return\ Steam + Blowdown + Flash\ Loss$$

SI Units

Example:

Non return condensate = 22.68 kg/hr
Blowdown = 11.94 kg/hr
Flash Steam = 1.79 kg/hr
Total = 36.41 kg/hr
Converting to liters /1 = 36.41 liters/hr makeup water

Annual water usage = LPH x annual hours of operation
Annual water usage = 36.41 x 5110 = **186,051 liters or 186.05 m^3**

(IP Units)

Example:

Non return condensate = 50.00 lb/hr
Blowdown = 26.32 lb/hr
Flash Steam = 3.937 lb/hr
Total = 80.26 lbs/hr
Converting to gallons /8.34= 9.62 gallons/hr makeup water

Annual water usage = GPH x annual hours of operation
Annual water usage = 9.62 x 5,110 = **49,158 gallons**

G3.5 Landscape Water Use (USGBC LEED-NC v2.2 Reference Guide, 2005)

To calculate landscape irrigation use, first determine the local evapotranspiration rate (Item 1 below) from a weather data source. Using this ET_O rate times the K_L factor, which is the resultant of the multiplication of the landscape factors from Table 7.10, determine the ET_L rate. Using Tables 7.11 and 7.12 determine the IE and CE values times the area gives the total water use. See the example below:

1. Obtain local Evapotranspiration Rate (ET_O) from local meteorological sources and determine vegetation type and determine the species factor, density factor and the microclimate factor. ET_O is typically expressed in units of millimeters or (inches of water)

evaporated per month. An ET_O calculator by zip code can be found at: http://www.rainmaster.com/historicET.aspx. This gives ETO values by month.

The species factor is separated into low water use, medium water use, and high-water use as a function of plant species, whereas the plant species density factor accounts for shading of the planting area. A low-density factor is where trees and plantings shade 60% of the ground, an average density factor is where trees and plantings shade 90-100% of the ground, and high density is where a tree canopy shades plantings that shade the ground.

The microclimate factor accounts for areas that allow sun or wind to increase the evaporation rate of the soil. High microclimate factors are parking lots, west sides of buildings, west and south side of slopes, meridians and areas exposed to wind tunnel effects. Low microclimate factors include shaded areas, areas protected from the wind, north sides of buildings, courtyards, areas shaded by building overhangs and north sides of slopes.

Step 1. Determine Reference Evapotranspiration Rate (ET_L)
$ET_L = ET_O \times K_L$, using the landscape factors from the table below
$K_L = K_S \times K_D \times K_{MC}$

Table 7.2.8 Landscape Factors

	Species Factor (K_S)			Density Factor (K_D)			Microclimate Factor (K_{MC})		
Vegetation Type	**Low**	**Average**	**High**	**Low**	**Average**	**High**	**Low**	**Average**	**High**
Trees	0.2	0.5	0.9	0.5	1.0	1.3	0.5	1.0	1.4
Shrubs	0.2	0.5	0.7	0.5	1.0	1.1	0.5	1.0	1.3
Groundcovers	0.2	0.5	0.7	0.5	1.0	1.1	0.5	1.0	1.2
Mixed trees, shrubs & groundcover	0.2	0.5	0.9	0.6	1.1	1.3	0.5	1.0	1.4
Turfgrass	0.6	0.7	0.8	0.6	1.0	1.0	0.8	1.0	1.2

<u>K Factor Definitions for Table 7.10</u>
Ks = 0 for native species (no irrigation)
Ks = Low. For adaptative species. Low watering.
Ks = Average. For adaptative species. High watering.
Ks = High. For invasive species.
K_D = Low. If leaf shading is less than 60% ground coverage
K_D = Average. If leaf shading is greater than 60% but less than 90% ground coverage
K_D = High. If leaf shading is 100% ground coverage
K_{MC} = Low. Areas protected from wind and sun, such as court yards and north shaded areas
K_{MC} = Average. Areas only partially protected from wind and sun.
K_{MC} = High. Areas exposed to wind and sun such as parking lots west and south exposures and areas with wind tunnel effects.

SI Units
Step 2. Calculate water use in liters by using the irrigation type factors from Table 7.11:
$K_L = K_S \times K_D \times K_{MC}$
TWA= Area x (ET_L/IE) x CE x ET_O where area is expressed in m^2 and ET_L is in CM.
TPWA= (TWA x 12) – Reuse Water
where TWA is irrigation water use and TPWA is potable water use.

Table 7.2.9 SI Irrigation Type			
Type	**IE**	**CE Dry Climate**	**CE Wet Climate**
Sprinkler	0.099	0.25	0.5
Drip Irrigation	0.1425	0.25	0.5

Example: Determine the irrigation water use for a drip irrigation system for 371.6 m^2 of shrubs in a wet climate for average watering with an average density and partially protected from direct sun and an ETO of 0.4.

	Formula		Unit
K_S	From Table 7.10	0.5	
K_D	From Table 7.10	1	
K_{MC}	From Table 7.10	1	
KL	$K_L = K_S \times K_D \times K_{MC}$	0.5	
Area	Given	371.6	m^2
IE	From Table 7.11	0.1425	
CE	From Table 7.11	0.5	
Et_o	Local evapotranspiration rate	1.016	CM
ET_L	$ET_L = ET_O \times K_L$	0.508	CM
TWA	TWA= Area x (ET_L/IE) x CE x ET_O	673	Liters / Month
Annual TWA	Annual TWA = TWA x 12	**8,076**	Liters / Year
TPWA	TPWA= (TWA x 12) – Reuse Water	**8,076**	Liters / Year

(IP Units)

Step 2. Calculate water use in gallons by using the irrigation type factors from Table 7.2.10 below:

$K_L = K_S \times K_D \times K_{MC}$

TWA= Area x (ET_L/IE) x CE x ET_O where area is expressed in ft^2 and ET_L is in inches.

TPWA= (TWA x 12)– Reuse Water

where TWA is irrigation water use and TPWA is potable water use.

Table 7.2.10 IP Irrigation Type			
Type	**IE**	**CE Dry Climate**	**CE Wet Climate**
Sprinkler	0.625	0.25	0.5
Drip Irrigation	0.9	0.25	0.5

Example: Determine the irrigation water use for a drip irrigation system for 4,000 ft^2 of shrubs in a wet climate for average watering with an average density and partially protected from direct sun and an ETO of 0.4.

	Formula		Unit
K_S	From Table 7.10	0.5	

K_D	From Table 7.10	1	
K_{MC}	From Table 7.10	1	
KL	$K_L = K_S \times K_D \times K_{MC}$	0.5	
Area	Given	4,000	ft^2
IE	From Table 7.12	0.9	
CE	From Table 7.12	0.5	
Et_o	Local evapotranspiration rate	0.4	in/m
ET_L	$ET_L = ET_O \times K_L$	0.2	
TWA	TWA= Area x (ET_L/IE) x CE x ET_O	178	gal/m
Annual TWA	Annual TWA = TWA x 12	**2,133**	gal/yr
TPWA	TPWA= (TWA x 12) – Reuse Water	**2,133**	gal/yr

G3.6 Water Softener Water Use (Chem-Aqua, Inc 2019) (Hach 2024)

Salt-based water softeners use a salt brine to backflush a resin bed to charge the bed with a negative sodium ion charge. During normal use with water flowing over the resin, any dissolved magnesium and calcium minerals that naturally have a positive charge will be held by the resin before releasing a sodium ion to the water. Once the hardness minerals have been removed er, the water is naturally softened. Backflush water is piped to the drain lines and is considered wasted and not used by the system. The calculations below assume the softener system is a flow-based control cycle and not a time-based cycle where the softener keeps track of the total gallons of water processed before entering a backwash cycle.

