GUIDELINE

ASHRAE Guideline 14-2014
(Supersedes ASHRAE Guideline 14-2002)

Measurement of Energy, Demand, and Water Savings

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Includes online access to RP-1050 and RP-1093 final reports, as well as downloadable software toolkits for analysis of building energy and environmental data.

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NOTE

Approved addenda, errata, or interpretations for this guideline can be downloaded free of charge from the ASHRAE Web site at www.ashrae.org/technology.

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 14 was developed by ASHRAE to fill a need for a standardized set of energy, demand, and water savings calculation procedures. The intent is to provide guidance on minimum acceptable levels of performance for determining energy and demand savings, using measurements, in commercial transactions. It is entirely possible to have a sale/purchase, lease, or other arrangement for energy-efficient equipment that does not involve measurements. Indeed, the vast majority of transactions are of this type. However, if the savings determination is to be based on measurements, certain minimum requirements are necessary to avoid a process that appears to be based on actual savings but might be highly inaccurate, biased, or random.

The anticipated use of ASHRAE Guideline 14 is for transactions between energy service companies (ESCOs) and their customers, and between ESCOs and utilities, where the utilities have elected to purchase energy savings. Guideline 14 is expected to provide savings results sufficiently well specified and reasonably accurate that the parties to the transaction can have adequate assurance for the payment basis. Other applications of Guideline 14 may include documenting energy savings for various credit programs (e.g., emission reduction credits associated with energy efficiency activities).

Determining savings with measurements in accordance with this guideline involves measuring postretrofit energy use and comparing that to the measured preretrofit use, adjusted or normalized, to act as a proxy for the conditions that would have prevailed had the retrofit not been performed. Therefore, determining energy savings through the use of measurements involves more than just verifying that new equipment has been installed and can function as expected, although those tasks are usually a necessary part of determining savings. In addition, energy savings cannot be claimed to be measured if no preretrofit data are available.

Sampling is often used in projects involving end-use monitoring or what is referred to here as the "retrofit isolation approach." Informative Annex B shows procedures to calculate the added uncertainty due to sampling. Guideline 14 may be used to measure the energy savings from a utility-sponsored or contracted multiple-building energy conservation project. Applying Guideline 14 to such a project would allow the use of Annex B to calculate the measurement uncertainty directly. The net impacts of large-scale utility energy conservation programs, such as those that may involve market transformation or standard offers for purchase of conservation energy, are specifically excluded from the scope of Guideline 14, although individual and multiple-building projects within such programs are covered.

Guideline 14 primarily addresses measurements of energy and demand for determining savings. Other tasks are needed in any energy performance contract. These can include determining appropriate utility rates, inspecting and commissioning equipment, etc. Users of Guideline 14 who are interested in learning more about some of the contractual issues and types of performance contracts will find relevant discussion in the Efficiency Valuation Organization's publication International Performance Measurement and Verification Protocol (IPMVP) *available for download at www.evo-world.org.*

Online Supporting Files

*This guideline provides online access to supporting files. These files can be downloaded from the ASHRAE website at **www.ashrae.org/G14_2014**.*

Included among these files are the full text of ASHRAE Research Reports RP-1050 and RP-1093, as well as software toolkits developed by ASHRAE to assist with the analysis of building energy and environmental data as described in Guideline 14.

1. PURPOSE

The purpose of this document is to provide guidelines for reliably measuring the energy, demand, and water savings achieved in conservation projects.

2. SCOPE

This document provides procedures for using measured preretrofit and postretrofit billing data (e.g., kWh, kW, Mcf, kgal) for the calculation of energy, demand, and water savings.

2.1 What Is Included. The procedures

a. include the determination of energy, demand, and water savings from individual facilities or meters;
b. apply to all forms of energy, including electricity, gas, oil, district heating/cooling, renewables, and water and wastewater; and
c. encompass all types of facilities: residential, commercial, institutional, and industrial.

2.2 What Is not Included. The procedures do not include

a. sampling methodologies used in large-scale demand-side management programs,
b. metering standards, or
c. major industrial process loads.

3. DEFINITIONS, ABBREVIATIONS, AND ACRONYMS

3.1 General. The following definitions represent the way each term is used in ASHRAE Guideline 14.

3.2 Definitions

actual energy savings: reductions in energy, demand, or water achieved by energy conservation measures (ECMs) and determined using one of the methods described in this document.

accuracy: the capability of an instrument to indicate the true value of measured quantity. This is often confused with inaccuracy, which is the departure from the true value to which all causes of error (e.g., hysteresis, nonlinearity, drift, temperature effect, and other sources) contribute.

avoided energy use: reduction in energy use during the reporting period relative to what would have occurred if the facility had been equipped and operated as it was in the baseline period but under reporting period operating conditions. Cost avoidance is the monetary equivalent of avoided energy use. Both are commonly called "savings." See also, *energy savings* and *normalized savings*.

baseline: pertaining to the baseline period.

baseline adjustments: nonroutine adjustments arising during the reporting period from changes in any energy governing characteristic of the facility within the measurement boundary except the named independent variables used for routine adjustments.

baseline conditions: values of all relevant baseline data, including independent variables and static factors describing facility operations and design during the baseline period. This includes building characteristics and other factors that may not be explicitly defined.

baseline data: measurements and quantitative facts describing facility operations and design during the baseline period. This includes energy use or demand and parameters of facility operation, which govern energy use or demand.

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

> ***adjusted baseline energy:*** the energy, demand, and/or water use of the baseline period after any routine and nonroutine adjustments have been applied.

baseline period: period of time selected as representative of facility operations before retrofit.

billing data: information collected from invoices sent to an owner from the energy supplier (e.g., electric or gas bills).

billing determinants: measured quantities that a utility uses to calculate the utility invoice.

calibrated simulation: measurement and verification (M&V) approach where a simulation model is calibrated to baseline or postretrofit energy use data. See also, *calibration*.

calibration: (a) process of verifying the accuracy of an instrument or meter by comparing the measured output of the instrument or meter against a measurement standard or calibrated instrument; (b) process of reducing the uncertainty of a model by comparing the predicted output of the model under a specific set of conditions to the actual measured data for the same set of conditions. In both cases, calibration includes following defined procedures that identify what 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.

coefficient of variation (CV): the ratio of the standard deviation to the mean.

coincident: occurring simultaneously or during the same interval.

confidence level: probability that any measured value will fall within a stated range of precision.

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 must be reported in the measurement and verification (M&V) plan.

commissioning: a quality-focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the owner's project requirements.

commodity: energy or water. Used when energy or water is purchased from on entity and transported and/or delivered by another entity. Used to distinguish between the cost of energy or water and the cost to deliver that energy or water.

confidence level: the probability that any measured value will fall within a stated range of precision.

CV-(RMSE): the coefficient of variation (CV) of the root-mean-square error (RMSE); an indication of how much variation or randomness there is between the data and the model, calculated by dividing RMSE by the average energy use.

cycle: period of time between the start of successive similar operating modes of a facility or piece of equipment whose energy use varies in response to operating procedures or independent variables. For example, most buildings have a cycle of 12 months because their energy use responds to weather conditions, while an industrial process may have a shorter cycle because it operates differently on Sundays than during the rest of the week. (*For an alternative definition of* cycle *related to Section 7, see below.*)

cycle* (Section 7 only)*: cycle of concentration of solids in the condenser water.

demand: the average rate of energy flow over a specified period of time. In the United States, demand usually refers to electric power, but it can also refer to natural gas. In many other countries, demand is commonly used with other energy sources, especially district heat.

> ***billing demand:*** demand used to calculate the demand charge cost. Rate structures and terms vary by jurisdiction and supplier but are typically based on monthly or annual peak demand. Utility rate schedules and commodity pricing contracts are beyond the scope of this guideline. See also, *peak demand.*
>
> ***peak demand:*** maximum demand during a specified time period (e.g., during the utility's peak time-of-use period for a given billing period). See also, *billing demand.*
>
> ***coincident peak demand:*** metered demand of a load (device, circuit, or building) that occurs at the same time as the peak demand of the facility (or loads on a specific meter). In some cases, it may refer to demand of a load that coincides with the utility's peak system load. This should be properly expressed so as to indicate the peak of interest (e.g., "demand coincident with the peak building demand" or "demand coincident with the peak utility system demand") See also, *peak demand.*

demand savings: reduction in the billing demand between the preretrofit or baseline period, and the postretrofit or reporting period, once independent variables such as weather or occupancy have been adjusted for. This term is usually applied to billing demand, to calculate cost savings, or to peak demand, for equipment sizing purposes.

degree-day: a measure of the heating or cooling load on a facility created by outdoor temperature. When the mean daily outdoor temperature is one degree below a stated reference temperature, such as 64°F (18°C), for one day, it is defined that there is one heating degree-day. If this temperature difference prevailed for ten days, ten heating degree-days would be counted for the total period. If the temperature difference were to be 12 degrees for ten days, 120 heating degree-days would be counted. When the ambient temperature is below the reference temperature, it is defined that heating degree-days are counted. When ambient temperatures are above the reference, cooling degree-days are counted (NCDC 2002).

drift (windage) **(Section 7 only)*:*** cooling tower mist ejected from the tower.

energy: (a) energy, demand, or water use; (b) capability of doing work. Energy can take a number of forms, which may be transformed from one into another such as thermal (heat), mechanical (work), electrical, and chemical. Customary measurement units are kilowatts (kWs), British thermal units or kilojoules (Btus or kJ), quantity of steam (in pounds or kilograms), or volume (in gallons or litres) of hydrocarbon fuel.

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

energy cost: see *total energy cost*.

energy performance contract: contract between two or more parties where payment is based on achieving specified results such as improvements in efficiency or reductions in energy costs.

energy savings: reduction in use of energy from the preretrofit baseline to the postretrofit reporting period once independent variables, such as weather or occupancy, have been adjusted for.

energy service company (ESCO): organization that designs, procures, installs, and possibly maintains one or more energy conservation measures (ECMs) at an owner's facility or facilities.

error: the difference between the true or actual value and the value indicated by the measurement system.

> ***random error—***general category for errors that can take values above or below the average value (i.e., not systemic errors).
>
> ***systemic error—***persistent error that does not occur by chance.

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 in the place 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.

full-time equivalent: 1 for each 1 person per 8-hour shift. Visitors are calculated as average number of daily visitors.

independent variables: factors affecting the energy used in a facility that change regularly but which are outside the control of energy conservation measures (e.g., weather or occupancy). See also, *routine adjustments* and *static factors*.

instrument: device used to measure a physical quantity.

interactive effects: energy effects created by an energy conservation measure 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 actual measured energy, demand, and/or water use.

kWh: 3412 Btu.

least squares method: a data-fitting method that minimizes the sum of squared residuals, a residual being the difference between an observed value and the fitted value provided by a model.

marginal price: cost of one additional unit of a commodity billed under a complex rate schedule.

mean: the most widely used measure of the central tendency of a series of observations; the "average" value of a data set, determined by adding up the individual data points and dividing by the total number of these data points.

mean bias error (MBE): an indication of overall bias in a regression model.

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

measured data: data collected using an instrument or meter.

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 actual energy, demand, and water savings achieved by one or more energy conservation measure(s). Savings cannot be directly measured because they represent the absence of energy use. Instead, actual savings are determined by comparing measured use before and after implementation of a project and making appropriate adjustments for changes in conditions.

measurement and verification plan (M&V plan): document describing in detail the proposed M&V activities, procedures, and methods that will be used to determine the actual energy savings.

measurement boundary: notional boundary drawn around equipment and/or systems to segregate those that are relevant to savings determination from those that are not. All energy uses of equipment or systems within the measurement boundary must be measured or estimated, whether or not the energy uses are within the boundary.

meter: device used to measure energy, demand, or water use. See also *utility meter.*

metered data: energy, demand, or water use data collected over time using an instrument or meter.

metering: the act of collecting energy, demand, or water data at a facility using an instrument or meter.

model: mathematical representation or calculation procedure used to predict the energy used in a building or facility. Models may be based on equations that specifically represent the physical processes (simulation models) or may be the result of statistical analysis of energy use data (regression models). See also, *inverse method.*

regression model: mathematical model based on statistical analysis of some measured data.

simulation model: model based on first-principles engineering methods that provides information on the energy using systems in a building (e.g., heating, ventilation, and air conditioning; lighting; occupancy; plug loads; building envelope). The model, along with weather data, serves as the input data for a specific computer building energy simulation program. When run, the computer simulation program will predict the energy use and demand in the described building for a time interval specified in the simulation model. Depending on the kind of simulation program and how it is set up to run, various kinds of output may be produced. (Refer also to Section 5.3)

monitoring: gathering data over time to evaluate equipment or system performance (e.g., chiller electric demand, inlet evaporator temperature and flow and outlet evaporator temperature, condenser inlet temperature, ambient dry-bulb temperature and relative humidity or wet-bulb temperature for use in developing a chiller performance map (kW/ton vs. cooling load and condenser inlet temperature).

net determination bias test: savings resulting from applying the baseline period's independent variable data to algorithms for savings determination. Data so applied must reflect all exclusions or adjustments to actual measured data as documented for the baseline model.

nonroutine adjustments: calculations used to account for changes in static factors within the measurement boundary since the baseline period. When nonroutine adjustments are applied to the baseline energy, they are sometimes referred to simply as *baseline adjustments*.

normalization: adjustment of the baseline or postinstallation energy use to reflect a common set of conditions.

normalized savings: reduction in energy use or cost during a reporting period relative to what would have occurred if the facility had been equipped and operated as it was in the baseline period but under a normal set of conditions. These normal conditions may be a long-term average or those of any other chosen period of time other than the reporting period. Normal conditions may also be set as those prevailing during the baseline period, especially if they were used as the basis for predicting savings. If conditions are those of the reporting period, the term *avoided energy use*, or just *savings*, is used instead of normalized savings.

performance contract: binding agreement between two parties prescribing the specific performance criteria range and magnitude of achievement required of equipment, subsystems, or systems; provided by one party for the benefit and use of the other.

postretrofit period: time following a retrofit during which savings are to be determined. This term is synonymous with *reporting period.*

precision: (a) indication of the closeness of agreement among repeated measurements of the same physical quantity; (b) amount by which a measured value is expected to deviate from the true value. Precision is expressed as a plus/minus tolerance. Any precision statement about a measured value should include a confidence statement. For example, a meter's precision may be rated by the meter manufacturer as ±10% with a 95% confidence level. See also *accuracy* and *uncertainty.*

process water: water used in a manufacturing or production process.

proxy: measured parameter substituted in place of direct measurement of an energy parameter where a relationship between the two has been proven on-site. For example, if a relationship has been proven between the output signal from a variable-speed-drive controller and the power requirements of the controlled fan, this output signal is a proxy for fan power.

r squared (r^2): a measure of the extent to which variations in the dependent variable from its mean value are explained by the regression model.

regression analysis: mathematical technique that extracts parameters from a set of data to describe the correlation of measured independent variables and dependent variables (usually energy data).

reporting period: period of time following implementation of an energy conservation measure when savings reports adhere to the guideline. This period may be as short as the time for an instantaneous measurement of a constant quantity, long enough to reflect all normal operating modes of a system or facility with variable operations, the length of the financial payback period for an investment, the duration of a performance measurement period under an energy performance contract, or indefinite.

resolution: smallest indicated increment in the value of a measured quantity that can be measured and reported by a recording instrument. Resolution is not related to accuracy, precision, or uncertainty.

retrofit: energy conservation measure or measures installed and/or implemented as a single project at a specific time. Although retrofit refers to work done in existing facilities, in the context of this guideline, retrofit is synonymous with energy conservation measures and may be used when referring to new construction.

retrofit isolation: savings measurement approach defined in this document that determines energy, demand, and/or water savings for a specific system. Retrofit isolation may be performed using energy measurements through the use of measurements to isolate the energy flows for the systems under consideration.

routine adjustments: adjustments to account for changes in selected independent variables within the measurement boundary since the baseline period. The methodology for routine adjustments must be defined in the measurement and verification plan by a specific formula or algorithm.

savings: general term referring to reductions in energy, demand, or water use or costs. See also, *actual energy savings*.

savings determination: see *measurement and verification.*

standard deviation: the square root of the variance.

standard error: the standard deviation divided by the square root of the number of observations.

standard error of the coefficient: the standard error of each coefficient in a regression model defines the range where the "true" value lies.

standard error of the estimate: a metric used to establish the reliability of a prediction when a model is used to predict a value for a given independent variable. The reliability of the prediction is measured by the standard error of the estimate.

static factors: those characteristics of a facility that affect energy use within the chosen measurement boundary but which are not used as the basis for any routine adjustments. These characteristics include fixed, environmental, operational, and maintenance characteristics. They may be constant or varying.

statistically valid sample: randomly selected sample where the actual uncertainty of the sample measurements is equal to or less than the targeted precision for the specified confidence interval.

system: one or more pieces of equipment (e.g., fan, pump, motor) working together (e.g., heating system or electrical circuit).

t-statistic: a measure of the probability that the value (or difference between two values) is statistically valid.

therm: 100,000 Btu.

time of use: pricing structures for some forms of energy, especially electricity, include different prices for different times of day and weekends to encourage consumers to shift or reduce consumption at peak demand times.

total energy cost: total cost for energy obtained by applying the billing determinants to the rate or price schedule. This may include base charges, demand charges, customer charges, power factor charges, miscellaneous charges, etc.

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.*

uncertainty analysis: (a) procedure or method by which the uncertainty of a measured or calculated value is determined; (b) process of determining the degree of confidence in the true value when using measurement procedures and/or calculations.

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 to the facility, 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.

utility meter: meter used by a utility to measure billing determinants to calculate monthly charges for energy, demand, and/or water at a facility. More than one utility meter may be installed at a facility. If a utility combines data from several meters to calculate a single bill, the meters may be treated as a single meter.

utility tariff: document describing how utility bills will be determined for a particular customer. Regulated utilities publish the rate tariffs for most classes of customers, but rates that are negotiated with large customers may be confidential. If the commodity is supplied by an entity different from the entity that delivers it to the customer, that portion of the utility costs may be determined by a separate contract. For the purposes of this guideline, the utility tariff refers to all documents that define how the utility or suppliers calculate their invoices to the facility.

variance: a measure of the extent to which observed values differ from each other (i.e., variability or dispersion), found by averaging the squares of the individual deviations from the mean.

whole-facility metered approach: savings measurement approach defined in ASHRAE Guideline 14 that determines energy and demand savings through the use of whole-facility energy (end-use) data, which may be measured by utility meters or data loggers.

3.3 Abbreviations and Acronyms

3D	three dimensional
AC	alternating current
AGA	American Gas Association
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AHU	air-handling unit
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
Btu	British thermal unit
BWM	box-whisker-mean

cfm	cubic feet per minute (f^3/min)
COP	coefficient of performance
CT	current transformer
CV(RMSE)	coefficient of variation of the root-mean-square error
CV(STD)	coefficient of variation of the standard deviation
DAS	data acquisition system
DC	direct current
DOE	U.S. Department of Energy
ECM	energy conservation measure
EMCS	energy management and control system
ESCO	energy service companies
ET	evapotranspiration
FCI	fuel consumption index
gpd	gallons per day (gal/day)
gpm	gallons per minute (gal/min)
HHV	higher heating value
hp	horse power
HRSG	heat-recovery steam generator
HVAC	heating, ventilating, and air conditioning
I-P	inch-pound
IC	integrated circuit
ID	inner diameter
IMT	Inverse Model Toolkit
IPMVP	International Performance Measurement and Verification Protocol
ISO	International Organization for Standardization (Organisation Internationale de Normalisation)
kVA	kilovolt-ampere
kVAR	kilovolt-ampere reactive
kW	kilowatt
kWh	kilowatt-hour
M&V	measurement and verification
MBE	mean bias error
LNG	liquid natural gas
MSE	mean square error
NCDC	National Climatic Data Center
NIST	National Institute of Standards and Technology
NMBE	normalized mean bias error
NOAA	National Oceanic and Atmospheric Administration
PF	power factor
ppmw	parts per million by weight
PRISM	Princeton Scorekeeping Method
PT	potential transformer
RE	relative error
RTD	resistance temperature detector
SaaS	software as a service
SI	International System (Le Système International d'Unités)
TS	time schedule
UFM	ultrasonic flowmeter
USB	universal serial bus
VAV	variable air volume
VBDD	variable-base degree-day
VSD	variable-speed drive
WCM	water conservation measure

4. REQUIREMENTS AND COMMON ELEMENTS

Section 4 defines the minimum requirements and common elements of each of the three approaches, describes the criteria used to select an approach, and ongoing management of the measurement and verification (M&V) process. This section also provides a brief overview of how energy savings are used to calculate cost savings. A detailed description of each approach, including the elements unique to each approach, is provided in Section 6.

Sections 4.1 and 4.2 define and summarize the common elements of the three approaches for savings measurement. Section 4.3 defines the mandatory elements of any savings determination activity claiming compliance with this guideline.

Section 4.3 also contains Table 4-2, which summarizes mandatory requirements for compliance with this guideline for each approach, including prescriptive- and performance-based requirements for the whole-facility approach.

Section 4.4 outlines the steps in selecting and designing a project-specific M&V process and presents additional issues to be considered when selecting an approach. Section 4.5 provides recommendations for ongoing management of the M&V process.

Section 4.5 outlines how energy savings are typically calculated and how this affects the selection and design of the M&V process.

4.1 Approaches. The three approaches to determining savings (Table 4-1) use similar concepts in savings computation. They differ in how they measure actual energy use and demand quantities to be used in savings determination.

4.1.1 Retrofit Isolation Approach. The retrofit isolation approach measures the energy use and relevant independent variables of the individual systems and equipment affected by the retrofit. Measurements of baseline and postinstallation energy are required. The duration of the measurements must be sufficient to capture the full range of operating conditions. Normalization of the measured energy use is usually required to account for differences in the operating conditions and to extrapolate measurements taken over a short period of time to represent annual energy use. The measurements may be normalized to the conditions during the baseline period or the actual postinstallation operation conditions. If neither baseline nor postinstallation conditions are representative of typical operating conditions, it may be necessary to define and use "normal" operating conditions. Both inverse methods and calibrated component simulations may be used to normalize savings. Savings are determined by comparing the normalized baseline and postinstallation energy use.

Savings derived from isolated and metered systems may be used as the basis for determining savings in similar but unmetered systems within the same facility, provided they are subjected to similar operating conditions throughout the baseline and postretrofit periods.

4.1.2 Whole-Facility Approach. The whole-facility approach uses the measured energy use of a building or an entire facility to determine savings. The building or facility energy use may be measured by the utility meter or by a separate submeter for the building or buildings to be evaluated. This approach may involve the use of monthly utility billing data or data gathered more frequently from the utility meter or existing submeters. Data regarding other statistically significant independent variables, such as weather, must be collected during the same period. If weather data are not available from an on-site source, data collected by government weather stations may be used.

A baseline model of facility energy use as a function of the independent variables is developed using inverse methods. The model is validated to ensure it is representative of baseline conditions. Savings are determined by comparing the baseline energy use calculated using the baseline model and the measured postinstallation values of the independent variables with the measured postinstallation energy use.

4.1.3 Whole-Building Calibrated Simulation Approach. The whole-building calibrated simulation approach involves the use of a computer simulation tool to create a model of energy use and demand of the facility. This model, which is typically of preretrofit conditions, is calibrated against actual measured energy, demand, and/or water consumption data. In some cases, additional data regarding the operation of the building and/or the energy use of specific systems or loads are used to refine and calibrate the model. The calibrated model is then used to determine the energy use, demand, and/or water use of the postretrofit conditions.

Simulations of existing buildings are usually calibrated against baseline data and then used to determine postinstallation energy use. In cases where baseline data do not exist, the simulations are calibrated after implementation, and the calibration adjustments are applied to the baseline model. Calibrating a simulation model to baseline and postinstallation measurements is not recommended because it is difficult to determine which postinstallation calibration adjustments should be applied to the baseline model. Savings are deter-

TABLE 4-1 Approaches to Determining Savings

Approach	Measurement Boundary	Measurements Required	Analysis Methods
Retrofit isolation	Equipment or systems affected by retrofit	• Baseline energy use • Postinstallation energy use • Significant independent variables	• Inverse methods; include regression analysis • Calibrated component models
Whole-facility metering	Building or facility	• Baseline energy use • Postinstallation energy use • Significant independent variables	• Inverse methods; include regression analysis
Calibrated simulation	Building or facility	• Baseline energy use OR postinstallation energy use • Significant independent variables	• Building simulation models

mined by comparing the calibrated baseline and postinstallation models.

4.2 Common Elements of all Approaches. Common elements of the three approaches for determining savings are presented below. Unique elements are presented in Sections 5.1 through 5.3.

4.2.1 Selecting Relevant Independent Variables. Independent variables are variables that directly or indirectly determine the energy use or demand of the system and which change during the baseline and/or postinstallation period. The most significant independent variables must be identified, measured over the periods of interest, and then considered in any savings computation. Examples of significant independent variables include, but are not limited to the following:

a. Weather (including outside air temperature, humidity, solar radiation, cloud cover, precipitation, wind, etc.)
b. Occupancy (including building or facility use, population, operating hours, etc.)
c. Production level and process operating conditions (for industrial facilities)

The measurement methodology, the duration, and frequency of measurements of independent variables depends on the availability of the data, the fraction of expected savings, and the desired level of uncertainty in determining savings. This guideline requires that the key independent variables be accurately quantified. If this is not technically or economically feasible, it may be impossible to verify savings with an acceptable level of uncertainty.

Independent variables for retrofit isolation techniques include the parameters that directly or indirectly influence the energy use of the equipment or systems affected by the retrofit. Whole-building or facility techniques require evaluation of all parameters that affect energy use or demand of the facility or building as a whole, including the energy use of equipment or systems not affected by the retrofit.

Determining which independent variables are relevant requires a thorough understanding of how the system (retrofit isolation methods) or facility (whole-facility methods) uses energy and how the retrofit will affect energy use and demand. All independent variables should be evaluated to determine which variables are most significant. The relevance of independent variables used as inputs to empirical modeling techniques (i.e., inverse methods) can be evaluated quantitatively using the F and t-statistics for each variable. Identifying the most relevant independent variables for engineering models (e.g., hourly building simulations) requires a sensitivity analysis. Documented experience with similar projects (i.e., similar facilities, systems, retrofits, climates, and rate structures) allows the sensitivity analysis to consider the variables that are likely to have the greatest impact. Adjustments for changes in known independent variables are discussed in Section 4.2.8.2.

The known independent variables rarely account for all of the variation in energy use or demand. Unaccounted for variables, including changes to the facility or its operation that go unnoticed and variables that cannot be accurately measured or quantified, are a primary source of uncertainty in any computed savings (see Section 4.2.11).

Parameters that may affect energy use but do not change during the baseline period are referred to as static factors. Static factors may include conditioned area, internal office, and process loads. Some parameters, such as occupancy levels and operating hours, may be independent variables for some projects (e.g., a hotel or industrial process) and static factors for others (e.g., correctional facilities). Adjustments for changes in static factors are discussed in Section 4.2.8.3.

4.2.2 Selecting the Baseline Period. The baseline period must include data across the full range of expected operating conditions, modes, and independent variables. Where possible, the baseline operating conditions should be similar to the expected operating conditions for the postretrofit period, to minimize bias or error from unaccounted for factors.

The baseline period is typically the period immediately before the retrofit is analyzed or proposed and should represent one or more complete operating cycles to minimize bias. For example, a facility that operates on an annual cycle in response to weather should have a baseline period of a full year, or several complete years. If data cannot be obtained for less than a full cycle of operation (e.g., 12 months for a facility with weather-dependent loads), shorter periods that are representative of each operating mode (e.g., one month in each season) may be acceptable if the data collection interval is reduced (e.g., from monthly to hourly). In all cases, care must be taken to ensure that the baseline period is representative of typical conditions and does not over- or underemphasize particular operating conditions.

If multiple years are included in the baseline period, each year must be evaluated independently to determine if the pattern of energy use or demand has changed during the period being evaluated. Evaluating several years of preretrofit data can help determine if there are long-term changes in the building energy use and indicate the magnitude of the change. For example, a gradual increase in the internal electrical loads (also referred to as "load creep") is common in many types of buildings and over time can obscure the impact of the retrofit. Even if the underlying cause cannot be precisely determined, the impact of these long-term changes needs to be addressed in the M&V plan so that the retrofit performance can be accurately evaluated.

The baseline period shall be agreed to by both parties and shall be documented in the M&V plan.

4.2.3 Documenting Baseline Conditions. Baseline conditions include all of the parameters that can affect the energy use of systems inside the measurement boundary, including both independent variables and static factors. The relevant independent variables (see Section 4.2.1) shall be measured during the baseline period and documented in the detailed M&V plan. Measurement and analysis of independent variables is described in Sections 5 and 6. Static factors are usually identified at the same time as the independent variables, but the precise impact of static factors on energy use or demand is typically unknown.

Accurate and complete documentation of the baseline conditions inside the measurement boundary is necessary for developing accurate baseline models and establishing baseline conditions for calculating normalized savings. Nonroutine adjustments require documentation of the static factors before and after the retrofit.

All static factors that may affect the energy use of the systems inside the measurement boundary shall be documented during the baseline and reporting periods. Procedures for collecting and documenting this information shall be mutually agreed to by all parties and included in the detailed M&V plan. The baseline values for all static factors that may affect energy use shall be recorded and documented in the M&V plan. If the static factors depend on the mode of operation and/or the time period or season, they must be documented for all conditions. Examples of static factors that need to be documented, include, but are not limited to

a. equipment nameplate and performance data;
b. occupancy, including population levels or density, schedule or patterns, and the use of the building;
c. HVAC equipment operating schedules and setpoints;
d. boiler and chiller plant control strategies, including sequencing, setpoints, and reset schedules;
e. lighting system operating hours and light levels;
f. miscellaneous equipment (e.g., office equipment) operating schedules, load profiles, and control strategies;
g. process loads, production levels, or other plant equipment energy use or load profiles;
h. conditioned space/volume;
i. energy use and operating conditions of equipment and systems not affected by the retrofit; and
j. maintenance activities, including the nature and timing of any equipment failures that have a material impact on energy use.

Note than some parameters may be independent variables for some retrofits and static variables for others (e.g., populations).

Baseline conditions shall be recorded for all the energy-using systems served by the meters to be used in the savings determination. Informative Annex C examples include descriptions of the information contained in the record of baseline conditions.

4.2.4 Setting the Duration of the Postretrofit Measurements. Postretrofit measurements of the dependent and independent variables used in calculating savings shall be measured over a period of time that is sufficient to

a. encompass all operating modes of the retrofitted system(s);
b. span the full range of independent variables normally expected for the reporting period; and
c. provide the intended level of certainty in the reported savings.

The postretrofit measurement period may occur once at the beginning of a project, periodically throughout the reporting period, or continuously throughout the reporting period.

4.2.5 Selecting Measurement Equipment. All meters for measuring energy use, demand or independent variables introduce error. Meter error can be a significant factor affecting the uncertainty in computed savings. The number and location of the measurement devices also influences the level of uncertainty. Section 6 and Informative Annex A summarize key factors to consider in selecting measurement equipment. The type and end-to-end accuracy of measurement equipment used for baseline and postretrofit measurements shall be documented in the detailed M&V plan. The costs of the measurement equipment should be assessed in the M&V plan outlined in Section 4.4.

All measurement equipment used should be calibrated prior to use and recalibrated at the intervals recommended by the manufacturer (typically once every 12 months). Initial calibration shall be performed by a qualified calibration facility independent of the parties involved. Recalibration may be performed by one of the parties if it is witnessed by the other parties, and if the instrumentation to calibrate the measurement equipment has been calibrated to third order NIST standards. The calibration and recalibration process shall be described in the detailed M&V plan. Documentation of initial calibration and subsequent recalibration shall be provided in the M&V plan (for measurements performed prior to submission of the M&V plan) and savings reports.

Calibration of meters used by the utility or energy supplier is not required because they are used to determine the utility bills. It is not necessary to document calibration instrumentation at government weather stations.

4.2.6 Weather Data. Weather data include a wide variety of measurements and observations, but the most common parameters that affect energy use are outdoor air temperature and humidity (sometimes referred to as "outdoor air conditions"). Solar radiation (or cloud cover), wind speed, and direction can affect building energy use but are more commonly used to evaluate the performance of renewable energy measures. Precipitation can be an important variable for projects where water is used for irrigation.

Weather data are the most common independent variable affecting energy use and demand. Accurate and consistent measurement and observations of weather conditions are critical. Data obtained from government weather stations (e.g., NOAA Class A) are considered to be very reliable, but the limited number of government weather stations and the variations in microclimates may justify the use of on-site instrumentation.

Government weather stations, such as the Class A sites operated by NOAA (NOAA data are available from NOAA's National Climatic Data Center, 191 Patton Ave, Asheville NC. See also www.ncdc.noaa.gov.), have rigorous measurements standards and extensive quality control procedures. Data from these weather stations are the most reliable source of weather data for sites in the immediate vicinity of the station. However, variations in microclimates can produce significant variations in weather over short distances (less than a mile) due to changes in terrain and altitude. Proximity to large bodies of water, urban centers, and even airports also affect microclimatic conditions. When using government weather stations, the station that most closely represents the microclimatic conditions at the project site should be used, even if there are other stations that are closer to the project site. Where a nearby weather station is unavailable, a more distant station may be used if its weather pattern is well correlated to the pattern at the particular facility, even if the total heating or cooling conditions are somewhat different. Where possible, short-term weather data from the site should be compared with the weather observations recorded at several weather stations to determine which station most closely corresponds to the site's local weather conditions.

If on-site measurement of weather data are used, the measurement devices must also conform to the calibration requirements in Section 6. If possible, the same instruments should be used for baseline and postinstallation measurements to minimize bias in the postinstallation results. If different instruments are used, calibration data for both sets of instruments shall be compared. If the postinstallation instruments calibrations are biased relative to the baseline instruments, the postinstallation instruments shall be recalibrated to eliminate this bias.

It is recommended that on-site weather observations be periodically validated against the nearest government weather station data to check for drift and/or instrument failure. An initial comparison of observations obtained from recently calibrated on-site instruments with observations from the government weather station will establish the correlation between observations at the two sites. If subsequent comparisons differ significantly from the initial comparison, the on-site sensors should be recalibrated.

The uncertainty of observations from government weather stations with rigorous measurement standards and quality control procedures (e.g., NOAA Class A) can be assumed to be negligible, as long as the station is in the immediate vicinity of the facility. The uncertainty associated with other sources of weather data, including on-site measurements, must be considered.

4.2.7 Demand. Many utilities include charges based on demand, the rate at which energy or water is consumed, for electricity, gas, or district heat supply. Billing demand is usually related to the peak demand during the billing period but may involve time-of-use periods, ratchets, and other rate structures. It may be different from the simple metered peak demand, requiring that determinations of savings recognize the differences that apply to each utility account.

Billing demand can be a fixed quantity (contract demand) associated with a negotiated capacity installed by the utility. Alternatively, it can be measured each billing period as the highest usage rate during the period (peak demand). Some utility supply contracts involve a combination of both contract and peak demand quantities for determining billing demand.

Two common examples of how billing demand is different from peak demand are as follows:

a. Electrical billing demand is determined by increasing peak demand beyond that metered when power factor is below a prescribed level.
b. Electrical billing demand is determined as the higher of contract demand and 60% (for example) of the highest of the previous twelve months' peak demands.

Demand savings determinations shall take into consideration all terms in the utility supply contract before computing the reduction in billing demand. Mathematical modeling of baseline demand should be applied to peak demand data as measured, before applying terms reflecting the utility's algorithm for determining billing demand. Demand savings can be high risk, depending upon the rate structure in use by the provider. ASHRAE Research Project, RP-1093, "Diversity Factor Toolkit" (Abushakra et al. 2001) can be used to determine demand savings.

Electric demand, in kilowatts or kilovolt-amperes, is usually metered over a 15-minute interval, though one-, three-, five-, and thirty-minute intervals are also used. Metering intervals may be fixed, sliding window, or instantaneous. The fixed interval uses the stated period as the measurement period. The sliding window interval uses a subset of the window interval to "slide" the interval in time. For example, a 15-minute sliding window interval may use one, three, or five minute subintervals to accumulate the total demand for the 15-minute period. A new value for the 15-minute period is calculated every subinterval time. Instantaneous billing periods are usually one- or three-minute intervals. Natural gas demand is usually measured over a 24-hour period.

Demand meters installed to submeter electricity shall use the same or shorter metering interval as the supplying utility meter. The peak demand shall be measured at the same time as the utility meter's peak demand is measured in order to measure demand coincident with the utility meter. A retrofit's reduction in electrical load may not necessarily be fully reflected in reduced peak demand since the time of postretrofit peak may have shifted to a former secondary peak.

Where a utility bill shows that energy use was estimated, a valid demand meter reading is usually not available.

All data needed for determining billing demand may not be shown on the utility bill. The utility company may need to provide extra information such as factors and procedures used in billing and/or the time of monthly peak. Electric demand intervals should remain the same during the baseline and postretrofit period.

4.2.8 Calculations. Conditions, such as weather and usage that govern energy use or demand, are usually different between the baseline and postretrofit periods. Measured use and demand must be normalized to a common set of conditions in order to report savings properly. The selection of that common set of conditions for normalization is discussed in Section 4.2.8.1.

The changes in conditions can be either routine or nonroutine. Routine changes, such as weather, occupancy, or hours of operation, which vary from one period of time to another, are those that can be anticipated and that can be readily documented. Calculations involving routine changes are discussed in Section 4.2.8.2. Nonroutine changes, such as change in building use from office to warehouse, follow no expected pattern and often require special effort for documentation. Adjustments for nonroutine changes are discussed in Section 4.2.8.3.

4.2.8.1 Selecting a Common Set of Conditions. To be comparable, baseline and postretrofit period energy use and demand data must be projected to the same set of conditions. These conditions may be those of the postretrofit period, a typical or average set of conditions, or the baseline period. The selection of the set of conditions establishes the type of savings that will be reported, as follows:

a. **Avoided costs, where baseline energy use is adjusted to postinstallation conditions.** The adjusted baseline represents what would have happened in the absence of the retrofit, and the reported savings are the avoided energy use for that postretrofit period. Reported savings reflect changes in both the performance of the retrofit and the postinstallation conditions.

b. **Normalize savings to typical conditions, usually the baseline conditions.** Postinstallation energy use is adjusted to reflect the baseline conditions. Reported savings reflect changes in the performance of the retrofit, allowing comparison of performance from one year to the next.

4.2.8.2 Routine Adjustments. Routine adjustments are the adjustments that are expected to occur frequently during the reporting period. The methodology for these adjustments is defined by the detailed M&V plan.

If avoided costs are being reported, a baseline model is developed to correlate measured baseline energy use and/or demand with statistically significant independent variables (Section 4.2.1.). This model is then used to calculate the adjusted baseline energy use at the actual postinstallation conditions, and the avoided costs are calculated as the difference between the adjusted baseline energy use and the actual postinstallation energy use.

If normalized savings are being reported, the postinstallation measurements are applied to a postinstallation model that normalizes postinstallation energy use or performance measurements to the agreed-upon normal conditions. This model is then used to calculate the adjusted postinstallation energy use at the normal conditions, and the normalized savings are calculated as the difference between the normalized baseline and postinstallation energy use.

Modeling techniques fall into two categories: empirical models, also known as "inverse methods," and engineering models. Inverse methods, which include regression models, linear change-point models, and neural networks, create models based on the mathematical relationships between independent and dependent variables, without any knowledge of the physical processes that link them. Engineering models, which include hourly building simulation models (e.g., DOE2.1E), component models (e.g., TRNSYS), and bin models (e.g., ASEAM), are detailed mathematical representations of the physical processes that link independent and dependent variables. For any given set of data, some techniques may more faithfully predict a period's actual energy use than others. The modeling method chosen should be consistent with the intended uncertainty of the savings determination, and the net determination bias should not exceed 10% of the estimated savings for regression models (see Section 4.2.10).