Table 7.3.8 Water Hardness Scale		
Classification	**Grains/Gallon**	**mg/l & ppm**
Soft	< 1	< 17.1
Slightly Hard	1 - 3.5	17.1 - 60
Moderately Hard	3.5 - 7	60 - 120
Hard	7 - 10	120 - 180
Very Hard	> 10	> 180

1. To calculate the amount of backflush water discharged by a salt-based water softener the following data is needed:
   - Average water flow during occupancy
   - Hours of occupancy
   - Hardness of incoming domestic water (ppm)
   - Amount of iron in the domestic water (ppm)
   - Total Hardness = ppm of water + 3 x Iron Content ppm
   - ft^3 of resin of the softener system
2. From data above calculate total grains of hardness captured
   - Convert the ppm to grains by dividing total ppm / 17.1 = grains
   - Find grains of hardness per liter or gallon of water
   - Find capacity of softener resin in liters or gallons of water before regeneration
   - Convert resin bed to grains capacity 1 liter = 1,130 grains (1 ft^3 = 32,000 grains)

SI Units

Example:

Resin bed size	198.22 liters
Average water flow during occupancy	37.85 liters/min
Hours of occupancy per day	12 hr
Average water hardness	1.59 grains/liter

Gallons per day	(37.85l x 12 hrs x 60 min)	= 27,254.88 liters
Total grains per day	(27,254.88 x 1.59 g)	= 43,200.00 grains
Total system grains	(198.22 l x 1130.07)	= 224000.00 grains
Total usable grains	(80%) (224,000g x .80)	= 179200.00 grains
Days per cycle	(179,200 g/43,200 g)	= 4.15 days
Assumed	3962.58 ppm of backwash (Salt Brine)	
Grains/gallon backwash (ppm/17.1)	(3,962.58 ppm/17.1)	= 231.73 grains/liter
Total gallons/Backwash	(179,000 g/231.73 g/liter)	= 773.31 liters
Backwash cycles per year	(365 days/4.15 days)	= 87.95 cycles/yr
Total annual water use	(87.95 cycles x 773.31 liters)	= **8,012.95** liters/yr or **68.01** m^3

(IP Units)
<u>Example:</u>

Resin bed size		7 ft^3
Average water flow during occupancy		10 gpm
Hours of occupancy per day		12 hr
Average water hardness		6 grains/gallon
Gallons per day	(10 gpm x 12 hrs x 60 min)	= 7200 gallons
Total grains per day	(7200 x 6 g)	= 43200 grains
Total system grains	(7 f^3 x 32,000)	= 224000 grains
Total usable Grains (80%)	(224,000 g x .80)	= 179200 grains
Days per cycle	(179,200 g/43,200 g)	= 4.15 days
Assumed	15,000 ppm of backwash (Salt Brine)	
Grains/Gallon backwash (ppm/17.1)	(15,000 ppm/17.1)	= 877.19 grains/gal
Total Gallons/Backwash	(179,000 g/877.19 g/gal)	= 204.29 gal
Backwash cycles per year	(365 days/4.15 days)	= 87.95 cycles/yr
Total annual water use	(87.95 cycles x 204.29g)	= **17,967** gallons/yr

G3.7 Reverse Osmosis Water Purification System Water Use (Puretec Industrial Water 2024)

Reverse Osmosis (RO) filter systems are used to purify water from impurities making brackish water near pure water. RO systems are grouped into two basic types as Point-of-Use (POU) and Point-of-Entry (POE) systems. POU systems are small capacity residential type systems and POE are larger pressurized systems that can produce larger quantities of water at higher efficiencies. All RO systems have a waste stream of water that flushes the impurities from the RO membrane to maintain the system removal efficiency. Traditionally this waste stream has been at ±20% efficiency, meaning the system has 4 times the wastewater for every unit of pure water generated.

1. POU systems are pressurized by the incoming water supply and include several water filters ahead of the RO membrane and normally a finishing filter after the RO membrane. Efficiency of the system is based on the design of the unit and selection of filters. POU systems are traditionally ±20% efficient but some manufacturers are listing efficiencies up to ±50%.
2. POE systems use pressure pumps to boost the incoming water well above city water pressures to improve the efficiency of the RO membrane and filters. POE systems are normally in the 40 - 50% efficiency range but some manufacturers are listing efficiencies up to 75% efficiency.
3. To calculate total wastewater use from an OR system, determine the total incoming average flow to the system from a submeter and use the following formula; efficiency is obtained from manufacturers literature:
   FW = Average waste water flow

FT = Average Incoming water flow
FP = Average process water flow
E = Efficiency Fraction
$FW = FT - (FT\ x\ E)$

3. To calculate total wastewater use, using the average pure water output, the formula becomes:
$FW = \left(\frac{FP}{E}\right) - FP$
4. Key to Accuracy for Calculating Flow
The most important factor to determine flow for RO units is determining the end use flow, which is sporadic. The easiest method is to use a flow meter on the incoming water supply over the period of measurement.

Example:
An RO system with a 40% efficiency feeds (20) drinking fountain & bottle filler stations in a midrise office building that is occupied 3,744 hours per year. Field testing indicates the average flow of the processed OR water is approximately 30.28 liters/min or (8 gpm).

SI Units

RO output water flow		30.28	liters/min
FT input water flow	FP / 0.40 Eff =	75.71	liters/min
FW waste water flow	FW = FT - (FT x E)	45.42	liters/min
Annual water waste	FW x Hours =	**170,070**	liters

(IP Units)

RO output water flow		8.00	gpm
FT input water flow	FP / 0.40 Eff =	20.00	gpm
FW waste water flow	FW = FT - (FT x E)	12.00	gpm
Annual water waste	FW x Hours =	**44,928**	gallons

G3.8 Swimming Pools and Fountains Water Use (Christopher Wanamaker 2011)
Outdoor swimming pools and fountains all lose water to evaporation, which varies depending on the temperature of the water, air temperature and the water's vapor pressure. Pools also lose water due to human activities of splashing, which is not considered here.

The following equation was developed by Warren Stiver and Dennis Mackay of the Chemical Engineering Department at the University of Toronto. It can be used to estimate evaporation from the surface of a pool that is at or near ambient temperature.

Where:
•E = Evaporation Rate (gallons/day)
•A = Pool Surface Area (ft^2)
•W = Wind Speed Above Pool (m/h)
•P = Water's Vapor Pressure (mm of HG) at Ambient Temperature
•T = Temperature (°F)

SI Units: E = (P x A x W/(T-5.346))
(IP Units:) E = (P x A x W/(T+459.67))
These formulas assume the surface of the water will be very near the temperature of the air where the evaporation takes place, even though the water below the surface will be a lower temperature.

Table 7.2.9 Vapor pressure of water at Atmospheric Pressure			
Temperature		Vapor Pressure	Vapor Pressure
°C	°F	psia	mm HG
4.44	40	0.122	6.309
10.00	50	0.178	9.205
15.60	60	0.256	13.239
21.10	70	0.363	18.773
26.70	80	0.506	26.168
37.80	100	0.949	49.077

SI Units
<u>Example:</u>
A 241.54 m^2 pool with an average wind speed of 6.44 kph and an air temperature of 26.67 ºC. From Table 7.14 the vapor pressure at 26.70ºC is 26.168 mm HG.

	Formula		Units
A	Size of pool	241.54	m^2
W	Average Wind Speed	6.44	kph
T	Air Temperature	6.67	ºC
P	Water vapor pressure	26.1689	mmhg
E	Evaporation rate(P x A x W/(T-5.346))	= **1,908.94**	liters/day

(IP Units)
<u>Example:</u> A 2,600 ft^2 pool with an average wind speed of 4 mph and an air temperature of 80 ºF. From the Table 7.14 the vapor pressure at 80ºF is 26.168 mm HG.

	Formula		Units
A	Size of pool	2,600	ft^2
W	Average Wind Speed	4	mph
T	Air Temperature	80	ºF
P	Water vapor pressure	26.1689	mmhg
E	Evaporation rate(P x A x W/(T-5.346))	= **504**	gallons/day

G3.9 Water Used for Area Cleaning (Green Line Industrial Hose Catalog, 2024)
Water used for cleaning surface areas or equipment can be calculated from standard hose flows. The hose flow Table 7.15 below indicates maximum GPM flow from a hose of 100’ length with no fittings or restrictors and no sharp bends. Multiply these values by the number of minutes the hose is in use to determine total GPM used.