4.2.8.3 Nonroutine Adjustments. Changes to static factors that affect the energy use of the systems inside the measurement boundary require nonroutine adjustments. The changes are typically related changes in a facility's use or operations, including, but not limited to renovations, facility expansion, changes in usage, and the addition or removal of equipment. Nonroutine adjustments are modifications to the M&V methodology to account for these changes when reporting savings and may be permanent or temporary.

The energy use and demand impacts of the change shall be determined by specific measurements and/or engineering calculations that are consistent with the M&V plan. The impact of the changes shall be reflected as an adjustment to the baseline or postinstallation energy use model. The additional uncertainty introduced by the adjustment must be reported.

While the M&V plan may be able to address some common and straightforward changes that will require nonroutine adjustments, in most cases, the detailed methodology cannot be developed until the scope and nature of the changes are known. All parties involved must agree to the methodology for nonroutine adjustments.

Nonroutine adjustments shall be reported for the interval when they occurred. If it is determined that nonroutine adjustments are necessary after results have been reported, previously reported savings should be restated. Where contract compliance or payments are dependent on the results of these calculations, the detailed M&V plan or the contract itself should contain provisions to address the process for developing nonroutine adjustments, including retroactive adjustments.

4.2.9 Missing Data. Missing data may be estimated or interpolated from measured data using statistically valid engineering techniques, provided that the subsequent calculation of the level of uncertainty in the reported energy use and/or savings reflects the appropriate change in the uncertainty. The data used to interpolate or estimate the missing data shall represent the full range of operating conditions experienced during the missing data interval (if the dependent variable data are missing) or similar adjacent intervals (if data for the independent variables are missing). The data set used for interpolation or estimation of missing data should be an order of magnitude greater than the missing data interval (e.g., for monthly data, 12 months; for daily data, 7 to 14 days; for hourly data, 12 hours, etc.).

The specific methodology for estimating or interpolating missing data shall be described in detail in the savings reports, and the same methodology shall be used throughout the reporting period. The methodology may be modified to address new circumstances, as long as the modification is documented in the corresponding savings reports. A summary of the missing data, including parameters that were missing and the quantity of data missing, shall be reported in the savings reports.

Documentation required by the section shall be sufficient enough that the reported savings can be reproduced by a third party based on the data provided in the savings report.

4.2.10 Net Determination Bias. The necessary assumptions and the unavoidable errors in metering of energy use and demand introduce random error and bias into the computed savings. However modeling and computations used to calculate savings should not add any more error or bias than might be generated by the computational accuracy of modern computational equipment for the whole-building and retrofit isolation approaches. For the whole-building calibrated simulation approach, modeling error is constrained by the calibration requirements of this guideline.

Computational methods used in the whole-building and retrofit isolation approaches include three steps:

a. Development of the mathematical model of the baseline
b. Filtering that may be applied to postretrofit independent variable data
c. Application of the possibly filtered postretrofit independent variable data to the baseline model to determine the baseline energy use or demand adjusted to postretrofit conditions

Together these steps are defined herein as the "algorithm for savings determination." Provided all steps are consistent with each other, only rounding errors will be added by the computational methods. For example the same logic must be used in filtering postretrofit data as is used in developing the model. Rounding errors should be insignificant so that no error is added by computational methods. In this guideline, such situation is defined as one with no net determination bias.

The algorithm for savings determination used in whole-building and retrofit isolation approaches shall be tested for net determination bias. The net determination bias test (see definitions) shall apply the baseline independent variable data to the algorithm for savings determination to recompute an algorithm-determined baseline energy usage or demand for each of the n baseline data points (i). These recomputed quantities are then compared to the actual baseline energy use or demand (i) in the baseline period to derive the net determination bias, as shown below.

Net determination bias should be no more than 0.5% for regression models for whole-building and retrofit isolation approaches.

4.2.11 Savings Uncertainty Calculations. This guideline presents simplified methods of assessing the quantifiable uncertainty in savings computations. Other uncertainty analysis methods are deemed compliant with this guideline if they can be shown to be relevant to the situation and use methods presented in published statistical textbooks.

Three primary sources of quantifiable uncertainty in savings determination are discussed herein along with key methods for computing their impact as noted below:

a. Sampling uncertainty (Sections 4.2.11.1 and B4.1)
b. Measurement equipment error (Section 4.2.11.2, Annex A, and Section B4.2.)
c. Modeling uncertainty (Section 4.2.11.3 and Annex B)

Equations 4-6 and 4-7 in Section 4.2.11.4 consolidate these uncertainties for constant and varying baseline use, respectively. Annex B provides further background on these derivations of the uncertainty in computed savings.

Bootstrapping methods can also be used to estimate uncertainty. In the case of complex rates, a bootstrap approach may be the only way to estimate the uncertainty of cost savings.

Other types of uncertainty are not quantifiable. These include such systematic errors as human errors and errors of technique. Additional random or accidental errors include errors of judgment and unaccounted for changes in conditions. In addition, there are illegitimate errors, such as mistakes and incorrect placement of transducers. Such sources of uncertainty may not lend themselves to explicit quantitative uncertainty calculations, as discussed below. Nevertheless, their existence should be recognized, and their range of possible impacts presented in the M&V plan.

Many methods shown here for the three categories of quantifiable errors are simplifications of strict statistical theory for general application. These methods are shown so that practitioners can easily make reasonable estimates of the level of uncertainty in computed savings.

Terminology

q = number of randomly selected items from a population of Q items

Q = total number of pieces of equipment in a group to be sampled

F = approximate percentage of the baseline energy use that is saved. This percentage should be derived for the m periods of the reporting period. Before savings are actually achieved, the predicted savings may be used in computing F for purposes of designing the savings determination algorithm.

m = number of periods (months, weeks, days, hours) in the postretrofit savings reporting period

n = number of data points or periods in the baseline period

n' = number of independent observations in a total of n observations during the baseline period, calculated as follows:

$$n' = n \times \frac{1-\rho}{1+\rho}$$

where ρ is the autocorrelation coefficient of the series of n observations at lag 1, derived from performing a regression of the series of n observations against the same data series offset by one time step. The correlation coefficient is as follows:

$$\rho = \sqrt{1 - \left[\frac{\sum_{i=1}^{n}(y_i - \bar{y})^2}{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}\right]}$$

For monthly data, this guideline permits an assumption that ρ is 0, so n' is equal to n.

p = number of parameters or terms in the baseline model, as developed by a mathematical analysis of the baseline data

$RE_{instrument}$ = relative error in an instrument's measurement of a value, determined at the instrument manufacturer's rating point, r_{rating}, expressed as a percentage

$\bar{r}$ = mean value of a series of instrument readings

r_{rating} = reading of an instrument at the point at which its manufacturer quotes its relative error (RE) (normally full scale)

t = t-statistic found in statistics textbooks. Selected values are shown in the following table for various confidence levels and values of $(n - p)$.

$n - p$	Confidence			
	68%	80%	90%	95%
5	1.00	1.48	2.02	2.57
10	1.00	1.37	1.81	2.23
15	1.00	1.34	1.75	2.13
20	1.00	1.33	1.73	2.09
25	1.00	1.32	1.71	2.06
Infinite	1.00	1.28	1.65	1.96

U = relative uncertainty in reported energy savings, expressed as a percentage of the savings

U_s = uncertainty created by sampling, expressed as a percentage of the mean

U_{iv} = savings uncertainty created by the error in measurement of postretrofit period independent variables, expressed as a percentage of the savings (See Section 4.2.11.2.)

y = dependent variable of some function of the independent variable(s)

$\bar{y}$ = arithmetic mean of the sample of n observations

$\hat{y}$ = regression model's predicted value of y

4.2.11.1 Sampling Uncertainty. The relative uncertainty created by estimating the mean ($\bar{y}$) of a population of Q items from a random sample of q items with values y_i is

$$U_s = \frac{100}{\bar{y}} \times \sqrt{(1 - q/Q)\left[\sum_{i=1}^{n}(y_i - \bar{y})^2/(q-1)\right]/q} \quad (4\text{-}1)$$

4.2.11.2 Measurement Equipment Error. The equipment used to measure physical quantities produces both measurement and data-capture errors due to the calibration, range, and repeatability of the equipment and installation effects. These factors influence the uncertainty of values reported for energy use and other variables.

This guideline assigns zero measurement error for the following items:

a. Energy use, demand, and independent variables included in a regression model for the baseline period. These errors are inherently assessed by the coefficient of variation determined for the baseline model (Section 4.2.11.3), assuming there is no bias in the reported data.

b. Postretrofit period energy use data that are reported on utility bills.

c. Postretrofit period weather data published by a government-operated weather reporting service in the United States and Canada.

Measurement error shall be assessed for nonbilling energy use meters, adjustments for inventories of stored energy quantities, and measurements of postretrofit independent variables. Errors shall be estimated in terms of both accuracy and confidence levels. Manufacturer's literature or a series of field measurement system verification tests will provide estimates of accuracy, termed "relative error" ($RE_{instrument}$), at some rating point (r_{rating}), usually full scale. Where accuracy or confidence intervals are unknown, the values shown in Section A5 may be used, assuming a 68% confidence interval. The source of measurement error estimates shall be indicated.

The combination of several components in measuring any value will combine the individual errors of each. The $RE_{instrument}$ of C dependent variables can be combined into a final value for overall instrument-error using Equation 4-2, where RE represents the mean reading on any instrument.

$$RE_{instrument} = \frac{\sqrt{\sum_{i=1}^{c}(RE_{instrument} \times r_{rating,i})^2}}{\sum_{i=1}^{c}\bar{r}_t} \quad (4\text{-}2)$$

Error in measuring postretrofit independent variables shall not be combined with any error in metered energy use. The impact of this independent variable error (U_{iv}) shall be simply assessed by computing the savings twice: once with the independent variables at their maximum values and once with them at their minimum values for the stated confidence interval. The difference between these two computed savings defines the total span of the extra uncertainty created by the error in measuring independent variables. The maximum and minimum independent variable values used shall be stated.

4.2.11.3 Modeling Uncertainty. This guideline uses the following three indices to represent how well a mathematical model describes the variability in measured data. These indices shall be computed for the single mathematical model used to describe the baseline data from all operating conditions (i.e., both summer and winter shall be consolidated in one model for evaluating these indices):

a. Coefficient of Variation of the Standard Deviation (CV[STD])

$$CV(STD) = \frac{\sqrt{\frac{\sum(y_i - \bar{y})^2}{(n-1)}}}{\bar{y}} \quad (4\text{-}3)$$

b. Coefficient of Variation of the Root-Mean-Square Error (CV[RMSE])

$$\mathrm{CV(RMSE)} = \frac{\sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{(n-p)}}}{\bar{y}} \quad (4\text{-}4)$$

c. Normalized Mean Bias Error (NMBE)

$$\mathrm{NMBE} = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)}{(n-p) \times \bar{y}} \quad (4\text{-}5)$$

For calibrated simulations, the CV(RMSE) and NMBE of modeled energy use shall be determined by comparing simulation predicted data ($\hat{y}$) to the utility data used for calibration (y_i), with $p = 1$.

4.2.11.4 Computing Savings Uncertainty. Overall savings uncertainty is estimated by considering sample size (q, Q), measurement error ($\mathrm{RE}_{instrument}$ and U_{iv}), modeling uncertainty (CV), the length of the savings determination period (m), and the fraction of baseline energy saved (F). Overall savings uncertainty shall be estimated as follows:

a. Adjust the measurement and modeling uncertainties to a common confidence interval, using the ratio of the relevant t-statistics in the table shown in Section 4.2.11.
b. Use Equation 4-6 or 4-7, as appropriate. The Section 4.2.11 table t-statistic used shall match the confidence levels used in assessing the measurement and modeling uncertainties.
c. Report the confidence level with the uncertainty.
d. Uncertainty associated with any baseline adjustments (Section 4.2.8.3) shall be included by treating it as part of the error in postretrofit energy use measurements, using Equation 4-2.

In cases where the baseline energy use or demand is essentially the same for all periods, or unaffected by any known independent variables (e.g., a lighting circuit's energy use read monthly):

$$U = \frac{t}{F}\sqrt{\frac{\mathrm{CV(STD)}^2}{m} + U_s^2 + \mathrm{RE}_{instrument}^2} \quad (4\text{-}6)$$

In cases where baseline energy use or demand varies from period to period in response to known independent variables,

$$U = \frac{t}{F} = \sqrt{\frac{\mathrm{CV(RSME)}^2}{m} \times \left[\frac{n}{n'}\left(1.6 + \frac{3.2}{n'}\right)\right] + U_s^2 + \mathrm{RE}_{instrument}^2 + U_{iv}^2} \quad (4\text{-}7)$$

Equation 4-7 simplifies to Equation 4-8 for the common situation where no sampling is done ($q = Q$), utility bills are the source of all energy use data ($\mathrm{RE}_{instrument} = 0$ and $n = n'$) and United States or Canadian government-published weather data are used as the only independent variable ($U_{iv} = 0$). Figure B-1 and Table B-2 in Annex B portray this relationship at 68% confidence and a 12-month baseline period.

$$U = t \times \frac{1.26 \times \mathrm{CV(RMSE)}}{F} \times \sqrt{\frac{n+2}{n \times m}} \quad (4\text{-}8)$$

It should be noted that savings uncertainty estimates using these formulas for the calibrated simulation approach apply only to the total savings determined for a meter, not to the savings of individual retrofits. Also, t should be determined for calibrated simulations using $p = 1$.

4.2.11.5 Managing Uncertainty. When planning a retrofit project, a target savings uncertainty level should be established. Equations 5-6 or 5-7 can then be used to evaluate feasible combinations of model CV(RMSE), instrument error, sample size, postretrofit period length, and expected savings fraction. The costs of feasible combinations of savings determination characteristics can be evaluated to find the lowest cost means of achieving the target uncertainty.

It should be noted that uncertainty (U) declines as the savings reporting period (m) lengthens. However compliance with this guideline's maximum level of uncertainty is determined from annual savings only.

Examples of the use of these equations are shown in Annexes B and C.

4.3 Compliance Requirements. To claim compliance with this guideline, the savings measurement shall meet the basic and specific requirements shown in Sections 4.3.1 and 4.3.2, respectively. Examples of compliant savings measurement processes are listed in Informative Annex C. The general methodology of all compliant methods is summarized below:

a. Prepare an M&V plan showing the compliance path chosen, the metering, and analysis procedures.
b. Measure the energy use and demand and the selected independent variables (see Sections 4.2.1 and 4.7) driving energy use in the baseline period. Document baseline conditions (see Section 4.2.3).
c. Measure the same energy use and demand and independent variables in the postretrofit period.
d. Project the baseline and/or postretrofit period energy use and demand measurements to a common set of conditions (see Section 4.2.8.1).
e. Subtract the projected postretrofit period use and billing demand from the projected baseline period use and billing demand to determine the savings. For performance path compliance, the level of uncertainty must be less than one half of the total savings reported in the postretrofit reporting period.

4.3.1 Basic Requirements

a. Prepare an M&V plan, as defined in Section 4.4.1, before retrofit implementation.
b. Measure and report postretrofit energy use and demand, independent variables, and conditions used in the algorithm for savings determination.
c. Apply the algorithm for savings determination for all periods where independent variables are no more than 110% of the maximum and no less than 90% of the minimum values of the independent variables used in deriving the baseline model.
d. For periods not complying with Section 4.3.1(c), any savings report shall note that the independent variable(s) for that period are beyond the range of applicability of the model derived from baseline data.

TABLE 4-2 Path Specific Compliance Requirements
(This table is only an aid to understanding. Requirements are defined in Section 4.3.)

		Minimum Requirements for Each Path			
		Whole Building		Retrofit Isolation	Whole-Building Calibrated Simulation
		Prescriptive	Performance	Performance	Performance
1	Measured data available from:	Baseline and postretrofit	Baseline and postretrofit	Baseline and postretrofit	Baseline and/or postretrofit; report source and accuracy
2	Energy use measurement type	Continuous	Continuous	Note c	Continuous
3	Minimum period spanned by baseline data	12 months	Full range	Full range	12 months
4	Minimum number of valid data points	9			12
5	Allow elimination of data?	No	Explain, Max 25%	Explain	
6	Algorithm for savings determination	Net determination bias <0.005%	Net determination bias <0.005%	Net determination bias <0.005%	
7	Baseline model uncertainty	Note a			Note b
8	Expected savings	>10%			
9	Uncertainty analysis		Required	Required	Required
10	Number and type of ECM	>1 or complex	>1 or complex	1	>1 or complex
11	ECM interaction with energy use of the rest of the building:	Can be significant	Can be significant	None	Can be adequately simulated
12	Special skills of personnel				Five years computer simulation experience
13	Maximum level of uncertainty		50% of annual reported savings at 68% confidence	50% of annual reported savings at 68% confidence	50% of annual reported savings at 68% confidence
14	Use of sampling	Not allowed	Note d	Note e	Not allowed
15	Minimum data interval	1 day			
16	Modeling tool				Simulation (hourly if include demand), public domain or commercially available, plus; report version number and provide input file.
17	Allow estimate of postretrofit data	No	From data spanning missing data	From data spanning missing data	From data spanning missing data

a. For <12-month postretrofit savings reporting period length: max 20% (energy use), 30% (demand).
For 12- to 60-month postretrofit savings reporting period length: max 25% (energy use), 35% (demand).
For >60-month postretrofit savings reporting period length: max 30% (energy use), 40% (demand).
b. For monthly calibration data, 15% and NMBE 5%. For hourly calibration data, 30% and NMBE 10%, if used.
c. If energy use measurement is not continuous, periodically measure demand and continuously record operating periods of relevant equipment.
d. Multiple similar facilities of one owner, providing sampling error is included in savings uncertainty calculation.
e. Multiple similar systems at one facility, providing sampling error is included in savings uncertainty calculation.

TABLE 4-3 Path-Specific Requirements of the Measurement and Verification (M&V) Plan

Measurement and Verification Plan Shall Describe		Whole Building		Retrofit Isolation	Whole-Building Calibrated Simulation
		Prescriptive	Performance		
1	Baseline model parameters, range of applicability, and CV(RMSE)	Yes	Yes	Yes	No
2	Name and version of software to be used for simulation	No	No	No	Yes
3	MBE and CV(RMSE) of computer baseline model relative to calibration data	No	No	No	Yes
4	Effectiveness of isolation metering, interactive effects included and excluded by the metering	No	No	Yes	No
5	Net determination bias of algorithm for savings determination	Yes	Yes	Yes	No
6	Expected level of uncertainty in savings determinations (see Section 4.2.11.4)	No	Yes	Yes	Yes
7	The possible impacts of unquantifiable sources of uncertainty (see Section 4.2.11)	No	Yes	Yes	Yes
8	Methodology to be used in computing the level of uncertainty in future savings reports (see Section 4.2.11.4)	No	Yes	Yes	Yes

Determine and document the effect(s) of any changes to baseline conditions.

4.3.2 Approach Specific Requirements. There are four compliance paths for the three approaches. Each path has its own requirements as described below. Since some of the requirements are similar but not identical, Table 4-3 presents a summary of the key path-specific compliance requirements.

4.3.2.1 Whole-Building Prescriptive Path. This path shall be used when no uncertainty calculations are included with savings reports. Compliance with this path requires that

a. expected savings shall exceed 10% of measured whole-building (or relevant submetered portion of whole-building) energy use or demand;
b. the baseline period shall span a continuous period of at least twelve months without any gaps in energy use or demand or independent variable data;
c. there shall be a minimum of nine valid measured data points in the baseline data;
d. no data points shall be eliminated from the baseline period;
e. the baseline model shall have a maximum CV(RMSE) of 20% for energy use and 30% for demand quantities when less than 12 months' worth of postretrofit data are available for computing savings. These requirements are 25% and 35%, respectively, when 12 to 60 months of data will be used in computing savings. When more than 60 months of data will be available, these requirements are 30% and 40%, respectively;
f. the algorithm for savings determination shall comply with net determination bias test as defined in Section 4.2.10;
g. savings shall not be reported for postretrofit periods without valid measured data; and
h. measured hourly or more frequent data shall be averaged to intervals of at least one day in length.

4.3.2.2 Whole-Building Performance Path. Compliance with this path requires the following:

a. The baseline data shall span the normal full range of all independent variables under normal facility operations.
b. Reasons shall be reported for data gaps, data elimination, or estimation of any actual measured data in the baseline or postretrofit periods. No more than 25% of the measured data shall be excluded.
c. Where multiple similar facilities of one owner are involved, uncertainty and confidence calculations shall include the impact of any sampling techniques used.
d. The algorithm for savings determination shall comply with net determination bias test as defined in Section 4.2.10.
e. With each annual savings report, show at least the level of uncertainty and confidence interval in the savings determined during the postretrofit period (see Section 4.2.11.4).
f. The level of uncertainty must be less than 50% of the annual reported savings, at a confidence level of 68%.

4.3.2.3 Retrofit Isolation Performance Path. Compliance with this path requires the following:

a. The baseline data shall span the normal full range of all independent variables expected to occur under normal facility operations.
b. A technique identified in Normative Annex E shall be used.
c. Reasons shall be reported for data gaps, elimination, or estimation of any actual measured data in the baseline or postretrofit periods.
d. Estimation of missing data shall use actual data points, which span the typical range of independent variables.
e. Where energy use measurement is less than continuous, periodic measurements shall be made of demand, and operating periods of relevant equipment shall be recorded continuously.
f. Where multiple similar systems at one facility are involved, uncertainty and confidence calculations shall include the impact of any sampling techniques used.

g. The algorithm for savings determination shall comply with the net determination bias test, as defined in Section 4.2.10.
h. With each annual savings report, show at least the level of uncertainty and confidence interval in the savings determined during the postretrofit period (see Section 4.2.11.4).
i. The level of uncertainty must be less than 50% of the annual reported savings, at a confidence level of 68%.

4.3.2.4 Whole-Building Calibrated Simulation Performance Path. Compliance with this path requires the following:

a. The simulation tool used to develop models for buildings shall be a computer-based program for the analysis of energy use in buildings. It shall be commercially available or in the public domain. The tool shall be able to adequately model the facility and ECM(s) (see Section 5.3.3.), performing calculations for each hour of the time period in question—e.g., for a one-year period, the model shall perform 8760 hourly calculations. In addition, it shall be able to explicitly model at least
   1. 8760 hours per year,
   2. thermal mass effects,
   3. occupancy and operating schedules that can be separately defined for each day of the week and holidays,
   4. individual setpoints for thermal zones or HVAC components,
   5. actual weather data,
   6. user-definable part-load performance curves for mechanical equipment, and
   7. user-definable capacity and efficiency correction curves for mechanical equipment operating at non-rated conditions.
b. Provide a complete copy of the input data, indicating which data are known and which are assumed. Report the source of all data described as "known," and assess its level of uncertainty.
c. Report the name and version of simulation software used.
d. Report the source and accuracy of the calibration data.
e. Calibration data shall contain, at a minimum, all measured monthly utility data from 12 bills spanning at least one year.
f. The computer model shall have an NMBE of 5% and a CV(RMSE) of 15% relative to monthly calibration data. If hourly calibration data are used, these requirements shall be 10% and 30%, respectively.
g. With each savings report, show at least the level of uncertainty and confidence interval for the annual savings determined during the postretrofit period (see Section 4.2.11.4).
h. The level of uncertainty must be less than 50% of the annual reported savings, at a confidence level of 68%.

4.4 Design of a Savings Measurement Process. The design of a savings measurement process shall be documented in an M&V plan as defined in Section 4.4.1. (See also, ASHRAE [2009b], Chapter 19.) This plan should address the balance between the level of uncertainty and the costs of the process as presented in Sections 4.4.2 and 4.4.3. Section 4.4.4 provides suggestions on choosing an approach, which may be considered in addition to the requirements of Section 4.3.

4.4.1 Measurement and Verification Plan. The design of a savings measurement process shall be documented in a savings M&V plan, before an ECM is installed. The M&V plan shall document the following:

a. The selected measurement approach and compliance path.
b. Baseline period data:
   1. Energy use and demand. Actual meter reading dates or times shall be recorded. With stored energy sources, shipment dates and volumes must be recorded along with period-ending inventory levels.
   2. All independent variables selected for use in analyses and the basis for selection, as well as the basis for not using any variables that may be reasonably considered. Measurement shall be made on the same day that meters are read for monthly quantities, or the same hour for daily quantities.
   3. Baseline conditions as defined in Section 4.2.3.
c. The algorithm for savings determination showing the following:
   1. The methodology to be used for all normal sets of postretrofit conditions.
   2. The means of dealing with each type of anomaly that was the subject of an exclusion or adjustment when developing the baseline model.
d. The measurement procedure as defined in Section 6.2 for any measurement equipment other than utility meters.
e. Quality control procedures (see Section 4.5.4).
f. The items shown in Table 4-4 for the intended compliance path.
g. The savings reporting frequency and format.

4.4.2 Establishing Levels of Uncertainty. The interests of all parties should be considered before establishing the expected level of uncertainty for a savings measurement. For example, where payments are made for savings for a fixed period of time, there may be greater interest in lower levels of uncertainty than if payments cease after the total payment meets some agreed total amount.

Section 4.2.11 and Annex B provide guidance for proper calculation of the level of uncertainty for savings measurements.

4.4.3 Cost. The annual cost of determining savings should normally be only a small fraction of the annual savings themselves. This cost constraint dictates the design of the savings measurement process. Careful planning is needed to constrain the cost of measurement, computation, and reporting of savings and uncertainty.

Some of the cost of measuring savings may be shared with other functions, such as operational monitoring or controls using the same measured data. Facility automation systems often present this opportunity.

Significant factors affecting the cost of savings measurement are

a. number of pieces of equipment needed to measure energy use, demand, and independent variables, and
b. length of time required for savings measurement.

TABLE 4-4 Considerations in Selecting a Compliance Path

		Best Applications for Each Path			
		Whole Building			
Considerations		Prescriptive	Performance	Retrofit Isolation	Whole-Building Calibrated Simulation
1	Ability to determine savings of individual ECMs	No	No	Yes[a]	Yes
2	Nature of possible future baseline adjustments	Minor but can be estimated adequately	Minor but can be estimated adequately	Complex, or effect on ECM performance is simple to estimate adequately	Many or complex
3	ECMs impact	Any component of the facility	Any component of the facility	No reduction of building envelope losses	Any component of the facility
4	Understanding by nontechnical personnel	Can be simple	Can be simple	Can be very simple	Difficult
5	Special skills of personnel			Metering systems	See Table 4-3
6	ECMs' interaction with the energy use of the rest of the facility	Can be complex	Can be complex	To be ignored or measured	Can be complex
7	Best length of postretrofit period	Multiyear	At least one year	Representative periods	Maybe none

a. The cost of using the Retrofit Isolation path for multiple ECMs in the same facility should be compared to the cost of using the Whole Building or Calibrated Simulation paths.

The choice of compliance path (Section 4.4.4) is a key determinant of the amount of measurement equipment and length of time. However, the complexity of the building or the ECMs and the nature of any contractual relationship between the facility owner and a contractor may also be factors.

For each piece of measuring equipment, cost is affected by the required accuracy of the meter, installation detail with recalibration/removal facilities, and data telemetry. Costs are incurred for recalibration, meter reading, data handling, and storage. Use of utility company meters and public weather data can minimize many of these measurement-related costs while reducing uncertainty as noted in Section 4.2.11.2.

The cost of computing savings also includes the labor to derive the baseline model and to maintain it as adjustments are needed.

Generally, the more complex the system for measuring savings, the more explanations will be required to gain the understanding of all stakeholders. Therefore, designing a savings measurement process as simply as possible to meet the uncertainty target can minimize costs.

4.4.4 Choosing a Path. The choice of savings measurement path must consider both the equipment required and the calculations needed to report savings and meet the uncertainty target. These issues should be considered during the conceptual design of the retrofit project, including the uncertainty impact of possible variances in the performance of measurement or savings equipment. This way the trade-offs between cost and level of uncertainty are assessed before committing to a retrofit design.

Every project must find its own balance between the benefits and costs of measurement and resultant accuracy. Any of the paths can be implemented to suit a range of costs and certainties. Users are cautioned that even two well-experienced modelers will not generally determine the same savings amount, sometimes with significant differences.

Table 4-4 summarizes some key considerations in selecting a compliance path. These recommendations should be considered together with the requirements in Table 4-4.

Because of the trade-off between cost and uncertainty, the optimal approach for a specific project usually results from an iterative approach, where incremental improvements in accuracy are assessed relative to the increase in measurement cost. Such optimization requires that a value be placed on the level of accuracy. One way to accomplish this is to consider the uncertainty of the proposed approach by calculating results using the highest and lowest values in the confidence interval. The difference between these values can be translated into a dollar amount that is at risk. It can then be determined whether further expense for improving the savings measurement process is warranted to reduce this uncertainty.

The following example highlights key factors in selecting a path. Other examples are in Annex C.

Consider a multifaceted energy management project expecting to save 30% of a hospital's current fuel use (F = 30). The parties interested in assessing the performance of the project wish to be reasonably assured, with 95% confidence, that there will be no more than 20% uncertainty in the annual reported fuel savings information.

Since this is a multifaceted project, without major changes expected in use or occupancy of the facility, the whole-building approach is most suitable. Monthly utility data of the year immediately before retrofit are compared to weather data and other factors. Using regression analysis, it is found that by simply correlating government reported heating temperature data with monthly gas use, a model with a CV(RMSE) of 6% can be defined. Since savings exceed

10%, and the CV(RMSE) is less than 30%, the prescriptive path may be followed.

However, an uncertainty calculation is needed to ensure that the 20% uncertainty specification is met (U = 20). Equation 4-8 can be used because

a. utility metering will be used,
b. government reported weather data will be used (Section 4.2.11.2 [c])
c. monthly data are used, so no autocorrelation exists ($n = n'$), and
d. no sampling procedures are to be used ($q = Q$).

The baseline model is derived from all 12 months (n = 12) preceding retrofit (y = 2560 + 33.91 × heating degree-days below 50°F). The model contains three parameters (2560, 33.91, 50). The t-statistic for 95% confidence and $n - p$ = 9 is interpolated from Table 4-2 to be 2.3. The resultant annual (m = 12) uncertainty (U) will be 18%. Therefore, the target uncertainty level will be met.

If the savings were to be assessed after just one month, Equation 4-8 would show that the uncertainty at 95% confidence is 63%, and the specification would not be met. Consideration may be given to using daily or hourly fuel use data, with additional well-correlated independent variables beyond temperature. The retrofits may also need to be separately assessed (retrofit isolation) to minimize the need to monitor and adjust for more independent variables that may dominate in a short period. Such switch to the retrofit isolation approach may dictate that some of the energy savings from operational changes and measure interactions cannot be measured following the procedures in this guideline.

4.5 Implementation of the Savings Measurement Process. Before beginning any savings measurement process, the process must be designed as outlined in Section 4.4. The subsequent implementation of the process will require proper integration of hardware, software, and personnel to achieve design uncertainty levels in computed savings.

4.5.1 Hardware. Meters and measuring equipment involved should be commissioned and maintained to ensure they function within the limits contemplated in the M&V plan. Data gathered should be regularly verified to identify any data loss or likely error. Equipment must be recalibrated as defined by the manufacturer. Section 6 contains guidance in these matters. The impact of any required recalibration should be reflected back onto any previously obtained baseline period data, possibly increasing the overall level of uncertainty.

4.5.2 Software. Computer methods developed for analyzing data shall be tested to demonstrate their ability to properly handle all potential combinations of input data. The methods shall identify periods where valid data are missing so that the associated increase in uncertainty can be determined.

4.5.3 Personnel. People involved with the savings measurement process range from the designer(s) of the ECM(s) and the M&V plan, to those handling data, to hardware service mechanics, to those preparing savings reports. All should appreciate their role in maintaining the intended level of certainty. Adequate time should be allowed for all personnel to be trained and to perform their ongoing roles.

Nontechnical readers often use savings reports, so the reports should include a simple presentation of the facts with a clear statement of the level of certainty as required herein. A layman's description of the savings determination approach can be helpful in ensuring correct understanding of routine savings reports.

4.5.4 Quality Control. The accuracy of any savings measurement process is dependent on the quality control of all data gathering and management processes. Procedures should be set up to catch any errors and inadvertent or unauthorized tampering of the data.

It is good practice to outline the processes that need to be followed in handling data and where and how the data are stored (both paper and electronic forms). ISO 9000 work instructions are often helpful in this area. Section 6.6 lists appropriate verification techniques that may be used during real-time data gathering. Other quality control techniques are suggested below.

a. Access for modifying data shall be restricted to properly trained persons with appropriate authority.
b. Use computer software to check the accuracy and reasonableness of an entry. For example, meter readings can be used to verify usage values.
c. Persons other than those directly involved in producing and reviewing the results shall regularly or on a spot basis check the data and resultant calculations.
d. Regularly test the backup and restore procedures for electronically stored data.

Permanently store the M&V plan, all raw data, baseline model development facts, baseline adjustment calculations, and any postretrofit period data adjustments. This information shall be organized, protected from inadvertent tampering, and readily available throughout the life of a project.

5. SPECIFIC APPROACHES

Three specific approaches are discussed in this section, generally following the outline of the International Performance M&V Protocol: (a) whole building, (b) retrofit isolation, and (c) modeling and simulation.

5.1 Whole-Building Approach

5.1.1 Overview. The whole-building approach, also called main meter approach, encompasses procedures that verify the performance of the retrofits for those projects where whole-building pre- and postretrofit data are available to determine the savings. This section discusses methods using utility billing data (usually monthly data). Methods that involve continuous measurements of whole-building energy use before retrofits and continuous measurements of whole-building energy use on a more detailed measurement level (weekly, daily, or hourly) after retrofits are also discussed.

Consumption and demand values taken from submeters are acceptable for use under the whole-building approach, where the meter measures energy use of a significant portion of the building area or a group of subsystems (e.g., motor control center). Such data must meet the same requirements as those for a utility meter. Submeters are particularly useful in multiple building sites served by one utility meter. Examples include university and college campuses, armed forces bases, and large industrial facilities.

5.1.2 Criteria for Whole-Building Approach. It is appropriate to use a whole-building approach when the total building performance is to be calculated, rather than the performance of specific retrofits. There are two paths for the whole-building approach, known as the "prescriptive" and "performance" paths, each having certain criteria and requirements for applicability. Table 5-1 summarizes the approaches described in Section 4 of this guideline.

5.1.2.1 Whole-Building Prescriptive Path. This path is most appropriate where the expected savings are greater than 10% of the measured energy use or demand and where the data are continuous and complete, no data points are to be excluded, and the data are expected to remain like this in the postretrofit period. The 10% rule of thumb is for monthly data. The figure can be much lower for interval data.

5.1.2.2 Whole-Building Performance Path. This path is most appropriate where the data are not continuous, have gaps, and are expected to have similar problems in the postretrofit period.

5.1.3 Methodology and Calculations. The prescriptive and performance paths each have specific data requirements, as described in Section 4 of this guideline. Both of these paths follow the same methodology:

a. Collect energy use, demand, and independent variable data.
b. Determine the path and best statistical model.
c. Calculate energy and demand savings.

5.1.3.1 Data Collection

5.1.3.1.1 Energy Use

5.1.3.1.1.1 Nonstored Energy Sources. For monthly or periodic electricity, steam, and pipeline-supplied gas or other nonstored energy sources, the following information must be recorded:

a. The date of the meter readings.
b. The amount of energy use measured for the utility billing period.
c. In certain cases for pipeline-supplied gas, if there is a variation in the energy content of the gas per unit volume, then the energy content should be measured and recorded.

5.1.3.1.1.2 Stored Energy Sources. For coal, liquid natural gas (LNG), oil, or other stored fuels (typically stored on-site), two types of data are applicable: inventory readings and delivery information. While greater accuracy is achieved by using both types, inventory readings can often be difficult to obtain. If the storage is completely filled with each delivery, so that consumption between deliveries is known, then only delivery information is required. If the storage is not filled at each delivery, there is no correlation between delivery quantities and consumption between deliveries. In this case, inventory information is also required.

a. **Inventory readings.** This involves measurements of the amount of fuel in storage at the start and end of a period and the amount used during that period.
    1. *Date of the inventory readings.* Inventory readings need to be made on a regular schedule: bimonthly, monthly, semimonthly, weekly, and daily are acceptable time frames.
    2. *Change in inventory.* This is based on the amount of fuel in storage.

b. **Delivery information**
    1. *Date of the delivery.* These dates can be determined from delivery invoice information from the fuel supplier.
    2. *Amount of fuel delivered.* This information is obtained from the delivery invoice information from the fuel supplier.

The energy use for a particular time period can be determined by calculating the change in inventory and adding the amount delivered during that period.

5.1.3.1.2 Peak Demand. For electric, steam, and pipeline-supplied gas or other demand measurements, the following information must be recorded:

a. The date range for the demand meter reading or the date of the meter readings.
b. The amount of peak demand for the utility billing period.
c. If possible, date and time when peak demand was set.

5.1.3.1.3 Time of Use. Many electric utility companies have moved toward time-of-use, time-of-day, or real-time electricity pricing. In this situation, the electricity bill shows energy use in on-peak (daytime), off-peak (nighttime), and sometimes shoulder periods (evening and morning) for cost calculations. Customers are charged more for on-peak use than off-peak use. When this situation arises, several options are available but some caution is needed.

Different baseline models can be derived for the different time periods. If hourly temperature readings are available,

TABLE 5-1 Sample Models for Whole-Building Approach

Name	Independent Variables	Form	Examples
No adjustment/ constant model	None	$E = E_b$	Non-weather-sensitive demand.
Day-adjusted model	None	$E = E_b \times \text{day}_b/\text{day}_c$	Non-weather-sensitive use (fuel in summer, electricity in summer).
Two-parameter model	Temperature	$E = C + B_1(T)$	
Three-parameter models	Degree days/ temperature	$E = C + B_1(DD_{BT})$ $E = C + B_1(B_2 - T)^+$ $E = C + B_1(T - B_2)^+$	Seasonal weather-sensitive use (fuel in winter, electricity in summer for cooling); seasonal weather-sensitive demand.
Four-parameter, change-point model	Temperature	$E = C + B_1(B_3 - T)^+ - B_2(T - B_3)^+$ $E = C - B_1(B_3 - T)^+ - B_2(T - B_3)^+$	Seasonal weather-sensitive-use buildings with two cooling or two heating modes (i.e., two weather-sensitive slopes with one change point).
Five-parameter models	Degree days/ temperature	$E = C - B_1(DD_{TH}) + B_2(DD_{TC})$ $E = C + B_1(B_3 - T)^+ + B_2(T - B_4)^+$	Heating and cooling supplied by same meter. Change point $B_3 < B_4$; otherwise use four-parameter model.
Multivariate models	Degree days/ temperature, other independent variables	Combination form $E = c_0 + c_1 x_1 + c_2 x_2 + \ldots + c_n x_n$	Energy-use-dependent non-temperature-based variables (occupancy, production, etc.). Linear model form shown.

then the model may use the mean temperature during each time period for the independent variable for each time period.

In some instances, a better model is achieved by summing up the components and using the total use in the analysis.

In many cases, the baseline period does not have time-of-use components and/or the billing process switched in the postretrofit period. In this case, dividing the baseline energy use into components, unless hourly records are available, is not allowed because the postretrofit data do not have the same components. The savings calculations should use the sum of the components to derive the projected baseline energy use. Therefore, it is important that this situation be recognized in any energy performance contract, as it may have a dramatic impact on savings calculations.