Table 7.2.10 Hose Flow													
Liters/min Flow for 30 meters of Hose at 15% pressure drop							GPM Flow for 100' of Hose at 15% pressure drop						
Inlet P	Inside Diameter in Millimeters						Inlet P	Inside Diameter in Inches					
KPA	12	15	19	25	31	38	PSI	1/2	5/8	3/4	1	1 1/4	1 1/2
137.9	15	30	45	98	178	288	**20**	4	8	12	26	47	76
206.8	19	34	57	121	220	356	**30**	5	9	15	32	58	94
275.8	23	42	68	144	257	416	**40**	6	11	18	38	68	110

344.7	26	45	76	163	291	469	**50**	7	12	20	43	77	124
413.6	30	53	83	178	322	519	**60**	8	14	22	47	85	137
517.5	34	57	95	201	360	583	**75**	9	15	25	53	95	154
689.5	38	68	110	235	424	681	**100**	10	18	29	62	112	180

SI Units

Example: A process line requires cleaning twice a day with a 19 mm hose and takes 30 minutes each time. The facility water pressure is 344.7 kpa.

From Table 7.15, maximum flow of a 19 mm hose at 344.7 kpa is 76 liters/min. 76 liters/min x 30 minutes = 2,280 liters, 2,280 x 2 = **4,560 liters/day**

(IP Units)

Example: A process line requires cleaning twice a day with a ¾" hose and takes 30 minutes each time. The facility water pressure is 50 PSI.

From Table 7.15, maximum flow of a ¾" hose at 50 PSI is 20 GPM. 20 GPM x 30 Minutes = 600 gallons, 600 x 2 = **1,200 gallons/day**

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX H
USING COMFORT METRICS IN ENERGY-EFFICIENT DESIGN/CONTROL OF BUILDINGS

The main design/control strategies involving thermal comfort can be categorized as follows.

a. Adjust thermostat and supply air temperature setpoints for climate-adaptive seasonal comfort, including air movement cooling and radiant heating (H1).
b. Provide local thermal comfort control options (H2).
c. Reduce excessive minimum supply air volumes (H3).
d. Control direct sunlight in work areas (H4).
e. Control humidity independently of supply air temperature (H5).

These strategies, each of which has the ability to both improve thermal comfort and reduce HVAC energy, are described in the following subsections.

H1. Adjust Thermostat Setpoints for Energy-Efficient Thermal Comfort

Because of interpersonal differences in physiology and dress habits, it is not possible to have everyone comfortable at any single temperature. The practical maximum of people regarding the space temperature as acceptable in offices appears to be 80%, which applies equally across a range of temperatures (Zhang et al. 2011). Within that temperature range some people become too warm and an equal number become too cool. This realization is based on field observations, not theory or comfort modeling.

However, it is very common to find a thermostat dead-band range of 72°F–74°F (22.2°C–23.3°C), or even narrower, in use year-around. This range is in the lower half of the winter comfort zone. In the United States, the average indoor temperature setting is now cooler in summer than in winter. This practice not only wastes energy but also causes elevated discomfort and health symptoms in both seasons (Mendel and Mirer 2009). The reasons for this wasteful practice are several. One is that the minimum flow rates for VAV diffusers are set too high, causing zones with low internal loads to be over cooled. Another is that supply air temperatures are not reset when loads change, either daily or seasonally. Another reason results from dehumidification taking place in the same coil as supply air temperature, without reheat. The cold temperatures required for dehumidification cause overcooling in many zones. Another reason may be that designers and operators believe that occupants seek a marked change in temperature when entering a conditioned space, not accounting for subsequent adjustment to the cooled environment.

For each degree Fahrenheit that the dead band can be extended, roughly 5% of heating or cooling HVAC energy use is saved, depending on the climate. Figure H.1 shows energy savings in commercial buildings simulated for a range of climates (Hoyt et al. 2009a). There are few other measures that can generate this amount of energy savings in either new or existing buildings.

The first step in combining energy efficiency and high thermal comfort performance is extending the dead band of ambient indoor temperatures (as controlled by the thermostat) to the allowable range specified in ASHRAE Standard 55 (2023). In the following figures, temperature is indicated as operative temperature, an average of air temperature and the temperature of the surrounding room surfaces. For setting controls in typical buildings, however, the operative temperature can be assumed to be equivalent to the thermostat temperature.

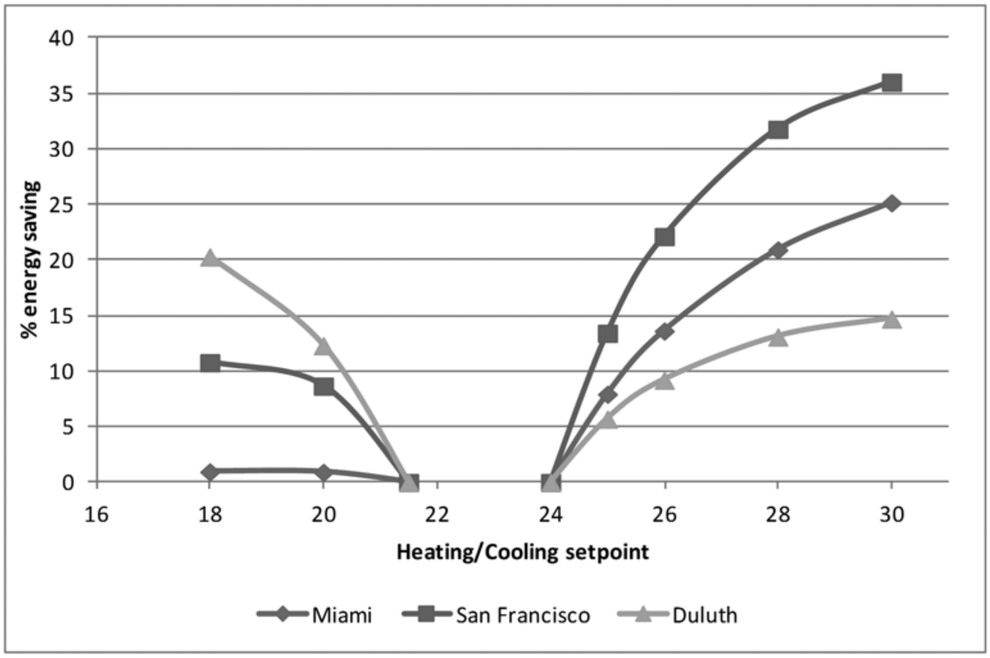

Figure H.1 Heating and Cooling Energy Savings by Setpoint Range (Courtesy of Center for the Built Environment; data source: Hoyt et al. (2009a)).

In buildings with air conditioning, the dead band should be set according to Figure H.2 (Figure 5.2.1.1 from Standard 55-2023). It should be roughly 7°F (3.5°C) wide for a given clothing level. This band should move with the seasons to encourage appropriate climate-adaptive clothing behavior. Clothing insulation values for summer ensembles for men are 0.6 or 0.5 clo, representing slacks with long-sleeved or short-sleeved shirts, respectively. Reasonable winter values are 1.0 to 0.8 clo, representing a man's business suit with or without a vest. Women's clothing should be estimated as 0.1 clo less than men's clothing.

At higher temperatures, occupants may perceive stuffiness. This is countered by a small amount of air movement at face level, such as 60 to 80 fpm (0.3 to 0.4 m/s). Such indoor air movement was traditionally available from operable windows, but it can also be supplied by area fans such as ceiling fans. Look for opportunities to introduce air movement in the occupied space, because such air movement can be generated more efficiently than cooling the entire space.

If the building has operable windows and is naturally conditioned, the thermostat dead band can be based on the Adaptive Model of ASHRAE Standard 55 (see Figure H.3). This model, which is based on empirical observations in occupied buildings, allows a slightly wider thermostat dead band (8°F–9°F [4°C–4.5°C]) that shifts with the seasons. Because the Adaptive Model comfort zone represents actual occupancies, it is not necessary to estimate clothing levels using the Adaptive Model.

Beyond taking advantage of the expanded temperature comfort zones for air-conditioned and naturally conditioned spaces as shown in Figures H.2 and H.3, it is possible to further expand the thermostat setpoint dead bands. One may use area-wide air movement to raise the cooling setpoint temperature above the upper comfort zone boundary and area-wide radiant heating to lower the heating setpoint temperature below the lower boundary. These are described in the following sections. The need for air movement cooling is supported by extensive field observation (Hoyt et al. 2009b).

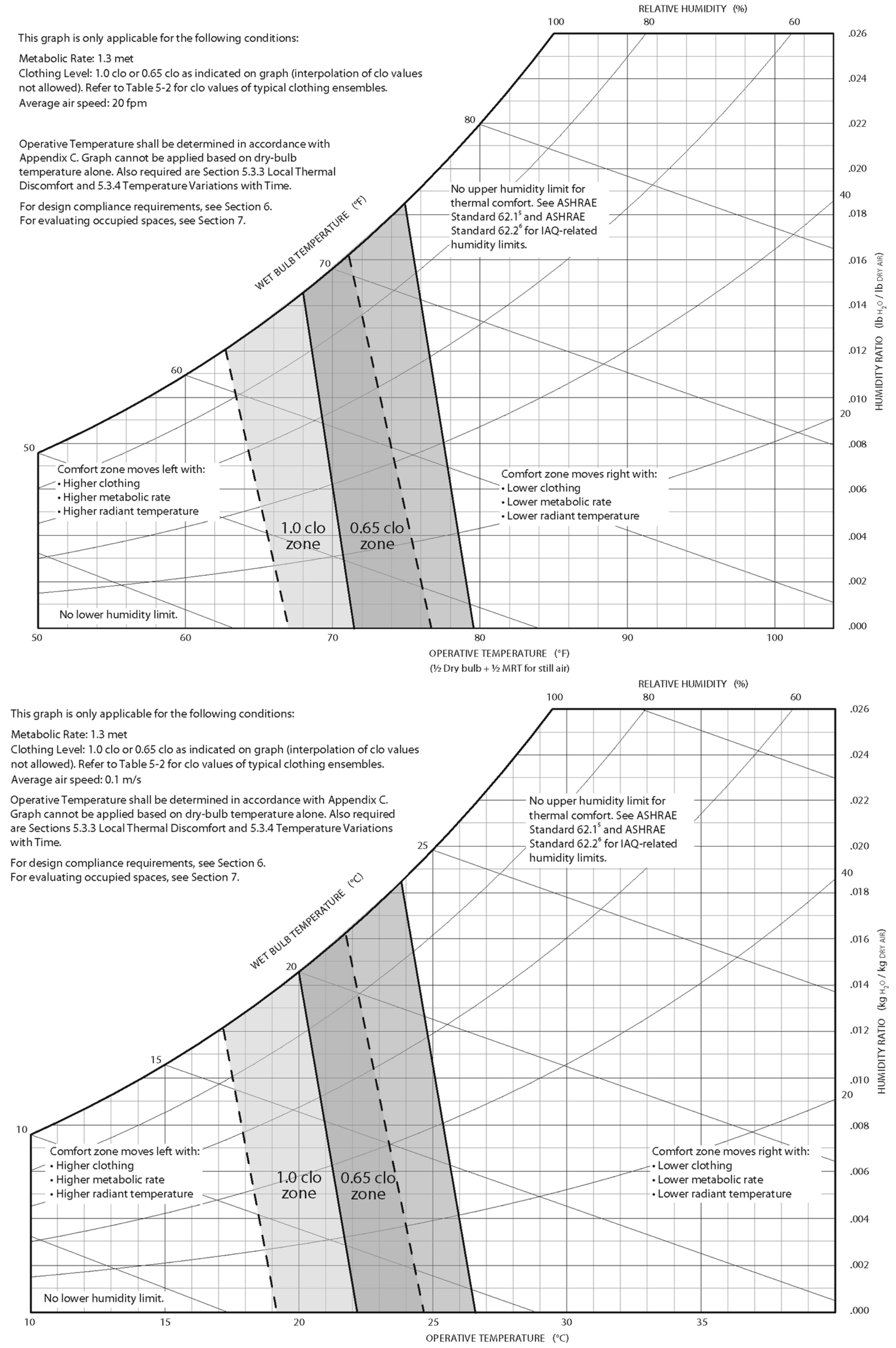

Figure H.2 Acceptable Range of Operative Temperature and Humidity (Source: ASHRAE Standard 55-2023, Figure 5-2).

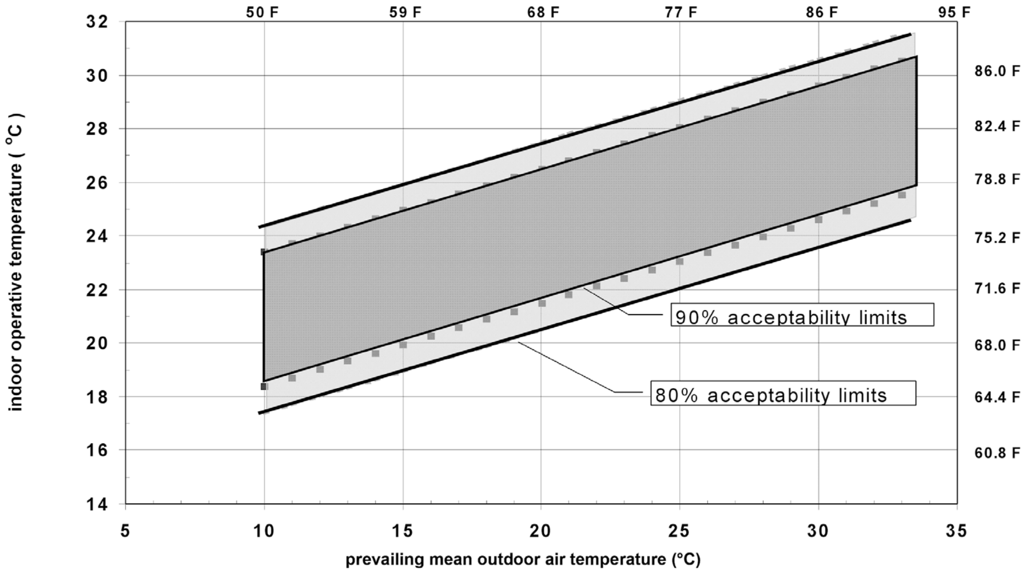

Figure H.3 Acceptable Temperatures for Naturally Conditioned Spaces (Source: ASHRAE Standard 55-2023, Figure 5-9).

a. Air Movement Cooling (HVAC Buildings)

The light-grey zone in Figure H.4 (Figure 5-4 from Standard 55-2023) shows that the space temperature can be raised another 5°F (3°C) by adding up to 160 fpm (0.8 m/s) air movement in the occupied zone. The thermal comfort remains equal in this warmer zone. The air movement in the light-grey zone is a feature of the ambient environment that does not have to be under local control; it can be automatically controlled based on a temperature sensor. The “local control of air speed” area of the figure is addressed in the Provide Local (Personal) Options for Controlling Thermal Comfort section that follows.