5.1.3.1.3.1 Weekly, Daily, or Hourly Data. The use of more granular or detailed energy use data may decrease or increase the uncertainty in the computed savings. The uncertainty of regression models is inversely related to the number of points in the model, favoring a model with more granular data, but the aggregated data will have a reduced scatter and associated coefficient of variation of the root-mean-square error [CV(RMSE)], favoring a model with less granular data. Therefore, whether more or less granular data will be better is dependent on the number of points available and the scatter in the data for the chosen model type.

With more granular data, however, there is often a need to track more independent variables to model the energy use and demand. For example, with daily data, there may be a need to account for different day types, since energy use may be different on weekdays and weekends. Such categorical (noncontinuous or nonnumeric) variables will often require separate models for each category.

Any additional, continuous independent variables that may need to be added with more granular data should generally be recorded at sufficiently granular time intervals to be able to be placed on coincident times with the energy data. Ideally, they would be measured at the same time as the energy data. However, it is common for weather data to be obtained from nearby weather sites, and such data will be interpolated to be placed on the same timestamp as the energy data. This introduces some uncertainty, but current approaches neglect this added uncertainty, with the implicit assumption that it is minor.

Regression models using hourly data points are allowed; however, there are situations that warrant aggregating hourly data into subdaily or daily occupied/unoccupied periods. Again, since uncertainty is inversely related to the number of points in the model, in some cases, it may be preferable to group the data into common categories, such as occupied or unoccupied, but keep the individual points separate rather than summing the energy use over the category.

5.1.3.1.4 Independent Variables. In many cases, the energy use and/or demand will depend on the change in an independent variable. The most common example is outdoor temperature, which will affect the energy used for heating and cooling the building. The following are examples of other variables that can affect energy use and demand in buildings.

a. Number of meals served in a restaurant.
b. Number of occupants (hotel guests) in a building.
c. Number of items produced in an industrial facility.

These independent variables must conform to the same data requirements as the energy use or demand specific to the two compliance paths in this approach. Furthermore, care should be taken to avoid multicollinearity in regression models. Multicollinearity is when two or more of the independent variables are correlated to each other. For example, because outdoor humidity is strongly correlated to outdoor temperature, most models should not include both of these variables. In the rare circumstances where both variables are required, adjustments should be made to account for the multicollinearity. It is especially important to recognize that the relative importance of each independent variable becomes highly uncertain when multicollinearity is present.

5.1.3.1.4.1 Weather Data. If outdoor temperature is to be used as an independent variable that affects energy use and/or demand, then temperatures can be measured on-site, or publicly available sources can be used. See Section 4.2.6 for more details.

5.1.3.1.4.2 Other Independent Variables. Data representing other independent variables are also required and must be obtained either

a. at frequencies that coincide with the reading dates of the energy use and demand data or
b. on a sufficiently granular time interval to allow for division into billing periods as mentioned above. This generally means a finer time interval than the energy use and/or demand data.

For example, by recording other independent variables on a daily basis, it is a simple matter to calculate the total or average of the variable for the monthly time periods typical of utility energy use and/or demand measurements.

5.1.3.2 Select Baseline and Define Model. A statistical analysis must be conducted on energy use and demand as it relates to weather data and/or one or more other independent variables. The most common technique is to use linear or linear change-point regression to correlate energy use or demand as the dependent variable, with weather data and/or other data for the independent variables.

Several different models are acceptable in developing an energy use baseline, as summarized in the table of sample models (Table 5-1) and as further detailed in Informative Annex D.

Each of these models will contain

a. the form of the linear equation that describes the energy use as a function of the driving variables;
b. the coefficients of each term in the equation; and
c. the value of CV(RMSE), which is related to the uncertainty of point predictions from the model.

The model must meet the CV(RMSE) or uncertainty requirements of Section 4.3.2.1. In most cases, the model will take the form of a multiple-variable linear or change-point linear equation:

$$E = C + B_1V_1 + B_1V_1 + B_1V_1 + \ldots + B_nV_n \tag{5-1}$$

In general, one would like a model selection procedure that is simple to apply and produces consistent, repeatable results. Several procedures have been recommended to select the best regression results. In general, these procedures calculate the results using several alternate models and then select the best model depending on the value of R2 and CV(RMSE). The simplest model can be calculated by statistically regressing average daily utility consumption data against billing period degree-days or average billing period temperatures.

Informative Note: By using the average daily consumption (monthly consumption divided by reading period days), the regression procedure must use a weighted regression technique. This is described in more detail in Annex D.

There are several advantages to using single-variable linear-type models, including

a. the application can be automated and applied to large numbers of buildings where monthly utility billing data and average daily temperatures are available,
b. linear and change-point linear models have physical significance to the actual heat loss/gain mechanisms that govern the energy use in most buildings, and
c. linear models are well understood and should yield results that are reproducible for independent cross checking.

The model should, as a minimum, meet the requirements in Section 4.3.2.1 and/or 4.3.2.2 for net determination bias and for CV(RMSE) if the prescriptive compliance path is chosen.

5.1.3.2.1 Sample Models. Table 5-1 summarizes the various models that can be used. See Figure D-1 for definition of terms.

Frequently, such models are conditional on the values of their variables or on the season. For example, the term in a driving variable, such as degree-days, may apply only for temperatures above or below a balance temperature or during a specified season. Similarly, for the change-point models—models with more than two parameters—the values of one or more coefficients may be valid only for a range in outdoor temperatures and be replaced by a different set of values in an adjacent (warmer or cooler) range of outdoor temperatures. More detailed information regarding each model, including example graphs and the computational form to apply for uncertainty calculations, are included in Annex D.

5.1.3.3 Calculate Savings

5.1.3.3.1 Calculate Energy Savings. Once the appropriate model has been chosen, the following methodology may be used for calculating the energy savings:

a. **Calculate the projected baseline energy use.** This energy use is the amount that would have been used if the changes (e.g., retrofits or modified operations) had not occurred, using the weather and/or other independent variables for the postretrofit billing period (or other measurement period). This is called the projected baseline and is determined by substituting the postretrofit billing period data into the baseline energy model equation. Baseline adjustments may be necessary because, for example, of changes in the facility or its use (see Section 5.1.3.4).
b. **Calculate the energy savings.** Energy savings are calculated according to the following formula:

$$E_{savings} = E_{projected} - E_{current} \pm \text{Adjustments}$$

where $E_{savings}$ represents the energy savings, $E_{projected}$ is the projected baseline energy use, and $E_{current}$ is the current energy use (postretrofit). Adjustments would include changes in conditioned area, schedule or occupancy variation, etc.

5.1.3.3.2 Calculate Demand Savings

a. **Calculate the projected baseline demand.** This demand is the amount that would have been used if the retrofits had not occurred, given the weather and/or other independent variables. This is called the projected baseline demand and is determined by substituting the current billing period data into the baseline demand model.

b. **Calculate the demand savings.** Demand savings are calculated according to the following formula:

$$D_{savings} = D_{projected} - D_{current} \pm \text{Adjustments}$$

where $D_{savings}$ is the demand savings, $D_{projected}$ is the projected baseline demand, $D_{current}$ is the current demand (postretrofit), and Adjustments include similar changes observed as indicated in the previous paragraph.

5.1.3.4 Baseline Adjustments. Frequently, the situation will arise where changes to the structure, operation, or use of the facility occur during the postretrofit period. Whenever possible, the method of calculating the effect of such modifications should be agreed upon before entering into a contract.

The most straightforward and possibly easiest way to account for changes, if possible, is to submeter the effect of any addition to the structure, operation, or use of the facility. For example, the addition of a new wing to a facility should be accompanied by the installation of submeters to monitor energy use and demand in the new wing. Henceforth, the postretrofit data would simply be the total metered amount less the submeter quantities. Only where such submetering is too costly, inappropriate, or impossible should the methods suggested below be used.

A method of estimating the effect of owner modifications on the projected baseline is to include another term to the baseline model equation (Equation 5-1]). Hence, the baseline model equation becomes

$$E = C + B_1V_1 + B_2V_2 + B_3V_3 + A_jV_j + \ldots + B_nV_n \qquad (5\text{-}2)$$

where A_j is the coefficient(s) of the independent variable for the adjustment, and V_j is the independent variable(s) for the adjustment.

In many cases, the baseline adjustment will be dependent on one of the already existing independent variables. That is, V_j may represent outdoor temperature, degree-days, etc. In other cases, the independent variable may be a new term added to the equation. For example, if cooling were added to a building in the postretrofit period, then the independent variable would be cooling degree-days or cooling season temperatures.

The following are general concepts for determining the baseline adjustment:

a. A separate calculation or simulation of the effect of the modification must be performed. This may involve a range of activities, from simple engineering calculations for the more straightforward modifications to detailed computer simulation models. For example, additional lighting would be a base load change that could be easily calculated; whereas an addition to the building might involve an hourly simulation of both the new and the old structures so as to determine the effect of this type of modification.

b. The time dependency of modifications must be accounted for, both for changes that occurred during the baseline period and for those that occurred during the postretrofit period. For example, if equipment is added to a building in the postretrofit period, the projected baseline energy use should not incorporate the modification for periods before the equipment was added.

5.1.3.5 Modeling and Uncertainty Analysis. For each of the two paths in this approach, the baseline model CV(RMSE) will be required to estimate the uncertainty in the model. See Section 4.2.11.3. In addition to this, the performance path must incorporate uncertainty calculations in the savings values as explained in Section 4.2.11.4. More details about uncertainty calculations and various linear regression models are included in Annexes B and D, respectively.

5.2 Retrofit Isolation Approach

5.2.1 Overview. The retrofit isolation approach is intended for retrofits where the end-use capacity, demand, or power level can be measured during the baseline period, and the energy use of the equipment or subsystem can be measured postretrofit for a short-term period or continuously over time. The retrofit isolation approach can involve a continuous measurement of energy use both before and after the retrofit for the specific equipment or energy end use affected by the retrofit or measurements for a limited period of time necessary to determine retrofit savings. Periodic inspections of the equipment may also be warranted. In most cases, energy use is calculated by developing statistically representative models of the energy end-use capacity (e.g., the kilowatts or British thermal units per hour) and use (e.g., the kilowatt-hours or British thermal units).

5.2.1.1 Review of Previous Work. The retrofit isolation approach relies heavily upon the in situ measurement of the energy used by a particular piece of equipment or system. There is a large body of standards related to heating, ventilating, and air-conditioning (HVAC) equipment testing. Various organizations have developed standards for these measurements to facilitate consistency in research and industry applications and for reference within other standards. In particular, there are several standards for laboratory measurement of temperature; pressure; airflow; liquid flow; power; thermal energy; and testing chillers, fans, pumps, motors, boilers, and furnaces. Advice is also available in the literature regarding the in situ measurement of lighting, thermal storage, and HVAC systems (air side). Such standards describe procedures for characterizing the equipment performance, executing the tests, and calculating performance indexes. In addition, there are separate standards for performing the individual measurements. See Section A3, "Laboratory Standards of Measurement," and Section A4, "Equipment Testing Standards."

5.2.2 Criteria for Use of Retrofit Isolation

5.2.2.1 When to Use the Retrofit Isolation Approach. The retrofit isolation approach should be used when the whole-building approach is not appropriate and the savings in question can be determined by measurements taken at a specific equipment item or subsystem. Examples include the following:

a. When the savings to be determined are relatively small. For example, a retrofit may involve replacing oversized pumps (that have to be throttled for proper balancing) with properly sized pumps and energy-efficient motors. In this case, the relative magnitude of the savings is probably too small for the whole-building approach.
b. When there is an unrelated change in the building served by the meter. For example, a major cooling system retrofit may also be accompanied by other unrelated changes (e.g., conversion of a warehouse area into an office area served by an independent HVAC system, installation of more efficient outdoor lighting by the owner).
c. When the total savings from several changes can be determined by taking measurements for a subsystem. For example, the cooling energy savings by retrofitting several air-handling units (AHUs) (economizers, conversion to variable air volume [VAV], etc.) in one wing of a large building could be determined by measurements taken at the chilled-water riser serving the AHUs (this would exclude fan energy savings).
d. When the interactive effects of ECMs do not exist or can be ignored.
e. When, contractually, only the performance of specific equipment or systems is of interest.

5.2.2.2 When not to Use the Retrofit Isolation Approach. There are several possible situations where the use of the retrofit isolation approach is not appropriate. For example, where interactive effects exist and are large, metering cannot be cost effectively established.

5.2.3 Methodology and Calculation. The application of the retrofit isolation approach involves the following steps:

a. Select independent variables and develop the model.
b. Select and document baseline conditions.
c. Select duration and frequency of monitoring for the baseline and postretrofit periods.
d. Project baseline use to postretrofit conditions.
e. Determine savings using the following formula:

$$D_{savings} = D_{projected} - D_{current} \pm \text{Adjustments}$$

The type of load and type of retrofit affects instrumentation and modeling requirements. Loads can be classified according to whether the load is fixed or variable or whether the use is constant or variable. This classification makes a distinction between constant or varying loads (i.e., different rates at which the system uses energy) versus constant or varying uses (i.e., different rates at which the system is used) primarily for purposes of measurement. This results in the following four classifications.

a. Constant load, constant use
b. Constant load, variable use
c. Variable load, constant use
d. Variable load, variable use

The kinds of retrofit isolation are characterized by the kind of load and schedule for the load before the retrofit and the effect that the retrofit has on the load and schedule. The load is either constant or variable, and the schedule is either known or unknown/variable. The retrofit may change the magnitude of the load and/or change it to/from a constant load from/to a variable load. The retrofit may also change the schedule.

The following sections discuss the instrumentation and calculation requirements for the various classifications.

5.2.3.1 Same Load Classification Before and After Retrofit. This section discusses the metering and calculation requirements for situations where the loads have the same classification before and after the retrofit. In these cases, the retrofit may affect the magnitude or the duration of a load.

5.2.3.1.1 Constant Load, Constant Use. Constant load, constant use systems consist of systems where the energy used by the system is constant (i.e., varies by less than 5%) and the use of the system is constant (i.e., varies by less than 5%) through both the baseline and postretrofit periods.

In such systems, the savings from an ECM can be calculated using (a) one-time end-use baseline energy use measurement and one-time end-use postretrofit energy use measurement, (b) one-time end-use baseline energy use measurement and continuous end-use postretrofit energy use measurement, or (c) continuous before/after end-use energy use measurement.

a. **One-time end-use baseline energy use measurement and one-time end-use postretrofit energy use measurement.** Savings are calculated by comparing the difference of the one-time end-use baseline versus postretrofit energy use measurement times the hours of operation in the postretrofit period using the following equation:

$$\text{kWh}_{save} = (\text{kW}_{onetime,baseline} - \text{kW}_{onetime,postretrofit}) \times \text{Hours}_{postretrofit} \quad (5\text{-}3)$$

where kWh_{save} is the electricity savings from the retrofit (in kilowatt-hours), $\text{kW}_{onetime,baseline}$ is the one-time, end-use watt-hour measurements made during the baseline period, $\text{kW}_{onetime,postretrofit}$ is the one-time, end-use watt-hour measurements made during the postretrofit period, and $\text{Hours}_{postretrofit}$ are the hours that the system is in use in the postretrofit period.

b. **One-time end-use baseline energy use measurement and continuous end-use postretrofit energy use measurement.** Savings are calculated by comparing the difference of the one-time end-use baseline times the hours of operation versus continuous postretrofit energy use measurement using the following equation:

$$\text{kWh}_{save} = (\text{kW}_{onetime,baseline}) \times \text{Hours}_{postretrofit} - (\text{kWh}_{continuous,postretrofit}) \quad (5\text{-}4)$$

where kWh_{save} is the electricity savings from the retrofit (in kilowatt-hours), $\text{kW}_{onetime,baseline}$ is the one time, end-use watt-hour measurements made during the baseline period, $\text{kWh}_{continuous,postretrofit}$ is the continuous end-use watt-hour measurements made during the postretrofit period, and $\text{Hours}_{postretrofit}$ are the hours that the system is in use in the postretrofit period.

c. Continuous before/after end-use energy use measurement: savings are calculated by comparing the difference of the continuous end-use baseline versus continuous postretrofit energy use measurement using the following equation:

$$kWh_{save} = (kWh_{continuous,baseline}) - (kWh_{continuous,postretrofit}) \quad (5\text{-}5)$$

where kWh_{save} is the electricity savings from the retrofit (in kilowatt-hours), $kWh_{continuous,baseline}$ is the continuous end-use watt-hour measurements made during the baseline period, $kWh_{continuous,postretrofit}$ is the continuous end-use watt-hour measurements made during the postretrofit period.

5.2.3.1.2 Constant Load, Variable Use. Constant load, variable use systems consist of systems where the energy used by the system is constant (i.e., varies by less than 5%), but the use of the system is variable (i.e., varies by more than 5%) through either the baseline or postretrofit period.

In such systems, the savings from an ECM can be made using (a) one-time end-use baseline energy use measurement and continuous end-use postretrofit energy use measurement or (b) continuous before/after end-use energy use measurement as defined in Section 5.2.3.1.1.

5.2.3.1.3 Variable Load, Constant Use. Variable load, constant use systems consist of systems where the energy used by the system is variable (i.e., varies by more than 5%) but the use of the system is constant (i.e., varies by less than 5%) through either the baseline or postretrofit period.

In such systems, the savings from an ECM can be made using the following.

a. **Continuous before/after end-use energy use measurement as defined in Section 5.2.3.1.1 for those cases where the variation in use is due to unpredictable schedule effects.** Energy use is calculated by comparing the forecast baseline use against the actual postretrofit end-use energy use.
b. **Continuous before/after end-use energy use measurement where a statistical model of the baseline use is created and used to forecast the baseline use into the postretrofit period.** Energy use is calculated by comparing the forecast baseline use against the actual postretrofit end-use energy use as follows:

$$E_{save,i} = E_{baseline,i} - E_{postretrofit,i} \quad (5\text{-}6)$$

where $E_{save,i}$ is the energy savings from the ECM for period i, $E_{baseline,i}$ is the baseline energy use projected into the postretrofit period by multiplying the statistical baseline models' parameters by the influencing variables from the postretrofit period, and $E_{postretrofit,i}$ is the actual postinstallation energy use during period i.

5.2.3.1.4 Variable Load, Variable Use. Variable load, variable use systems consist of systems where the energy used by the system is variable (i.e., varies by more than 5%) and the use of the system is variable (i.e., varies by more than 5%) through either the baseline or postretrofit period.

In such systems, the savings from an ECM can be made using the following:

a. **Continuous before/after end-use energy use measurement as defined in Section 5.2.3.1.1 for those cases where the variation in the use is due to unpredictable schedule effects.** Energy use is calculated by comparing the forecast baseline use against the actual postretrofit end-use energy use.
b. **Continuous before/after end-use energy use measurement where a statistical model of the baseline use is created and used to forecast the baseline use into the postretrofit period.** Energy use is calculated by comparing the forecast baseline use against the actual postretrofit end-use energy use as follows:

$$E_{save,i} = E_{baseline,i} - E_{postretrofit,i} \quad (5\text{-}7)$$

where $E_{save,i}$ is the energy savings from the ECM for period i, $E_{baseline,i}$ is the baseline energy use projected into the postretrofit period by multiplying the statistical baseline model's parameters by the influencing variables from the postretrofit period. $E_{baseline,i}$ must also take into account the varying hour of operation in the postretrofit period. $E_{postretrofit,i}$ is the actual postinstallation energy use during period i.

5.2.3.2 Different Load Classifications Before and After Retrofit. A retrofit may change the magnitude of the load and/or change it to/from a constant load from/to a variable load. The retrofit may also change the schedule. For conversion of a constant load to a varying load, such as photocell dimming controls installed on manually controlled indoor light fixtures, it is necessary to measure preinstallation kilowatts and install a kilowatt-hour meter and run-time meter on the line side of the dimmer. Savings are calculated by multiplying the measured circuit full-load kilowatts by the operating hours from the run-time meter minus the kilowatt-hours measured at the dimmer.