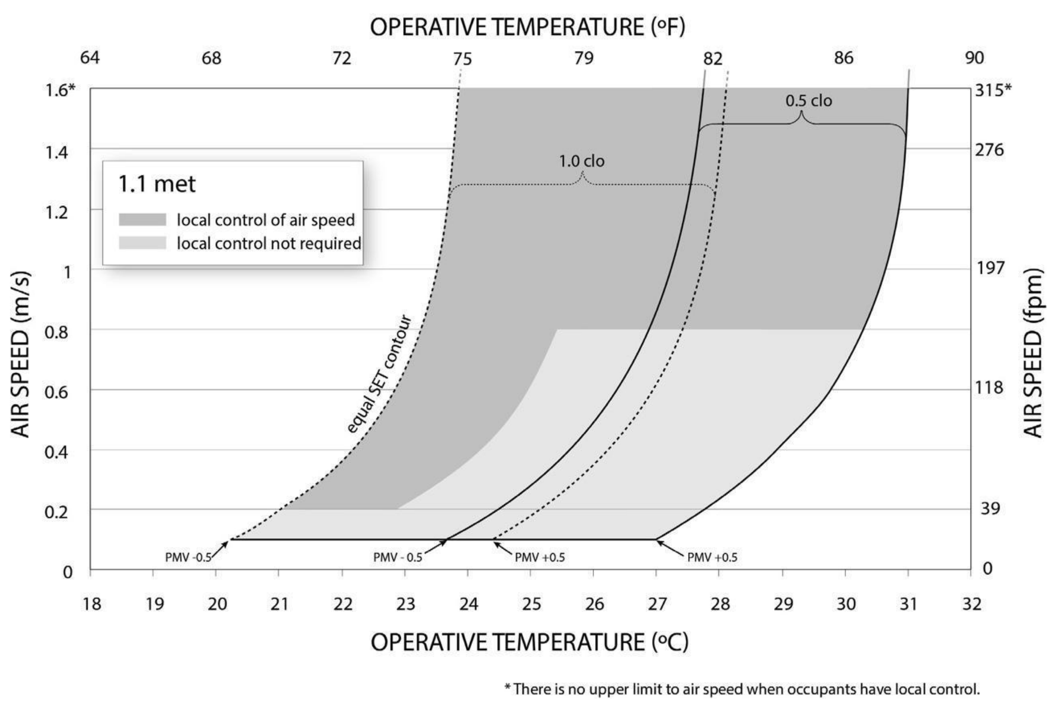

Figure H.4 Comfortable Temperature Increases with Air Speed (Source: ASHRAE Standard 55-2023, Figure 5-4).

b. Air Movement Cooling (Naturally Conditioned Buildings)

For buildings with operable windows, Standard 55-2023 allows the Adaptive Model comfort zone boundary to be raised by air movement above 60 fpm (0.3 m/s), as reproduced in Table H.1. This allows fans to be employed in naturally conditioned buildings to reduce the occurrence of discomfort during times when indoor temperatures exceed the Adaptive Model comfort zone.

Table H.1 Increases in Acceptable Temperature Limits in the Adaptive Comfort Model (Figure H.3). Resulting from Increasing Mean Air Speed above 60 fpm (0.3 m/s) (Source: ASHRAE Standard 55-2023, Table 5-12).

Mean Air Speed = 120 fpm (0.6 m/s)	Mean Air Speed = 180 fpm (0.9 m/s)	Mean Air Speed = 240 fpm (1.2 m/s)
2.2°F (1.2°C)	3.2°F (1.8°C)	4.0°F (2.2°C)

c. Radiant Heating (All Buildings)

At lower temperatures, area-wide radiant heating in the floor allows the heating temperature setpoint to be lowered by 4°F (2°C). The "Adaptive" zone in Figure H.5 shows the great extension to the conventional thermostat range that is possible by adding area-wide radiant heating and air movement cooling to a space conditioned to the full range of the Standard 55 comfort zones.

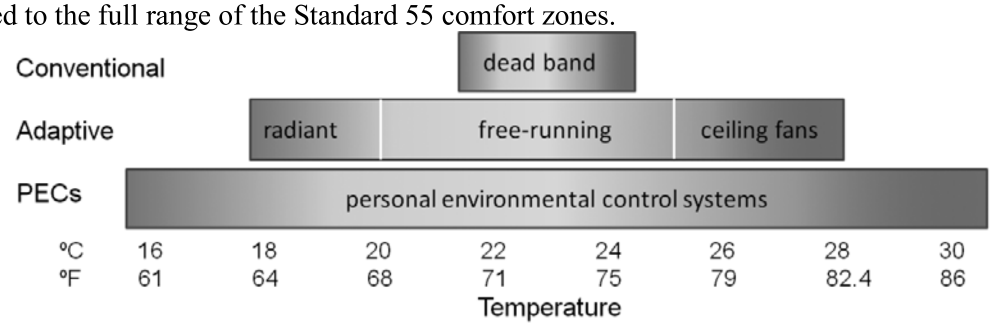

Figure H.5 Extended Thermostat Dead Band Zones Providing Equal Comfort (Courtesy of Center for the Built Environment).

H2. Provide Local (Personal) Options for Controlling Thermal Comfort

Beyond the extended zone shown in Figure H.5, comfort can be augmented through the use of systems that are under local or personal control and that warm or cool the occupants directly. The local application of warming or cooling to the human body is inherently much more energy-efficient than conditioning the temperature of the entire building or zone, and it can provide equal comfort over a wider range of temperatures than is possible with ceiling fans or radiant-floor heating.

The "personal environmental control systems" zone in Figure H.5 shows how far such systems can extend the ambient thermostat dead band while providing equal thermal comfort (Zhang et al. 2011). Personal environmental control (PEC) also makes it possible for all occupants in a space to be satisfied by allowing them to individually adjust for their interpersonal differences in comfort requirements. Uniform heating and cooling systems rarely produce thermally acceptable votes for more than 80% of the occupancy, whereas a PEC system tested in offices has been found to deliver 100% acceptable votes (Bauman et al. 1998).

PEC systems need to have sufficient corrective power to produce comfort for all occupants within the ambient temperature dead band. For a wide variety of applications, PEC systems provide about 9°F (5 K) cooling and 8°F (4 K) heating above and below the ambient comfort zone temperature. At the same time, PEC systems must be energy efficient. It is possible to have local systems (such as conventional 500–

1500 W heaters) that when widely used are not much more efficient than central heating; these should not be used for PEC.

a. **Personal Cooling**

For cooling, air movement must be perceptible within the occupied space, especially around the face region. It can be provided by operable windows and fans; ventilated and cooled seats are also possible.

1. Windows: Although operable windows are discussed under the previous subheading Cooling Naturally Ventilated Buildings, the ASHRAE Standard 55 (2023) Adaptive Model applies only in naturally conditioned spaces. Windows may also be used as PEC systems in mixed-mode buildings that are also mechanically air conditioned. Windows are effective at producing personally controlled air movement within nearby workstations. External wind pressure and buoyancy effects produce fluctuating breezes and temperature changes near the window that are readily perceived by the occupants as cooling them. However, occupants in workstations farther from the window are less likely to perceive air movement unless there are openings on opposing sides of the room, providing cross or corner ventilation (Brager et al. 2004; Carrilho da Graca and Linden 2002). In the warm season, opening windows may be detrimental if the external temperature or humidity is above that indoors. Some control systems employ signals (analogous to traffic lights) to suggest when occupants may best open or close windows. In the thermal comfort section of the Basic Evaluation and Diagnostic Measurement chapters of this Guideline, the degree of compliance with such signals is observed so that problems can be corrected.
2. Fans: Fans can cover areas with multiple occupants (i.e., ceiling or area fans). Group control of air movement by fans is provided for in the light-grey zone of Figure H.4, as previously described. Fans can also be at the personal level as PEC devices, also known as Task-Ambient Conditioning (TAC). Fans for cooling are most effective when they supply air movement to the occupant's facial region and hands and closely around the torso, as in ventilated chairs. The wattage of PEC fans can range from below 1 to 25 W, depending on the area covered and the fan's distance from the occupant. Figure H.6 shows nozzle fans on two workstation desktops.

b. **Personal Heating**

PEC radiant devices are most energy efficient when they focus radiation to the feet and hands. The radiation on the feet should preferably be on the top of the feet, and the radiation source should be in a reflective enclosure that minimizes the heat lost to the environment (see the foot warmer in Figure H.6). PEC may also employ contact heating through conductive surfaces. For hands, the desktop or keyboard surfaces can be locally warmed using low wattage heating devices. Heated chairs are effective at conditioning the whole body; long used in cars, they are becoming available in office chairs.

Figure H.6 Personal Environmental Control Devices (Fans and a Radiant Foot Warmer) in an Office Photograph by Ed Arens (Courtesy of Center for the Built Environment).

H3. Reduce Excessive Minimum Supply Air Volumes

In practice, minimum flow rates for VAV diffusers are often set too high, resulting in zones with low internal loads being overcooled. Overcooling is becoming a major comfort and health issue in the U.S., as mentioned previously (see also Arens et al [2015]; Mendel and Mirer [2009]; Choi et al. [2010]). The fan power consumed is also substantial (Hoyt et al. 2009a), constituting as much as 25% of HVAC energy use (Figure H.7).

The high minimum flow rates (often 30% to 50% of the maximum flow) originate from a concern by manufacturers that low flows might cause insufficient mixing in the space and that cold supply air might dump on the occupants. There was also concern that the VAV control would become unstable at low flows. The stability concern is not borne out in tests of VAV boxes and controllers at minimum flow rates of 10% maximum (Dickerhoff and Stein 2007). The air exchange at 10% maximum generally exceeds the minimum requirements for ventilation. The dumping concern has also been disproved in recently completed field and laboratory research (Arens et al, 2015).

Buildings operating at low minima are not uncommon, and they are evidently more comfortable due to the decreased overcooling in zones with low internal loads. Reprogramming the zone VAV minimum flow to 10% of maximum or to ventilation minimum requirements is a best-practice recommendation. If there is any doubt, a follow-on survey, such as the survey used during Basic Evaluation, can be used to detect whether such changes have caused any problems.

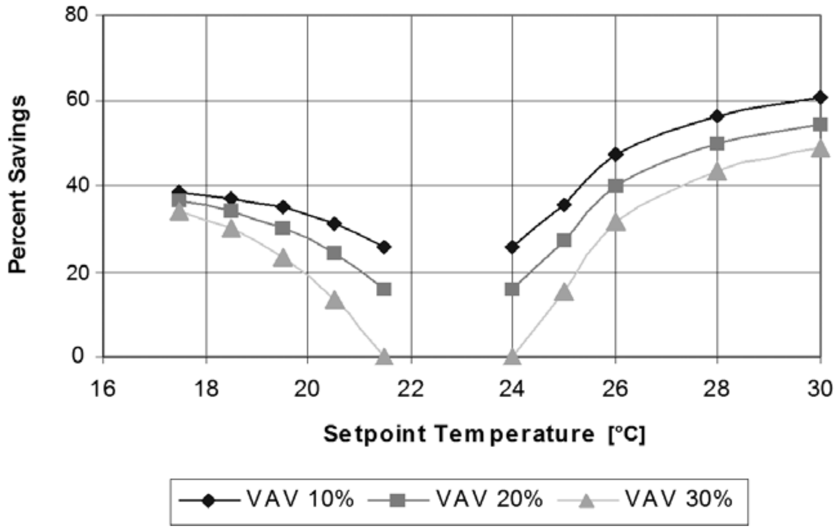

Figure H.7 Annual Energy Use for an Office Building in San Francisco with Different Dead Bands and VAV Minimum fractions at 10%, 20%, and 30% (Courtesy of Center for the Built Environment; data source: Hoyt et al. (2009a)).

H4. Provide Solar Control

It is unfortunately very common to find glazing that is installed for daylighting or view but that does not control direct beam sunlight. The unacceptable thermal conditions produced by unshaded and oversized windows cannot be efficiently corrected through HVAC cooling because the temperature differences required to offset direct solar gain on the human body are very large. The highly directional beam radiation also reflects off work surfaces and computer screens, impeding vision and legibility. Direct solar gain must be controlled directly before it hits the occupant, preferably before it enters the space. Solar controls (blinds, shades, changes to glass transmittance) help solve both thermal discomfort and visual glare.

ASHRAE Standard 55 (2023) provides radiant asymmetry limits (horizontal and vertical), but these are intended for limiting longwave radiation exchange to and from building surfaces. The impact of direct sun on building occupants is not yet adequately addressed in this standard. A National Fenestration Rating Council report (Huizenga et al. 2006) recommends that for workstations there should be no direct solar gain allowed on the occupant, even when it is filtered through screens; as little as 5% of incident radiation produces discomfort.

Preferable solutions involve the following:

a. External shading (fixed or moveable). Preferably the shading also can act as a light shelf to redirect sunlight to the ceiling, where it becomes a useful light source.
b. Internal venetian blinds. The adjustable louvers allow views out while blocking direct sun; each louver also serves as a small light shelf.
c. Changes to glass transmittance, especially in the glare-producing upper window areas. Changes can be achieved by adding reflective or absorbing films or by reglazing.

Interior shades are less energy efficient than the above solutions and do not produce as high-performance indoor environmental quality because

a. the heat absorbed by the shades is already trapped within the conditioned volume of the building and requires extra air conditioning energy to remove it,
b. daylight harvesting measures such as dimmable lights are abrogated because when shades are pulled down they tend to stay down, and
c. views are blocked when the shades are down.

H5. Provide Separate Humidity Control

Many buildings are being maintained at 50% relative humidity or less. This has significant impacts on energy for dehumidification. However, such low limits are not supported by comfort requirements, and Standard 55 does not impose upper humidity limits for this reason. At normal room air temperatures, humidity up to 80% can be acceptable for thermal comfort (Fountain et al. 1999; Tsutsumi et al. 2007; Toftum et al. 1998). Microbiological considerations may be more restrictive than comfort considerations, but for these the upper limits are also well above 50%RH. (Baughman et al, 1998).

In addition, indoor space temperatures are often driven by humidity control since space thermal loads and outdoor air dehumidification are being handled by the same cooling coil, resulting in overcooled spaces in summer. Installing separate dehumidification of outdoor air (with or without dedicated outdoor air) is a best practice for comfort and energy.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX I
INDOOR AIR QUALITY MONITORING AND REPORTING

I1. Sample IAQ Checklist

Table I.1 provides a sample IAQ checklist to confirm the implementation and operation of the HVAC system is in conformance with ASHRAE Standard 62.1-2007 (ASHRAE 2007).

Table I.1 Sample Checklist to Confirm Implementation and Operation of HVAC System in Conformance with ASHRAE Standard 62.1-2007 (ASHRAE 2007).

Requirement	Measurement	Tools	Applicable Under These Conditions
OA Quality Documentation	Y/N	Check Documentation	All Conditions
Natural Ventilation	Dimensions	Tape Measure	If Natural Ventilation
Balancing Assumptions	Y/N	Check Documentation	All Conditions
Exhaust	Yes, Fan Location or Pressure	Visual	All Conditions
Ventilation System Controls	Check Documentation	Visual or Test	All Conditions
OA Intake Location	Dimensions	Tape Measure	All Conditions
Capture	Y/N	Visual	If Required
Combustion Air		Visual	If Required
Particulate Matter Filters		Visual	If Moisture
Dehumidification	Humidity and Exfiltration	Humidity and Pressure	
Drain Pans	Dimensions	Tape Measure and Visual	
Fin Tube Coils	Dimensions	Tape Measure	If Present
Humidifier	Specs	Visual	If Present
Access	Dimensions	Visual	
Envelope	Drawings and Specs	Visual	
Garages	Pressure	Gauge	If Present
Classification	Drawings		
Environmental Tobacco Smoke	Pressure	Gauge	If Present
Ventilation Rate Procedure, Prescriptive Path	Drawings and Calculations	Airflow per Table 6.1	
Volume of OA (Vot)	Air Quantity	As Required	