For variable load changed to higher efficiency variable load, such as converting a VAV system using inlet vanes to a variable-speed drive (VSD) on the fan motors, an energy indexing method can be used. This is done by measuring preinstallation kilowatts of the fan at several flow rates to determine the baseline power flow relationship. After installation, measure the variable-speed-drive power and flow rates to determine the new power-flow relationship. By recording the flow rates for a representative postretrofit period, the savings are calculated as a function of flow by the differences in the kilowatts or cubic feet per minute (cfm) values times the hours of flow at representative flow levels.

There are numerous possible combinations of before and after retrofit load classifications. Table 5-2 summarizes the possible combinations and lists the metering requirements for each combination.

a. **Load**
   1. Constant load—it must be known that under no circumstances could the load (kilowatts or kilovolt-amperes) have varied by more than ±5% for that full year of operation or some other percentage considered acceptable to the client. For the client to decide whether the percent variation is sufficiently close to constant, the worst-case effect of this approximation should be expressed to the client in both billing deter-

TABLE 5-2 Retrofit Isolation Applications and Metering Required to Calculate Energy and Demand Savings

Preretrofit	Retrofit Changes	Required Metering	
		Preretrofit	Postretrofit
CL/TS	Load but still CL	One-time load measurement	One-time load measurement
CL/TS	Load to VL	One-time load measurement	Sufficient load measurements to characterize load
CL/TS	Schedule but still TS	One-time load measurement (either pre- or postretrofit)	
CL/TS	Schedule to VS	One-time load measurement (either pre- or postretrofit)	Sufficient measurement of run time
CL/TS	Load but still CL and schedule but still TS	One-time load measurement	One-time load measurement
CL/TS	Load to VL and schedule but still TS	One-time load measurement	Sufficient load measurements to characterize load
CL/TS	Load but still CL and schedule to VS	One-time load measurement	One-time load measurement and sufficient measurement of run time
CL/TS	Load to VL and schedule to VS	One-time load measurement	Sufficient load measurements to characterize load
CL/VS	Load but still CL	One-time load measurement and sufficient measurement of run time	One-time load measurement and sufficient measurement of run time
CL/VS	Load to VL	One-time load measurement and sufficient measurement of run time	Sufficient load measurements to characterize load
CL/VS	Schedule to TS	One-time load measurement (either pre- or postretrofit) and sufficient measurement of run time	
CL/VS	Schedule but still VS	One-time load measurement (either pre- or postretrofit) and sufficient measurement of run time	Sufficient measurement of run time
CL/VS	Load but still CL and schedule to TS	One-time load measurement and sufficient measurement of run time	One-time load measurement
CL/VS	Load to VL and schedule but still TS	One-time load measurement and sufficient measurement of run time	Sufficient load measurements to characterize load
CL/VS	Load but still CL and schedule to VS	One-time load measurement and sufficient measurement of run time	One-time load measurement and sufficient measurement of run time
CL/VS	Load to VL and schedule but still VS	One-time load measurement and sufficient measurement of run time	Sufficient load measurements to characterize load
VL/TS or VS	Load to CL	Sufficient load measurements to characterize load	One-time load measurement and sufficient measurement of run time
VL/TS or VS	Load but still VL	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load
VL/TS or VS	Schedule still or to TS	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load
VL/TS or VS	Schedule to or still VS	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load
VL/TS or VS	Load to CL and schedule still or to TS	Sufficient load measurements to characterize load	One-time load measurement
VL/TS or VS	Load but still VL and schedule still or to TS	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load
VL/TS or VS	Load to CL and schedule to or still VS	Sufficient load measurements to characterize load	One-time load measurement and sufficient measurement of run time
VL/TS or VS	Load but still VL and schedule to or still VS	Sufficient load measurements to characterize load	Sufficient load measurements to characterize load

CL = constant load, TS = (known) on/off time schedule, VL = variable load, and VS = variable (unknown) schedule.

minants (kilowatt-hours and kilovolt-amperes or kilowatts) and in dollars over the year so that the client can make an informed decision. Loads with a predictable use profile that result in constant energy use over a known period (work week, weekend, etc.) can be treated as constant loads.

2. Variable load, including any conditions that are not satisfied or expressed in the previous paragraph.

b. **Schedule**

1. Known on/off time schedule—must be known so the total hours of operation can be calculated based on the scheduled settings without any run-time measurements (e.g., controlled by a time clock or emergency management control system or always on). If the load is constant for either the preretrofit or postretrofit cases, and demand savings are to be calculated, the schedule has to be detailed enough to indicate exactly when the load was on or off in order to determine the coincident demand. If this is not possible, the schedule must be considered variable for that particular time period (pre- or postretrofit).
2. Unknown/variable schedule, including randomly turned on/off; controlled by occupancy sensor, temperature, or on time clock but often manually overridden.

Terms in Table 5-2 are defined as follows:

one-time load measurement: the load has to have been measured at least once, more if necessary to prove that load is a "constant" load (i.e., does not vary by more than ±5%). Load is measured in the units corresponding to the billing determinants (e.g., kilowatts and, if necessary, kilovolt-amperes). If one-time load measurement and sufficient measurement of run time are required, these could be replaced by "sufficient load measurements to characterize the load" as defined below.

sufficient measurement of run time: continuous measurement of run time, unless it can be shown that sufficient data have been measured in that year to predict what the run time would have been for that full year of operation.

sufficient load measurements to characterize the load: continuous measurement of the load, unless it can be shown that sufficient data have been measured in that year to predict what the energy use and coincident demand would have been for that full year of operation. If the preretrofit load is variable, one needs to have sufficient information on what controls the variation in the load before the retrofit to develop a model to predict what the energy use and coincident demand would have been had the retrofit not taken place. This also would require sufficient information for the postretrofit period to apply the model for that time period.

5.2.3.3 Data Characteristics. As outlined in Table 5-2, the data requirements sufficient to characterize loads will vary depending on the application. The required data can range from single measurements (or a few measurements to establish that load and use are constant) to continuous measurements (subhourly/hourly) over the full range of independent variables to sufficiently characterize loads and operating periods.

The whole-building approach often relies on utility-grade meters to measure energy use and demand. When utility meters are used for the energy and demand measurements, measurement uncertainty can be ignored. Retrofit isolation measurement protocols can use a wide range of field-installed measuring instruments, and the uncertainty of the measured data can vary over a wide range. The energy use and demand of a lighting circuit or a chiller can be measured with little uncertainty. In contrast, the measurement uncertainty of the charging rate of a thermal storage system can be significant.

The retrofit isolation approach can also result in large amounts of subhourly/hourly data. While this could improve the accuracy of the baseline model, care must be taken to avoid the development of an unnecessarily complex model where simpler models may be adequate.

5.2.4 Modeling and Uncertainty Analysis. A statistical model of the energy use baseline must be developed to relate the energy use/demand in terms of one or more independent variables. The most common independent variable is outdoor temperature. Annex D discusses regression techniques and describes several models that can be developed. Section 5.1.3.2 discusses several models that are applicable for the whole-building approach. In general, these models are also valid for the retrofit isolation approach. In some cases, other types of regression models may be required. For example, the energy use of a variable flow fan or pump system more typically follows a polynomial relationship with flow (or ambient temperature when ambient temperature is used as a proxy for flow) rather than a change-point linear relationship.

Depending on the chosen model and the measurement techniques, data may be available in the form of a few readings, discrete readings at long intervals of time, or continuous data (short-time-interval data). The simplest model that meets the desired objectives should be used. As discussed in Annex D, the number of independent variables can be reduced by examining the physical parameters and including only those that are independent and have physical causality. A clear benefit may be had by separating the data into different regimes of behavior (e.g., heating/cooling season, weekday/weekend). Even where subhourly/hourly data are available, weekly or daily analysis with separate weekday/weekend models may provide the best results for many buildings. Hourly analysis can provide a greater range of the independent variables in a given monitoring period and hence may be preferred when baseline periods are relatively short. Hourly analysis may also be needed for some buildings with unusual energy use characteristics such as strong on/off effects.

Section 4 gives the compliance requirements for the retrofit isolation approach. These include the requirement to perform an uncertainty analysis showing a net determination bias of less than 0.005% and to report the maximum level of uncertainty, which must be less than 50% of the reported savings with 68% confidence. The contracting parties may choose to require a lower level of uncertainty at a higher confidence level.

The overall uncertainty for the retrofit isolation approach will be the sum of

a. modeling uncertainty, and
b. measurement uncertainty.

Because the modeling involves the characterization of specific loads in terms of independent variables, the modeling uncertainty may be low in comparison to the whole-building approach. Depending on the specific measurements being taken, the measurement uncertainty can be significantly higher. The fractional uncertainty is expressed by Equation 5-8:

$$\frac{\Delta\sum E_{savings}}{\sum E_{savings}} = t \times \frac{\sqrt{\Delta(\sum E_{pre})^2 + \Delta(m\bar{E})^2}}{m\bar{E}F} \tag{5-8}$$

This equation can be simplified for situations where the measurement uncertainty is low, as would be the case for lighting or chiller use and demand measurements.

Annex B contains a general discussion on uncertainty and its determination. It presents examples of simplified equations for different situations where measurement uncertainty can be ignored. Example equations are provided for the following (equation numbers refer to numbers in Annex B).

a. Energy uses independent of weather and other variables (e.g., lighting retrofits)—Equation B-10.
b. Monthly energy use data varying in response to known independent variables (e.g., weather)—Equation B-13.
c. Daily or hourly energy use data varying in response to known independent variables—Equation B-15.

See Normative Annex E for detailed examples of retrofit isolation approach techniques by system.

5.3 Whole-Building Calibrated Simulation Approach (Calibrated Simulation)

5.3.1 Overview. This section refers to computer-based simulation of whole-building energy use behavior. This technique is particularly suited to accounting for multiple energy end uses, especially where interactions occur between measures. Additionally, this technique is useful for situations where baseline shifts may be encountered and where future energy impacts may need to be accessed.

5.3.1.1 Hourly Simulation Programs. Of the hourly simulation programs available, there is one category that is not suitable for the techniques described in this section: programs that use average weather days. Unlike the major hourly simulation programs which accept hourly weather files containing data for 8760 hours, these other programs contain an average weather day and a peak weather day for each month. The average weather day programs simulate building energy processes for these few average days and extrapolate the results to represent annual energy performance. Average weather day programs cannot accept weather data from specific time periods and so are not appropriate for calibration purposes.

5.3.1.2 Compliance. Use of this technique should conform to all requirements outlined in Section 5.3, "Compliance Requirements."

5.3.2 Criteria for Calibrated Simulation

5.3.2.1 When to Use Calibrated Simulation. Calibrated simulation is an appropriate method to consider when one or more of the following conditions are present.

a. **Either preretrofit or postretrofit whole-building metered energy data are not available.** The building may either be a new building or there may be new equipment to meter whole-building energy use and demand that was not installed until after the retrofit.
b. **Savings cannot be easily determined using before/after measurements.** For example, savings achieved by modifying HVAC equipment are strongly influenced by weather. Simply taking before and after measurements would not necessarily yield an accurate representation of savings. By using calibrated simulation, savings can be normalized to represent the savings that would have been achieved over the course of a specific period to match any measured data, or normalized to an average or typical weather year. Typical weather year files are available for such analyses.
c. **Measures interact with other building systems, it is desired to account for those interactions, and retrofit isolation methods are not readily feasible.** When lighting systems are improved in air-conditioned buildings, for example, typically the lighting systems emit lower levels of heat to be removed by the air-conditioning system. During the heating season however, that saved lighting heat adds burden to the building heating system. Building simulation is capable of accounting for these interactive energy flows if the HVAC systems are appropriately modeled.
d. **Only whole-building energy use data are available, but savings from individual retrofits are desired.** When building simulations are calibrated to whole-building data, information regarding energy flows among individual retrofits and other building changes can be discerned by the simulation model.
e. **Baseline adjustment needs.** In situations where significant changes in the facility's energy use and demand occur over time, and these changes are not related to the ECMs, adjustments to account for these changes will be needed. Changes of this nature, especially those involving multiple factors, can readily be addressed using simulation. Examples might include cases where weather patterns, changes in hours of operation, and the addition of new uses simultaneously impact the facility.

Calibrated simulation should also be considered where a number of the above conditions exist that can all be addressed through the use of simulation. Finally, calibrated simulation is quite useful where future work in the facility would benefit from the availability of a model to explore potential changes as well as adjust for their impacts.

5.3.2.2 When not to Use Calibrated Simulation. The calibrated simulation method is not recommended when any of the following five conditions are evident.

a. **Measures that can be analyzed without building simulation.** The use of calibrated simulation is *not* recommended if less expensive methods produce similar results.

For example, end uses that do not impact HVAC energy use may be much more economically analyzed using a combination of spot measurements, hand calculations, or computer spreadsheets. Measures that fall into this category include outdoor lighting retrofits, some motor replacements, elevator machinery improvements, and domestic water heater replacements.

b. **Buildings that cannot be readily simulated.** Most building types can be simulated. However, buildings that may not be easily simulated with commonly available programs include (1) buildings with large atriums where internal temperature stratification is significant and thermal convection is an important feature of the heating or cooling system, (2) buildings that are underground, (3) buildings with unusual exterior shapes or extremely complex shading configurations, and (4) buildings with continual and/or poorly defined load changes other than energy conserving measures.
c. **HVAC systems that cannot be simulated.** Most commonly available HVAC systems can be simulated with today's public-domain simulation programs. However, certain control options that are in use in existing buildings are extremely difficult to reproduce with a simulation program, especially local controls options in large buildings that have a large number of HVAC systems, because many simulation programs are limited in the number of zones they can simulate.
d. **Retrofits that cannot be simulated.** Examples include savings from the addition of radiant barriers in an attic that contains ductwork, or changes to certain HVAC control settings that are outside of the allowable settings in many of today's simulation programs or require expensive modifications to an existing code.
e. **Project resources are not sufficient to support calibrated simulation.** Before committing to the calibrated simulation method, ensure that a model of the building can be created, calibrated, and documented within the project's time frame and budget constraints.

5.3.3 Methodology and Calculation Steps. When using calibrated simulation to estimate the savings associated with ECMs, follow the procedure summarized below and detailed in Sections 5.3.3.3.1 through 5.3.3.3.13.

a. **Produce a calibrated simulation plan.** Before a calibrated simulation analysis may begin, several questions must be answered. Which software package will be applied? Will models be calibrated to monthly or hourly measured data, or both? What are to be the tolerances for the statistical indexes? The answers to these questions have to be documented in a simulation plan. (See Section 5.3.3.1.)
b. **Collect data.** Data may be collected from the building during the baseline period, the retrofit period, or both. Data collected during this step include dimensions and properties of building surfaces; monthly and possibly hourly whole-building utility data; nameplate data from HVAC and other building system components; operating schedules; spot-measurements of selected HVAC and other building system components, including interior temperature and humidity data, airflow, etc.; and, when available, the weather data coincident to the spot measurements and the utility data. (See Section 5.3.3.2.)
c. **Input data into simulation software and run model.** Over the course of this step, the data collected in the previous step are processed to produce a simulation-input file. Modelers are advised to take care with zoning, schedules, HVAC systems, model debugging (searching for and eliminating any malfunctioning or erroneous code), thermal mass, and weather data. Modelers should compare simulated and actual interior conditions. (See Section 5.3.3.3.)
d. **Compare simulation model output to measured data.** The approach for this comparison varies depending on the resolution of the measured data. At a minimum, the energy flows projected by the simulation model are compared to monthly utility bills and spot measurements. At best, the two data sets are compared on an hourly basis. Both graphical and statistical means may be used to make this comparison. (See Section 5.3.3.3.9.)
e. **Refine model until an acceptable calibration is achieved.** Typically, the initial comparison does not yield a match within the desired tolerance. In such case, the modeler studies the anomalies between the two data sets and makes logical changes to the model to better match the measured data. The user should calibrate to both pre- and postretrofit data wherever possible and should only calibrate to postretrofit data alone when both data sets are absolutely unavailable. While the graphical methods are useful to assist in this process, the ultimate determination of acceptable calibration will be the statistical method. (See Section 5.3.3.3.12 and Annex C.)
f. **Produce baseline and postretrofit models.** The baseline model represents the building as it would have existed in the absence of the ECMs. The retrofit model represents the building after the ECMs are installed. How these models are developed from the calibrated model depends on whether a simulation model was calibrated to data collected before the conservation measures were installed, after the conservation measures were installed, or at both times. Furthermore, the only differences between the baseline and postretrofit models must be limited to the measures only. All other factors, including weather and occupancy, must be uniform between the two models unless a specific difference has been observed that must be accounted for. (See Section 5.3.3.3.9 and Annex C.)
g. **Estimate savings.** Savings are determined by calculating the difference in energy flows and intensities of the baseline and postretrofit models using the appropriate weather file. (See Annex C.)
h. **Report on observations and savings.** Savings estimates and observations are documented in a reviewable format. Additionally, sufficient model development and calibration documentation should be provided to allow for accurate recreation of the baseline and postretrofit models by informed parties, including input and weather files. (See Annex C.)

The following sections of this guideline describe each of these steps in detail.

5.3.3.1 Produce a Calibrated Simulation Plan. Prepare a simulation plan that addresses the following items:

a. **The baseline scenario.** The baseline scenario represents the building as it would exist in the absence of any ECMs (refer to measurement and verification plans in Section 4.3). For example, if the building is under construction, the baseline scenario represents the building as it would have been built without any ECMs. If the building is an existing building, the baseline is usually the building as it existed before the ECMs. In the event changes are planned for the building that would have been implemented whether or not any conservation measures were undertaken, the baseline scenario represents the existing building with those planned changes.
b. **The postretrofit scenario.** The postretrofit scenario represents the building after the ECMs are implemented. Both the measures and their energy conservation characteristics should be documented in the plan.
c. **The simulation software package.** Full 8760-hour simulation programs should be used (see Section 4.3.2.4). Document in the plan the name and version of the simulation software package that will be used. The input file and weather file should also be part of the documentation.
d. **Calibration to monthly or hourly data.** Monthly data are readily available, and calibrations to such data are less time consuming than calibrations to hourly data. Calibrations to hourly data are more accurate but also more difficult and expensive. In either case, at least 12 continuous months of whole-building energy use and demand data in at least 12 valid meter readings are required, along with hourly weather data corresponding to the same period as the utility data. Document in the plan the planned interval of the measured data (e.g., monthly or hourly), the source of weather data, and any missing data.
e. **Tolerances for statistical calibration indexes.** Annex C describes graphical calibration parameters as well as two main statistical calibration indexes (mean bias error [MBE] and CV[RMSE]). Document the acceptable limits for these indexes on a monthly and annual basis.
f. **Spot and short-term measurements of building system characteristics.** Even though a reasonable match is developed between the modeled and measured energy flows, it is not certain that the model is a good representation of the actual building. There remains the possibility that there are offsetting internal errors in the model. By taking spot and short-term measurements of building system characteristics, the likelihood that significant offsetting errors exist can be reduced, but these measurements add cost to the calibrated simulation effort. Such measurements are described in the subsection on conducting spot and short-term measurements below. Describe in the simulation plan guidelines for selecting and implementing spot and short-term measurements.

5.3.3.2 Collect Data. Over the course of this step, the data required to support the remainder of the analysis are collected. These data may be collected before the conservation measures are installed, after the conservation measures are installed, or at both times. The methods to be followed are described in the following paragraphs.

5.3.3.2.1 Obtain Building Plans. As-built plans are preferable, but collect whatever plans are available. When onsite, confirm that building geometry and construction materials represented in the plans are accurate. Photograph the building exterior and its surroundings to document architectural and shading features such as trees, type of tree, etc. Make note of the building's north-south orientation.