OA Treatment	Specs	Visual	If Required
Particulate Filtration	PM_{10} MERV 6	PM_{10} Sensor of OA; Visual	If High OA Particulates are Suspected
Ozone Filtration	Second Highest Hour >160 ppb	Ozone (O_3) Meter	If air data from www.epa.gov indicate OA ozone levels are exceeded
OA in Breathing Zone	Occupants, area, cfm (L/s)	Airflow Sensor, CO_2 with curve fit for Ez	
Outdoor Airflow One Zone	Oa Intake and Total Delivered to Space	Airflow Sensor, Ez per Table 6.2	
Outdoor Airflow no Return Air Mixing	OA Intake and Total Delivered to Space	Total Airflow to All Zones	
Outdoor Air with Return Mixing	OA Intake and Total Delivered to Space	OA Fraction, Ez, Occupant Diversity	
Varying Conditions	Drawings and Calculations		
Dynamic Reset	Drawings and Calculations	Test System, CO_2	Energy Saving Option —Not Required
IAQ Procedure, Performance Path			If Used Need Cited Limits
Contaminant Sources	Identify CoC and Measure Each	As Required for CoC	
Concentration Duration	Limits for CoC Integrated	Interval logs to Present Typical	
Perceived Air Quality	Survey Occupants		
Mass Balance	Calculations		
Contaminant Monitoring and Subjective Survey	Measure Each CoC	Survey per Appendix B of ASHRAE Standard 62.1 (2007)	Measure in Completed Building

I2. IAQ Parameters for Continuous Monitoring

Table I.2 provides a list of IAQ parameters to be continuously monitored at Basic, Diagnostic and Advanced levels.

Table I.2 Parameters to be Continuously Monitored at Basic, Diagnostic and Advanced Levels.

Parameter	Basic (Level 1)	Diagnostic (Level 2)	Advanced (Level 3)
Carbon dioxide, CO_2	✓	✓	✓
Air temperature	✓	✓	✓
Relative humidity	✓	✓	✓
Total volatile organic compounds, TVOC		✓	✓
Particulate matter, $PM_{2.5}$		✓	✓
Particulate matter, PM_{10}			✓

I3. IAQ Monitoring Data Coverage (Spatial and Temporal)

Measurement location and conditions:

a. Measurement locations should be selected to accurately represent occupiable areas, giving preference to regularly occupied spaces.
b. Measurements should be made in the space between 0.9 m (3 ft) and 1.8 m (6 ft) above the floor (ASHRAE 62.1-2022 addendum AB).
c. Sampling points should be at least 0.9 m (3 ft) (and preferably 1.8 m (6 ft)) away from doors, windows, air filters, and air supply/exhaust outlets. In areas where this is not possible, monitors should be located closer to air returns than air diffusers (WELL Performance Verification Guidebook 2022 with units converted to a round number in feet; RESET Air Standard for Commercial Interiors 2024).
d. Additionally, follow manufacturer placement recommendations.
e. Intermediate and advanced: Sampling points should be at least 0.9 m (3 ft) away from potential air pollution sources.
f. For one-time and targeted testing, additional specs: The measurement should be conducted with the HVAC system in normal operation and at the lowest outdoor air intake setting expected during the year (ASHRAE 62.1-2022).

Density of measurement points:

a. **Basic:** The minimum number of measurement points should be specified according to Table 7-3 from ASHRAE 62.1-2022 (see Table I.3; roughly corresponds to a sensor per 2,500 m^2 or 25,000 ft^2), with attention to covering a range of occupiable space types.

Table I.3 Recommended Number of Sampling Points by Total Occupied Floor Area.

Total Occupied Floor Area, m^2 (ft^2)	Number of measurements
≤2,500 (25,000)	1
>2,500 (25,000) and ≤5,000 (50,000)	2
>5,000 (50,000) and ≤10,000 (100,000)	4
>10,000 (100,000)	6

b. **Diagnostic:** Model after RESET's spatial requirements, which correspond roughly to a sensor (or, for targeted and time-integrated measurements, a sample) per 500 square meters (or 5,000 ft^2) and additionally account for space type differences.
c. **Advanced:**
    1. The advanced level of sensor placement requires a step beyond the intermediate level. It is intended to support sophisticated goals for building design and operations or field research on the influence of the indoor environment on health.
    2. The advanced level requires an increase in granularity of measurement as applied to one or more of the following options including: 1) increasing the quantity and density of sensors in a given spatial area; 2) monitoring more than a representative sample of each space type (i.e. monitoring every regularly occupied zone); 3) ensuring meaningful comparisons between spaces served by different mechanical zones and air handling equipment; 4) enabling control of mechanical equipment based on feedback loops for more than indoor temperature and humidity (e.g. increasing air flow in response to human-generated CO_2 levels, reducing outdoor air flow or increasing mechanical filtration to reduce introduction of particulates from outdoor air, or other parameters); and, 5) providing optimal placement of sensors for measurement of non-heterogeneous IAQ parameters (e.g. providing more dense placement of particulate matter sensors near indoor sources of this pollutant).

3. The advanced methodology is only partially based on existing peer-reviewed literature (e.g., Yun and Licina, 2023). It may represent new approaches that support field research and provide adequate measurement of parameters for eventual peer review. Additionally, it can facilitate new operational approaches intended to improve building resilience in response to extreme events (e.g., wildfires, biodefense), high levels of local outdoor pollution, and/or differences in local community needs.

Temporal Coverage (Source: RESET Air v2.1, 2023):

a. Minimum polling frequency (or data output interval) – this is the minimum frequency at which a data sample is captured by a sensor: 5 min
b. Minimum data resolution or averaging time – 30 min
c. Data loss rate no higher than 10%

I4. Naming Schema, Data Analytics, and Reporting

The utility of measured IAQ data depends on effective post-processing. This post-processing encompasses operations on the data, such as: 1) cleaning, which involves the removal of values surpassing a predefined threshold; 2) transforming, which includes actions like scaling or shifting the data; and 3) rounding, truncation, or conversion. For additional insights, refer to Section 6.3 of the CIBSE TM68 Monitoring Indoor Environmental Quality guideline (2022), as well as RESET Standard v2.0 (2018).

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX J
VISUAL FACTORS AND OCCUPANT SURVEY QUESTIONS

J1. Visual Factors

An occupant's ability to perform a visual task is dependent on how well his/her eyes perceive the details of the task. Factors determining the visibility of task details include the age of the occupant, processing time, task size, light levels, contrast, and glare.

a. Occupant Age

As a whole, the portion of older adults population is increasing. As people age, a number of changes occur to both the structure of the eye and the capabilities of the human visual system (IES, 2020c):

1. Accommodation (the ability to focus based on distance to the task). By age 45, most people can no longer focus at near working distances and may need optical assistance; this is known as presbyopia. By 60, most of the population has very little ability to accommodate and are working with a fixed focus optical system.
2. Pupil Size. The issue of accommodation is somewhat mitigated by the smaller pupils found in the elderly (senile myosis). However, smaller pupils mean that the task luminance (the "brightness" of the task) must be increased to result in the same amount of light reaching the retina.
3. Lens Clarity. With age the lens tends to yellow and therefore less light reaches the retina, more light is scattered within the eye, and colors become altered. This results in
   i. reduced visual acuity (the ability to distinguish fine details)
   ii. need for increased contrast
   iii. reduced color discrimination
   iv. increased time required to adapt to changes in luminance
   v. increased sensitivity to glare

b. Processing Time

It takes time to see. When a balloon pops, one can see both the inflated and the deflated balloon but cannot capture the actual act of popping. A more practical example might be looking for defects in a manufacturing process; as the time allowed to "see" the defects is decreased, background luminance must be increased to compensate. It should be noted that there is a limit to how much increasing luminance can compensate for insufficient processing time.

c. Task Size

Visual acuity is inversely proportional to the size of task needed to see correctly at a given background luminance. As task size is decreased (or the task is moved farther away), background luminance must be increased to maintain visual acuity. However, again, there is a limit to how much increasing luminance can compensate for other variables.

d. Light Level

Visual performance requires sufficient light. The optimum level of light needed to perform a task depends on the nature of the activity; walking down a hallway requires significantly less light than looking for defects in a manufacturing operation. Visibility is poor when task luminance is low; however, above a certain level of illumination, little improvement will be gained through increased light levels.

e. Glare

Bright light that interferes with visual perception is called disability glare. Such glare can come directly from light sources, such as a luminaire or a window, or can be reflected off of other objects in the space. Disability glare may come in several forms, as listed below (the last two are referred to as veiling reflections).