5.3.3.2.2 Collect and Review Utility Data

a. At a minimum, collect utility bills spanning at least 1 year and comprising at least 12 valid meter readings, including: monthly electricity use, peak electric demand for the month, and monthly fuel use for heating (e.g., natural gas, fuel oil). If electric demand data are available, identify the type of demand data (e.g., sliding window or fixed window) and the integration period (e.g., 15, 30, or 60 minute data) as there may be significant differences between the actual electric peak demand and the hourly peak demand reported by the simulation program. Collect bills from submeters if they are installed, and obtain information regarding the dates meter readings were taken.
b. Obtain hourly (or smaller interval data) electric meter data if available from the utility.
c. If hourly data are not available from the utility but are required to calibrate the simulation model, install equipment to collect such data. Hourly data metering capabilities may be integrated into the utility meter, built into the electrical switchgear, or provided by add-on watt transducers. Most electric meters that collect interval data may be interrogated by modem, linked to an energy management system, or added onto an electronic network. Sometimes this service is available from the electric utility for a small charge.

5.3.3.2.3 Prepare for Data Collection as Defined in the Simulation Plan. Develop data collection forms to document and archive use, thermostat settings, occupancy, and operational data as defined in the simulation plan.

5.3.3.2.4 Conduct On-Site Surveys. Visit the site and collect data by making visual observations of in situ building system components. The specific data to collect vary widely depending upon the desired tolerances of the calibration and the individual building characteristics, so they cannot simply be described here. Instead, the determination of which data to collect is left to the modeler and any agreements between buyer and seller. Data that may be collected during a site survey include the following:

a. **Lighting systems.** Fixture counts, fixture types, nameplate data from lamps and ballasts; 24-hour weekday, weekend, and holiday schedule of indoor-outdoor lighting use; characteristics of fixtures for estimating radiative and convective heat flows; thermal zone assignments; illuminance measurements; and diversity of operation.

b. **Plug loads.** Counts of and nameplate data from plug-in devices, 24-hour weekday and weekend use schedules, and diversity of operation.

c. **HVAC systems.** Quantities, capacities, and operating characteristics of primary equipment (e.g., chillers and boilers); part-load performance curves for primary equipment (efficiency vs. load); quantities and characteristics of secondary equipment (e.g., AHUs, terminal boxes); fan sizes and types (e.g., forward curved, backward curved); motor sizes and efficiencies; determination whether motors are located in conditioned space; design flow rates and static pressures; types of duct systems (e.g., dual duct constant volume and VAV); system zoning; interior zone temperature setpoints; control setpoints and schedules (e.g., cold deck temperature, hot deck temperature, and economizer setpoint); airflow control types (discharge damper, inlet vanes, VSD); coil characteristics, including sensible heating factor; condenser characteristics and controls; temperatures of the air leaving the heating and cooling coils; characteristics of supply and return ducting; and functionality of economizers and other major components.

d. **Building envelope and thermal mass.** Dimensions and thermal resistance of external and interzonal surfaces, orientation of external surfaces, thermal mass characteristics of materials of construction, dimensions, visible and infrared transmittance of external transparent surfaces (windows, doors, and skylights), spacing of framing materials, and shading from nearby objects.

e. **Building occupants.** Population counts; weekday, weekend, and holiday schedules; activity levels; and assignments to thermal zones.

f. **Other major energy using loads.** Identification of special loads (industrial processes, air compressors, water heaters, vertical transportation), energy use, schedules of operation.

5.3.3.2.5 Interview Operators and Occupants. Confirm schedules of occupancy and operation. Identify any operating problems/special conditions that must be replicated by the calibrated model.

5.3.3.2.6 Conduct Spot and Short-Term Measurements. These measurements include spot measurements that are taken for a moment, usually using handheld instruments, or short-term measurements for which instruments with data logging capabilities are set up and left in place to collect data for longer periods of time. Spot measurements are less expensive, but short-term measurements provide valuable information regarding schedules of use. The appropriate measurements to make, as well as their duration, vary widely depending on the desired accuracy of the calibration and the individual building characteristics and so cannot simply be described here. Instead, the determination of which measurements to take is left to the modeler and any agreements between buyer and seller. Such in situ measurements may include the following:

a. **Lighting systems.** Operating schedules, fixture power, and lighting levels.

b. **Plug loads.** Operating schedules and electric power.

c. **HVAC systems.** Space temperatures and humidities, carbon dioxide levels, air and water flows, static pressures and temperatures, motor power, and duct leakage.

d. **Building ventilation and infiltration.** Airflows through outside air ducts and building pressurization or tracer gas tests of infiltration rates (if infiltration is expected to be an important issue).

e. **Other major energy using loads.** Energy use and operating schedules. If short-term metered data are not available, the building should be visited when it is unoccupied to verify what building systems are operating.

5.3.3.2.7 Collect Weather Data. Two different kinds of weather data may be required to estimate savings using calibrated simulation. At a minimum, the modeler collects hourly weather data that correspond to the same time period as the energy use data to which the model will be calibrated. If the savings are to be normalized to represent a typical year, the modeler also collects typical year weather data using a site that is near to the facility (usually an airport).

Weather data that correspond to a specific time period may be collected either from an on-site station or from the National Climatic Data Center (NCDC), which maintains records from hundreds of sites in the United States and around the world. Although NCDC data are available in most of the formats accepted by simulation programs, most specific time period data sets do not include solar radiation data. Most hourly simulation programs, however, include modules that can synthesize solar radiation from the cloudiness values in the NCDC data. NCDC data can also contain significant amounts of missing information that will need to be filled in by the user.

If average hourly weather data are to be used to project typical year savings (as opposed to a specific year's), it can be obtained from ASHRAE (weather year for energy calculations [WYEC2]), NCDC (typical meteorological year [TMY] data), and the National Renewable Energy Laboratory (TMY2,TMY3). Test reference year (TRY) weather data files, which are available from NCDC, are not recommended for this purpose (Huang and Crawley 1996). While it is possible for users to generate their own formatted 8760 weather input files containing actual weather conditions representative of a building's location, a number of companies now provide software as a service (SaaS) models to generate worldwide actual meteorological year weather files as a fee for service. These services use various technical approaches that offer differing capabilities, and consumers of these services are encouraged to research their applicability for use before purchasing.

Although some modelers have reported using average or typical year weather data for model calibration, this approach is not recommended, as the comparison utility data are probably related to actual weather from the time in question. Several studies have shown that using an average year weather file in a simulation can introduce error into the simulation that is as large as some of the differences that are being sought in the analysis (Haberl et al. 1995; Huang and Crawley 1996).

5.3.3.3 Input Data into Simulation Software and Run Model. The best guide for entering data into a model is the manual that accompanies the simulation software package.

When preparing the simulation input data and performing preliminary runs, special attention should be paid to the issues discussed below.

5.3.3.3.1 Architectural Rendering. Many software programs have the ability to allow for architectural rendering or viewing of building simulation input files (Degelman 1995; Hirsch et al. 1995; Huang and Associates 1996). These software features can be used to help ensure that building input parameters are consistent with the actual facility. However, the user is cautioned to avoid overspecifying those architectural details that do not have a significant impact on the building energy use.

5.3.3.3.2 Estimating Plug Loads Based on Nameplate Ratings. Although measurements are preferable, plug loads may be estimated by taking inventory and summing connected loads. When doing so, do not enter the nameplate power into the simulation software. On average, most plug-load devices operate at an average power much lower than that of the nameplate rating. To estimate actual operating power, nameplate power is multiplied by a use factor. A common rule of thumb for the use factor is 0.3. Note that there are a number of publications reporting actual loads for computers and office equipment. Additional information about measured diversity factors, including a toolkit for entering diversity factors into several public domain simulation packages, can be found in Abushakun et al. (2004).

5.3.3.3.3 Converting Lighting and Receptacle Loads into Simulation Program Inputs. Because some programs also require information about the heat gain characteristic of each lighting fixture, attention should be paid to this input. Usually, determining the heat gain multiplier requires that the modeler identify the extent to which the lighting fixture is in thermal communication with unconditioned spaces and return air plenums.

5.3.3.3.4 HVAC System Zoning. The most important aspect to duplicate when zoning the simulated HVAC system is the on/off characteristic of a zone. Testing the zoning assumptions in a simulation program usually requires simulating the building with actual hourly weather data and taking hourly recordings of interior zone temperatures to compare against the simulated temperatures.

In large internal-load-dominated buildings, proper zoning can often be accomplished with as few as 15 thermodynamic zones for a large, multistoried office building, including five zones on the uppermost floor, five zones on the ground floor, and five zones for the intervening floors.

5.3.3.3.5 HVAC System Simulation. In many cases, especially in simulation programs that use predetermined systems, it may not be possible to exactly simulate a building's HVAC system. In such cases, the modeler is cautioned to ensure that the operating conditions of the HVAC system being modeled are being met by the simulation program, even though the schematic diagram may differ from the system being modeled.

5.3.3.3.6 Estimating Infiltration Rates. Infiltration rates are difficult to measure and may be treated as an unknown that is iteratively solved with the simulation program once the other major parameters are determined. This approach is only recommended as a last resort. To solve for the infiltration rate and/or the ventilation rate iteratively, conduct a series of simulation runs such that only the infiltration and/or ventilation rates are changed from one-tenth to as much as ten times the expected rates. Next, compare the simulation outputs produced to the measured building data as discussed below. In addition, supporting evidence should be used to justify the final choice of variables.

5.3.3.3.7 Minimizing Default Values. Check and thoroughly understand all default input variables in the simulation program, as many of the default values have little resemblance to the actual building being simulated. The fewer the number of default values used, the more representative the simulation will be—but only if the changes are well reasoned. This also includes inspection of the default performance curves of the various systems and plant equipment, because such curves can significantly impact the results of the simulation. Any program default values that are altered, however, should be well documented.

5.3.3.3.8 Debugging Models. The number of simulation iterations in the later steps can be minimized by thoroughly examining the simulation inputs and outputs (to identify and eliminate input errors) or debugging. Kaplan et al. (1992) recommend the following checks as a minimum.

a. **Simulation input checks.** Building orientation, zoning, external surface characteristics (orientation, area, zone assignment, thermal resistance, shading coefficient), lighting and plug load power densities, operating schedules, HVAC system characteristics (cfm, input power, zones served, minimum outside percentages, system types, heating and cooling capacities, fan schedules), plant equipment characteristics (type, capacities, rated efficiency, part load efficiencies).
b. **Simulation output checks**
    1. HVAC systems satisfy heating and cooling loads.
    2. Lighting and equipment schedules are appropriate.
    3. Fan schedules are appropriate.
    4. Ventilation air loads are appropriate.
    5. HVAC plant efficiencies are appropriate.

5.3.3.3.9 Compare Simulation Model Outputs to Measured Data. After entering data into the simulation model and debugging the model, compare the energy flows projected by the model to the measured utility data. It is also important to ascertain that interior conditions and system settings in the simulation model match those in the building being simulated. This guideline covers comparison of two different types of measured data: monthly utility bills and hourly data.

5.3.3.3.10 Compare to Monthly Utility Bills and Spot Measurements. Section 5.3.3.2.2 discusses the collection of monthly utility bills. Where available, not only electric bills should be used for comparison, but also any other heating fuel bills, such as natural gas or fuel oil, as well as spot measurements of key components and systems. This approach is not as reliable as comparing to hourly data, as monthly utility bills present so many fewer data points for calibration. Because of this, comparing to monthly utility bills is only acceptable when hourly whole-building data are not available and cannot be collected.

Of the techniques described in this guideline, comparing energy use projected by simulation to monthly utility bills and spot measurements, is relatively uncomplicated. After the model developed in Section 5.3.3 is run using weather data that correspond to the billing periods, the monthly simulated energy use, including electric energy, electric demand, and any other fuels, is subtracted from the quantity listed in the utility bills and the difference is divided by the bill amount. This calculation is repeated for each month and then for the entire year. It is important that the simulated quantities be summed over the exact same days that the meter was read for the bills. Acceptable tolerances for this comparison range from ±10% for MBE to ±30% for CV(RMSE) of the bill's represented energy use and/or demand quantity when using hourly data or 5% MBE and 15% CV(RMSE) when using monthly data (see Annex C).

In cases where demand savings are important, refer to Section 5.1.3.3.2.

5.3.3.3.11 Compare to Hourly Measured Data. When comparing simulation output to hourly measured data, two different techniques are used: graphical and statistical. There are a variety of graphical comparison formats, but in general, computer software is used to generate a graphic image from both the measured data and the simulation output data, and these two images are overlaid. Occasionally, the difference between these two data sets is used as the basis for a graphical image. Statistical methods use two different indexes to determine whether the differences between the two data sets are within an acceptable tolerance.

It is recommended that both graphical and statistical techniques be used when comparing to hourly measured data. The statistical indexes provide two numbers, which allows the modeler and any other interested parties to judge how closely the simulation output matches the measured data. The graphical techniques provide information regarding the time periods during which the two data sets diverge. By interpreting the graphics, modelers may infer what inputs may be responsible for such differences. In any event, users must report their statistical results and base their model tuning success on this technique.

5.3.3.3.12 Model Calibration. The comparison process is an essential first step in model calibration. Calibration is accomplished by an iterative process of refining and adjusting the model until an acceptable fit to actual data is achieved (see Annex C).

5.3.3.3.13 Hourly Data Comparison and Calibration Techniques. Hourly data comparisons are difficult to analyze using tabulated methods. Such comparisons are best analyzed graphically and statistically. A variety of methods are used.

6. INSTRUMENTATION

6.1 Introduction. This section discusses the selection and application of instruments used in measuring the information required to evaluate consumption and demand savings. It includes discussions of data acquisition and sensor types, application methods (survey, temporary, and permanent installation), calibration complexity, uncertainty analysis, data validation methods, and measurement system maintenance. Instrument selection is dependent on clear definition of project requirements, cost constraints, technology options, and uncertainty requirements.

6.2 Measurement Techniques. Measurement techniques will vary depending on the requirements of the specific measurement application. Such requirements include measurement budget, limits of uncertainty in the measured result, and the time required to gather the necessary data.

6.2.1 Measurement Duration. Measurements may be classified into three categories: spot measurements, short-term measurements, and long-term measurements (Table 6-1).

a. **Spot measurements.** Spot measurements typically are made with portable survey or handheld instruments over a brief period of time (e.g., <1 hour per point or test condition). Instruments are not left in place, and the data gathered are only a small sample of actual conditions. For constant loaded equipment that has less than a 5% variation in load, multiple spot measurements can be made or one day to two weeks of data logging can be used to analyze the load. Spot measurements are typically used to determine existing conditions or to verify other measured data. In the retrofit isolation approach, spot measurements may also be made to quantify constantly loaded equipment. Example instruments include clamp-on power meters and handheld temperature indicators.
b. **Short-term measurements.** Short-term measurements are typically made with temporarily installed instruments over a short-term test period, typically for one week to six months. These measurements are often made by installation of portable, modular temperature, flow, or power devices that can be applied to existing mechanical-electrical-plumbing systems without disruption of operations.
c. **Long-term measurements.** Long-term measurements, which are six months or longer in duration, typically use permanently installed instruments selected for data reliability and safety. Data acquisition will often be by remote data access and require secure power sources.

6.2.2 Measurement Methods. Measurement techniques should be aligned to the process data required and selected to offer the least complexity, sufficient accuracy and durability, and minimum expense for the required uncertainty in the result. Processes that are static or steady-state-type systems (i.e., those that provide a narrow range of conditions or vary little with time) may only require spot or short-term measurements be taken. Dynamic or non-steady-state energy processes (i.e., those that provide a wide range of conditions or vary significantly with time) are more complicated to evaluate and may require long-term measurement, process calculations, and an extended evaluation period. This is especially true for systems that provide a wide range of rapid and unpredictable changes in conditions.

To reduce the impact of equipment failures, the measurement plan should identify critical points and develop fail-safe or backup plans to ensure critical data are collected. Such backup plans may include redundant sensors measuring the same point, establishing online systems for frequent checking of data, and frequent downloads of collected data. Critical data include cases where parameters directly relate to the calculation of energy flows and where the associated energy use is a significant component of the total savings. See Informative Annex A for detailed discussion of measurement approaches for various measurement types.

6.3 Uncertainty Analysis. Any statement of measured savings includes a degree of uncertainty, regardless of whether or not it is provided. The uncertainty in savings can be attributed to assumption errors; measurement errors in both the independent and dependent variables; random and systematic measurement errors; and errors in the regression model, which include predictive and normalization errors.

Though measurement errors are relatively well known, and the complex methodology for estimating their effect is adequately covered in classical engineering textbooks, measurement errors are often not well understood by the practitio-

TABLE 6-1 Measurement Types

Measurement Type	Description	Typical Loads	Measurement Instrument Type
Spot measurement	Instantaneous measurement (for example, the power used by a continuously operated constant-speed fan)	Static or steady state systems; limited variability and predictable schedule or trend data available	Handheld measuring instruments
Short-term measurement	One week to six months (for example, the on/off status of a fan)	Loads and schedules with high variability that fluctuate in known patterns over designated time periods	Building control system, logging equipment, energy metering, interval utility data
Long-term measurement	Six months to life of building (for example, the electric energy consumption of an HVAC system or building)	Loads and schedules with high variability that fluctuate in known patterns over longer time periods or that have no consistent pattern	Building control system, logging equipment, energy metering, interval utility data; usually permanent installations

ner, who may simply use manufacturers' published data that are not suitable for the applied context or are not provided in a consistent manner. A proper uncertainty analysis evaluating the instrumentation under consideration and expected data to be gathered should be performed before testing to refine the measurement system to the level of uncertainty desired. After the test, the uncertainty analysis should be reevaluated using the actual data gathered during the test. See Informative Annex B for a detailed discussion of uncertainty.

Measurements made in the field are especially subject to potential errors. In contrast to measurements made under the controlled conditions of a laboratory setting, field measurements are typically made under less predictable circumstances and with less accurate and less expensive instruments. Field measurements are vulnerable to errors arising from variable measurement conditions (i.e., the method used may not best represent all operating conditions), from limited instrument field calibration (i.e., field calibration is typically more complex and expensive), from installation errors (i.e., spatial errors in temperature and flow due to sensor location), from simplified data sampling and archiving methods, and from limitations in the ability to adjust instruments in the field. With appropriate selection, analysis, pretesting, and posttesting of data, the measurement practitioner should minimize many of these sources of error and ensure cost-benefit to the measurement system design.

6.4 Instrumentation Plan. A well-thought-out instrumentation plan can aid in selection of the most appropriate instruments for the particular application, optimal location of instruments, and development of appropriate maintenance and calibration schedules to ensure optimal operation over the lifetime of the instruments (and, coincidentally, to maximize useful life). The best place to start when developing an instrumentation plan is to develop the final analysis products to be produced. From these, determine the data to be measured. Finally select appropriate instrumentation.

An appropriate measurement plan should be developed before selecting and placing instruments. The plan should first consider the variables required for performance verification, the means for determining them, and the uncertainty associated with their value. Measured quantities such as temperature or flow are often not the final values required for comparison to assess equipment or system performance but are combined as necessary with other measurements, assumed constants, and formulas to verify performance.

A measurement plan starts with total savings and required uncertainty of the savings. It then works back through calculations to the required measurements and assumed variables. The plan includes the following:

a. Measurement point name.
b. Instrument description, installation method, location, suitable operating conditions, expected range of values, and instrument uncertainty estimates.
c. Instrument calibration plan, as required, including discussion of factory and/or field methods and calibration frequency.
d. Minimum level of data performance and alternate methods of obtaining the required information and allowable methods of error remediation.
e. Applicable maintenance requirements.

The quality of any measurement depends on the effect of the measurement location, the capability of the measurement sensor and the data recording instrument, and the sampling method used. Where preexisting equipment is available, it may be considered for use. To be properly considered, preexisting instrument systems must first meet the data integrity requirements of their new application, including accuracy and data acquisition requirements. Added costs for calibration and maintenance may make the use of preexisting measurement points prohibitive; however, in such cases, the points can often offer qualitative information for system and pretest data checks.