1. A bright source in front of the occupant in his/her field of view.
2. A bright source almost directly overhead.
3. Light reflecting off certain surfaces, such as a glossy magazine; this can reduce the contrast between a task and its surroundings.
4. Bright light sources reflecting off of a screen; this can also reduce contrast. However, this has become less of an issue with the increased use of flat screens and screens using dark text on a white background.

Glare can also occur due to excessive saturation or contrast, leading to more subtle sensation that causes discomfort without necessarily impairing the vision of objects (CIE, 2019). This is overall referred to as discomfort glare and is considered a more subjective sensation, requiring different metrics to quantify it.

f. Contrast

There are two types of contrast: color contrast and luminance contrast. Two items can have the same luminance and insufficient color contrast (e.g., yellow text on a white background). The color contrast is equally critical to the luminance contrast.

Contrast defines the relationship between the luminance of the task (how bright this letter "a" is = Lt) and the luminance of its background (how bright the white paper around this letter "a" is = Lb):

$$\text{Contrast} = \frac{L_b - L_t}{L_b}$$

In general, in very low light levels, greater contrast is necessary for minimal detection (e.g., deer in the road at night). However, as adaptation luminance (background luminance) increases the minimum contrast threshold is low. Conversely, if occupants work with materials that have low contrast, the luminance of the background needs to be increased. This relationship between contrast and visibility is asymptotic. For a given adaptation luminance there is a level of contrast above which visibility is nearly constant; however, the drop off below this point is sharp. Smaller tasks are most adversely affected by reductions in luminance or contrast.

Beyond contrast, conspicuity plays a large role in vision and detection. For something to be detected, it needs to be conspicuous. Factors that affect conspicuity include camouflage, attention, visual clutter, and object shape/size. Objects can have contrast, but appear similar to the background and thus camouflage into the background. If the user is not attentive to the focused object, even high contrast objects may not be conspicuous. Visual clutter also affects conspicuity, a visual scene could have many high contrast items making it hard to determine the specific item of focus. Finally, an object could have high contrast, but size or shape could result in it not being conspicuous.

g. Correlated Color Temperature (CCT)

Correlated color temperature represents the perceived color of a light source and can set the visual "mood" of a space. Warmer colored light (i.e., that at a lower temperature, less than 3000 K) is often used in public areas to promote relaxation while cooler, whiter light (3500 K to 4100 K) is frequently used in offices to promote alertness. CCT is not a strong metric by itself to promote light quality or human health, and it is difficult to say that one CCT is strictly better than another for a given application, so it is not included for benchmarking in this document. However, consistency in CCT throughout a space is a factor in lighting design, and the maintenance staff plays an important role in that they need to replace lamps using lamps with the same CCT as the original design.

h. Daylighting Issues

As the following factors can have an impact on providing daylighting in a space, they should be carefully considered:

1. Direct Sunlight:
   i. Direct sunlight at workspaces should be avoided as even in short durations it causes extreme discomfort or disability glare.
2. Fenestration, Windows, Skylights, and Clerestories:
   i. Windows and clerestories distribution and height
   ii. Skylights occupying 2-6% of the ceiling area are an effective way to provide illumination and maximize energy savings from daylighting
3. Electric Lighting:
   i. Electric lighting near windows should be controlled as a separate zone
   ii. Commissioning of daylighting and shading controls is essential.
   iii. Shading, interior and exterior can be effective against excessive daylighting; as interior shading can be accessed by occupants, it is possible that they may be set based on the worst glare encountered during a day and left at this position, compromising beneficial daylight at all other times; to address this issue, automation is preferred with time-limited override options.
4. Workstation and Furniture Layout:
   i. Workstations should be laid out aiming for computer screens to avoid reflections from windows.
   ii. Workstations near windows may interfere with occupants' privacy, therefore this should be considered as a factor.
5. Space Finishes:
   i. Materials that are in long-term sunlight exposures might show deterioration overtime.
   ii. Specular interior surfaces may amplify glare; matte finishes are preferred to address that issue, with high-reflectance colors to prevent excessive contrast between the window and other surfaces.

J2. Occupant Survey Suggested Questions

Questions from the pool below may be selected to be used in an occupants' survey, depending on the focus of the issues that need to be assessed.

a. View-related survey questions:

1. Do you have visual access to window(s) at your workstation?
   i. Yes
   ii. Yes, but it is blocked by some objects (e.g., furniture)
   iii. No
2. How satisfied are you with the window view quality at your workstation?
   i. Very satisfied
   ii. Satisfied
   iii. Slightly satisfied
   iv. Neither satisfied nor dissatisfied
   v. Slightly dissatisfied
   vi. Dissatisfied
   vii. Very dissatisfied
3. How far is your workstation located from the window?
   i. Right next to the window(s); within 2.5 m (7.5 feet)

ii. Pretty close but not right next to the window(s); between 2.5 m (7.5 feet) to 5 m (15 feet)
iii. Somewhat far from the window(s); between 5 m (15 feet) to 8 m (24 feet)
iv. Quite far from the window(s); more than 8 m (24 feet)

b. Glare-related questions (can be more general and reveal other issues as well):

1. How satisfied are you with the visual conditions in your workspace?
   i. Very satisfied
   ii. Satisfied
   iii. Slightly satisfied
   iv. Neither satisfied nor dissatisfied
   v. Slightly dissatisfied
   vi. Dissatisfied
   vii. Very dissatisfied
2. If you mentioned that you are dissatisfied with your visual conditions, which of the following contribute to your dissatisfaction (check all that apply):
   i. Too dark
   ii. Too bright
   iii. Shadows interfering with my task area
   iv. Not enough daylight
   v. Excessive daylight
   vi. Excessive contrast
   vii. Reflections on my screen
   viii. Feeling of discomfort glare
   ix. Flickering from lights
   x. Shading position/operation
   xi. Other (please describe)

c. Visual acuity questions:

1. How satisfied are you with the electric (overhead and task) lighting in your primary workspace?
   i. Very dissatisfied
   ii. Somewhat dissatisfied
   iii. Neither satisfied nor dissatisfied
   iv. Somewhat satisfied
   v. Very satisfied
2. Which of the following electric lighting issues do you experience in your primary workspace?
   i. Too dim
   ii. Too bright
   iii. Automatic lighting turns off, on, or dims when not desired
   iv. Undesirable light color (too cold/blue, too warm/orange, etc.)
   v. None

d. Non-visual effect questions:

1. How satisfied are you with the brightness of the ambiance of your primary workspace?
   i. Very dissatisfied
   ii. Somewhat dissatisfied
   iii. Neither satisfied nor dissatisfied
   iv. Somewhat satisfied
   v. Very satisfied

e. Flicker-related survey questions should be used to:

1. Identify the presence of flicker at workstations. For example: “When sitting at your typical workstation, do you experience any flicker from light sources?
2. Rate the severity and/or frequency of perceived flicker. For example: “How frequently do you experience at your typical workstation (ranging from very frequently to never)?”
3. Indicate the effect of flicker on occupants’ professional tasks. For example: “If you experience flicker at your typical workstation, how often does it hinder your ability to perform your professional tasks (ranging from very frequently to never)?”

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX K
REFERENCES FOR APPENDICES

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K7. References: Informative Appendix H

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