6.4.1 Selection Criteria

6.4.1.1 Instrumentation. Sensor selection depends on the measurement duration (e.g., spot, short-term, or long-term), quality required (i.e., accuracy, precision, drift, rate of response), quantity of measurement points, installation restrictions, signal output requirements (or signal conditioning), measurement range, turndown, and capabilities of the intended data recording device and the resources available to purchase and/or support it. Typical measurements include runtime; electric demand and use; temperature; fluid and airflow; potable water flow; thermal energy; psychometric properties such as relative humidity and wet-bulb temperature; pressure; and ambient weather conditions such as wind speed, wind direction, and horizontal insulation.

6.4.1.2 Data Acquisition Systems. Whether handheld or component systems are planned, data acquisition is an important criterion in selecting instruments. The data acquisition system (DAS) is selected to ensure accuracy in reading electronic inputs, allow conversions between voltage and current into engineering units, and provide sufficient storage to hold all collected data between data downloads. The following are some factors to consider when selecting a DAS:

a. **Measurement quality.** Manufacturer specifications on DASs should include descriptions of accuracy, precision, drift, and rate of response.
b. **Quantity and type of inputs.** Simple loggers may be limited to only temperature or power measurements; other more robust equipment offers various current, voltage, and pulse options that can accommodate temperature, pressure, flow, and power. All systems will have input or grounding issues to consider and may also require additional signal conditioning where instrument inputs cannot be accepted without modification.
c. **Scan rate.** The DAS should be capable of scanning inputs at least ten times more frequently than the period of the process being measured. This is especially true with dynamic processes. For example, a packaged alternating-current (AC) unit compressor may cycle on and off every 20 minutes. To minimize error in runtime measurements, the scan rate of the DAS sampling the compressor on/off status should be at least two minutes.

d. **Time measurement characteristics.** Performance measurements are directly affected by the resolution, accuracy, and precision of the DAS internal clock. Even where data are required infrequently, using internal averaging of more frequent scans can reduce scatter and improve measurement accuracy.
e. **Engineering unit conversions.** DASs offer various conversions from voltage and current into engineering units. These may include linear scalar and offset, polynomial curve fitting, or point-to-point interpolation. The capability reflects both hardware features and software functionality.
f. **Math functions.** As with conversions, additional DAS software functionality is often available and adds value to compute averages, sums, maximums, minimums, and other metrics as the data are scanned. Building automation systems should be evaluated for the ability to perform time-interval-based averaging to be considered for data acquisition.
g. **Data archival and retrieval format.** Data acquisitions and limited channel data loggers typically allow instantaneous measurements and engineering or calculated values to be transferred to various text and delimited formats for use in spreadsheet programs. Building energy management systems may be usable for data collection as an alternative to stand-alone and portable data logger systems. However, they often have limited capabilities, including restrictions on storage intervals and storage capacity.
h. **Communications.** New technologies allow for a wide range of data communication. Meter data can be concentrated and uploaded to a central computer using wireless technologies, data hubs, and landline modems. The data can be collected by hand using RS232, USB, or other wired connections to a laptop computer and retrieved for off-site analysis. Many building energy management, boiler, and chiller control systems offer data collection and storage capabilities and have ports for downloading the diagnostic information.

6.4.2 Instrument Calibration. It is recommended that instruments used in measuring the data required to evaluate energy and demand savings be calibrated with procedures developed by the National Institute of Standards and Technology (NIST). Primary standards and no less than third-order NIST-traceable calibration equipment should be used wherever possible by third-party testing laboratories and in-house and/or manufacturers' facilities.

The level of calibration required will be dependent upon the rigor of the test plan. Listed below are suggested requirements for minimum, optimal, and advanced/rigorous plans. It is recommended that any equipment that is used for calibration and verification be appropriately calibrated.

a. **Minimum requirements.** The manufacturer's instrument accuracy specification is accepted. A simple through-system (end-to-end) calibration is performed in the field at a known condition, such as the process, ambient, or reproducible test condition. If necessary, the instrument is adjusted or an appropriate offset is determined and correction is made at the DAS or in the data. Changes made are recorded and verified.
b. **Optimal requirements.** Instrumentation is provided with a qualitative multipoint factory calibration (including minimum, typical, and maximum). Multipoint through-system (end-to-end) calibration is conducted in the field. If necessary, the instrument is adjusted or an appropriate offset is determined and correction is made in the DAS. Changes made are recorded and verified.
c. **Advanced/rigorous requirements.** Instruments are calibrated at an in-house or independent facility at minimum, typical, and maximum conditions before placement in the field. Multipoint through-system (end-to-end) calibration is conducted in the field. Appropriate correction factors are determined. The instruments are adjusted or corrections are made in DAS. Changes made are recorded and verified.

Recalibration frequency for instruments will be established in the instrumentation plan based on manufacturer recommendations. If data validity is in doubt, recalibrate or substitute a calibrated instrument. Recalibration should focus on the most critical measurement points.

6.5 Measurement System Verification and Data Validation

6.5.1 Measurement System Verification. Measurement system verification determines the installed functionality and uncertainty of the measurement system. The method and rigor should be defined in the measurement procedure for the particular instrument/test. The most stringent method, independent measurement against measured value, verifies the uncertainty of a measurement system result via an in situ through-system calibration of each measurement system input with other instruments of known uncertainty or via a different measurement method of known uncertainty. The most basic method, parallel monitoring, compares individual measurements with other similar measurements; comparison sources may be from the measurement system or field-installed gages, portable surveys, or handheld instruments.

If the measurement system is capable of archiving time-series data and recovering it remotely, the data retrieval process should also be evaluated and verified.

6.5.2 In Situ Data Validation Methods. Internal DAS sensors, such as resistance or temperature, or external inputs, such as resistance, of known value should be archived along with measured data to provide an indication of analog-to-digital quality and drift. Subsequent computerized data validation should flag conditions that are out of range.

6.5.3 Computerized Data Validation Methods. Archived data that do not pass all of the following validation checks would be flagged for further investigation (Mazzucchi et al. 1996).

a. **Logical checks.** The time interval between consecutive time-series records is compared with the programmed interval, and each archived data entry is determined to be numerically correct (e.g., does not contain more than one decimal point or contain unnecessary characters).
b. **Relational checks.** Each measurement is compared against an expected minimum and maximum value, and

calculation results, such as thermal load or coefficient of performance using individual time-series records or daily totals, are compared with expected values. If multiple measurement methods are available, their results can be compared.

c. **Graphical validation.** Selected measured data or calculated results are plotted to indicate their change with time or how they compare with one another.
d. **Statistical checks.** Pretest and test measurements are evaluated using statistical checks, such as mean, standard deviation, and min/max, and trended for systematic errors. Values may be checked and flagged with alarms during acquisition or checked once transferred from the DAS.
e. **Process heat balance/conservation of flow or energy methods.** If all components required to determine a heat balance are measured, the percent difference between energy supplied and delivered is compared to the uncertainty analysis to confirm that it is within the range determined in the uncertainty analysis. A range outside this amount would be investigated for measurement or analysis error.

6.6 Measurement System Maintenance

6.6.1 Instrument Maintenance

6.6.1.1 When to Check. The interval for checking measurement results will depend upon the criticality of the measurement point to the overall result and the cost effectiveness of checking or not checking. The timeliness of correcting any problem should always be taken into account. If data are checked on a weekly basis, it may take an additional two weeks to correct a discovered problem.

6.6.1.2 When to Recalibrate. For critical measurement points that are a part of a long-term project, a six-month to yearly calibration interval is highly recommended. Actual calibration requirements should be established based on the term of use, operating conditions, and type of instrument. Projects using long-term monitoring should also include a postcalibration. All spot measurement or temporary instruments should have had an appropriate calibration within the past six months.

6.6.1.3 When to Replace. A decision to replace a failing sensor depends on the error it introduces or mitigates in the measured result, available sensor redundancy, and replacement cost (e.g., purchase, rewiring, calibration, and installation). For noncritical measurements where sufficient data have previously been gathered, the time of sensor failure may only need to be noted, and data collection can proceed without interruption. For critical measurements, it is probably better to recalibrate once and then replace as soon as possible if the sensor continues to show signs of nonperformance. It is always important to verify the sensor's nonperformance with other data sources; the "wayward" sensor may in fact be fairly representing actual conditions. Being forced to replace a sensor midtest often adds to the overall uncertainty of the results when compared to the uncertainty of the result had the original sensor not failed. A complete recalibration of the measurement system may be required. This is especially true with matched sensors used to determine differential temperature. But the alternative is no data at all, which may lead to a failed test.

6.6.2 Data Collection Errors and Lost Data

6.6.2.1 Data Collection Errors. No collected data are without error. Data collection methods differ in degree of rigor and, therefore, in the number and source of errors and the resultant degree of uncertainty. A minimum level of data performance should be established as part of the measurement procedure. This level should define the overall result uncertainty needed to provide the appropriate confidence level to the user. Higher levels of data accuracy may have a dramatic effect on the cost of verification and data validation and should be decided as part of the overall project economics.

Errors in the data identified through calibration, pretesting, and data validation methods will require some form of remediation. The data may be omitted, adjusted by recalibration, adjusted by interpolation between preceding and acceding data, adjusted to a nominal value, or ignored. The allowable methods of error remediation should also be identified in the measurement procedure.

6.6.2.2 Unrecoverable Data. Data can be lost for many reasons, including the following:

a. Sensor failure (power failure, broken sensor)
b. DAS failure (loss of interface with the sensor, power interruption, program, or data storage scram)
c. Data archive failure (data transfer error or loss)
d. Improper conversion to engineering data

Data loss must be detected and corrected as soon as possible. Even with the best of preventive measures, 100% data capture is almost never achieved; it is important, therefore, that a method be developed and provided in the measurement procedure for accounting for data that are missing or determined to be incorrect, including how the associated uncertainty will be documented in the final analysis.

Generally, missing data can be handled by omitting analysis for the interval of lost data or substituting a rational replacement value that may be fixed, interpolated, synthesized, or calculated from known information (Haberl et al. 1990). Large gaps in the whole data set are more difficult to restore. Irrespective of the method chosen, always maintain a record of the raw data and instructions on how the replacement value was obtained in the instrument log.

7. WATER

7.1 Forward. Because of the increasing importance of water and water conservation to the calculation of building efficiency, this section on water is intended to provide guidance on methods of calculating savings from water conservation measures (WCMs).

Potable water is a precious resource, and the reduction of its use is becoming more important to building owners and operators. Changes in climate, population and population centers, land and water use, and technology will continue to put pressure on this scarce resource so that its conservation and reuse will be increasingly important in the twenty-first century. In addition to ethical and environmental considerations, conservation of water reduces costs by reducing the amount of water used and its associated utility costs, including costs of pumping, treating, and heating.

Water conservation is directly coupled to energy conservation in that supplying potable water requires a great deal of energy in a municipal setting. Energy is used to treat and pump water for delivery. Wastewater also requires energy for transport and treatment. Reducing waste flow, in addition to being environmentally sound, can also lower municipal water bills through reduction of the sewer fee component. Conserving water provides a double savings, both in water and energy. Furthermore, reduction of hot-water use is important since it also reduces the energy required to heat the water.

7.2 Scope. This guideline provides a method for using measured preretrofit and postretrofit data to quantify the billing determinants for gallons of water used and costs. The following water use types/sources are included: plumbing fixtures, landscape applications, water features, process flows, and cooling towers.

7.3 Use

7.3.1 Basic Method. This guideline addresses determination of water savings by comparing before and after water use and making adjustments for non-WCM changes that affect water use. This involves projecting water use patterns of the preretrofit (baseline) period into the postretrofit period.

Such projections require adjusting baseline water use to account for different operating variables, such as occupancy, HVAC (heating, ventilating, and air conditioning) load, and weather. Savings are then determined as follows:

Savings = (Baseline water use projected to
postretrofit conditions) − (Postretrofit water use)

7.3.2 Range of Approaches. Guideline 14 includes two basic approaches for determining savings, whole-building and retrofit isolation, and advises on appropriate application of each. No one way can be used in all situations. The approaches described here must be tailored to suit each project's budget and its need for certainty and timeliness.

7.3.3 Variability of Measurements and Costs. Measurements of water savings compare the actual water use to an estimate of what water use would have been in the absence of the WCMs. The estimate of what water use would have been requires data analysis and assumptions about how factors affecting water use have changed since the baseline period. Many factors affect water use; the ability to quantify them with measurements and use them in analyses reduces the uncertainty of the water savings calculation. Many factors may be measured directly, others may be derived from the data, and some can only be assumed. Typical factors include the following:

a. Domestic water use
    1. Number of occupants
    2. Number of uses per day per occupant
    3. Amount of time for each use
    4. Water pressure
    5. Leaks
    6. Control system accuracy and adjustment
b. Landscape water use
    1. Evaporation rate variations
    2. Wind and local microclimate variations
    3. Malfunctioning watering devices
    4. Leaks
    5. Control system accuracy and adjustment
    6. Manual watering practices
c. Mechanical system water use
    1. Cooling tower load variations
    2. Wind and drift variations
    3. Cooling tower cycles of concentration
    4. Boiler load variations
    5. Condensate return
    6. Leaks
    7. Control system adjustment

Uncertainty in the analysis of water savings can be lessened by providing more metering and improving the verification of the variables. Some items that are variable but are not measurable, such as frequency of fixture use per person, must be assumed constant between preretrofit and post retrofit.

7.4 Requirements and Common Elements

7.4.1 Introduction. Reducing potable water use and the amount of waste stream flows is becoming very important to municipalities the world over because of the growing shortage of quality potable water supplies. Building owners and operators should begin to actively monitor and control their water use to conserve the water reserves in their area.

The following are some approaches to water use reduction.

a. Repairing leaks
b. Using low-flow plumbing fixtures for both cold and hot water flows
c. Reducing cooling loads and improving cooling tower management
d. Managing boiler water, including improving condensate return
e. Improving management of process water
f. Improving management of irrigation systems and landscape practices
g. Harvesting and reusing rainwater
h. Improving wastewater management, including capture, treatment, and reuse

The best way for a building operator to lower water use is to continuously monitor the building's water use, comparing past readings with present readings to see whether reduction strategies are working. To do this effectively, measurements should be made for as many separate end uses as is practical. Normally this is accomplished using the main city/municipal water meter, a separate landscape water meter, and a separate water meter on the cooling tower and boiler feed. To establish baseline water use and verify water reduction strategies, data on the items in the following subsections should be obtained.

7.4.1.1 Building Water Use. The following building 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 size (gross floor area, based on exterior dimensions [including exterior walls] and including occupied and minor unoccupied spaces, but excluding major unoccupied or unconditioned spaces)
c. Estimated average number of annual occupants by gender
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 (hp or Btu/h [kJ/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 toilets and lavatory fixtures
j. Design water use of on-site kitchens, food service preparation equipment, and showers (e.g., gymnasiums or dormitories) (average gal/day [gpd] or L/d)
k. Water softener size, cycle times, and flow rates and average water hardness
l. Process water use (average gpd [L/d])

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

a. Total square footage of landscaped area. Site areas that have no landscaping, such as parking lots, gravel areas, or nonirrigated natural areas, should not be included in calculations of landscaped area. Distinguish between areas of native and nonnative plants or by vegetation that requires different irrigation water flows, such as turf, trees, and shrubs.
b. Irrigation type. Where landscape areas are irrigated, determine which type is used (drip, sprinklers, or flooded) and the flow rates.
c. Climatic zone parameters that determine estimated annual water use.

7.4.1.3 Wastewater Streams. The following data should be collected to provide the basis for wastewater calculations and reduction strategies:

a. Cooling tower blowdown (measured using a flowmeter on the blowdown pipe between the basin and the blowdown solenoid valve).
b. Process and landscaping water flows that do not end up in the wastewater stream (determined from design criteria [average gpd (L/d)]).
c. Wastewater stream from building toilets, lavatories, sinks, and showers (calculated from design criteria and occupancy [average gpd (L/d)]).
d. Volume of wastewater (gray water and black water) treated on the site and reused (estimated, if necessary).
e. Total wastewater flow (calculated by deducting landscape water flow and known nonwastewater flows [process flows and non-return-steam flow] from main meter flow).

7.4.2 Water Meters. Water meters used for measuring water flows should be of the positive displacement type with visible readout dials or registers to indicate total volumetric flow. Meters may be manually read meters or meters with pulse translators for input to a building management system or a system control and data acquisition system for automatic reading. Water meters used for cooling tower blowdown or other nonpotable water with contained solids need to have upstream strainers that are maintained at regular intervals.

7.4.3 Selecting Relevant Independent Variables. A proper analysis of any system requires that the most significant independent variables be identified, measured over the periods of interest, and then considered in any savings computations. Examples of significant independent variables for WCM include the following:

a. Number of occupants
b. Number of uses per day per occupant
c. Amount of time for each use
d. Water pressure
e. Evaporation rate variations
f. Cooling tower load variations
g. Cooling tower cycles of concentration

Refer to Section 4 for additional elements common to both energy- and water-saving calculations.

7.4.4 Creating the Baseline Model. A baseline model should be developed to correlate actual baseline water use with substantive fluctuating independent variables. This model is then regularly applied in an algorithm for savings determination to derive water use under postretrofit period conditions.

A wide variety of modeling techniques may be used, ranging from simple averaging to regression analysis. The modeling method chosen should be consistent with the intended uncertainty of the savings determination and should contain no net determination bias. (See Section 4.2.10.)

7.4.5 Measurement and Verification Plan. The design of a savings measurement process should be documented in a savings measurement and verification (M&V) plan before a WCM is installed. The M&V plan should document the following:

a. The selected measurement approach and the infrastructure to be used in the M&V process.
b. Baseline period data

1. Water use actual meter reading dates or times. If water storage is used, M&V meters must be downstream of the water storage.
2. All independent variables selected for use in analyses, including the basis for selection as well as the basis for not using any variables that might be reasonably considered. Measurements should be made on the same day as meters are read for monthly quantities or the same hour for daily quantities.
3. Baseline conditions that may have changed during the postretrofit period. The conditions to be recorded depend upon the facility type, its operation, and the methods used to detect changes. Typical conditions include
   i. occupancy changes, density, and gender by schedule;
   ii. process flows;
   iii. operating schedules;
   iv. nature and timing of significant leaks or breakdowns of significant water using equipment; and
   v. changes to space, service, or function.
4. Billing periods should be normalized for the same number of days for both pre- and postretrofit determinations.
5. Levels of uncertainty and how they were calculated. The M&V plan should clearly define the variables that will be used in calculating savings and how the level of uncertainty that will affect the outcomes is to be calculated. (See Section B4.1.)

7.5 Approaches. The two approaches that are used to determine water savings, whole-building and retrofit isolation, use similar concepts in savings computation. They differ in their ways of measuring the actual water use quantities to be used in savings determinations. The whole-building approach is used where there are many retrofit areas that cannot, or will not, be metered separately. Retrofit isolation is used where the retrofit flows are easily metered.

7.5.1 Whole-Building Approach. The whole-building approach uses a main meter to measure the water flow to the whole building or a group of buildings, or there may be separate meters or submeters to other parts of the building or systems. WCMs may have been applied to one or more of the systems served by the meters. This approach may involve the use of monthly utility bill data or data gathered more frequently from a main meter or submeters.

The whole-building approach requires the following:

a. The baseline data should span the normal full range of all independent variables under normal facility operations.
b. Reasons should be reported for data gaps, data eliminations, or estimation of any actual measured data in the baseline or postretrofit periods. No more than 25% of the measured data should be excluded.
c. Where multiple similar facilities of one owner are involved, uncertainty and confidence calculations should include the impact of any sampling techniques used.
d. The algorithm for savings determination should comply with the net determination bias test as defined in Section 4.2.10.
e. With each annual savings report, show at least the level of uncertainty and confidence interval in the savings determined during the postretrofit period.
f. The level of uncertainty must be less than 50% of annual reported savings at a confidence level of 68%.

7.5.2 Multiple Retrofit Isolation Approach. The multiple retrofit isolation approach uses several meters to separate major water flows within the facility to more accurately determine water savings. Normal meters include the main meter that measures the incoming water supply and, at a minimum, submeters for landscape water use and cooling tower water use. Some facilities may have more than one main meter or separate meters for the flows mentioned above. More water meters may be used to further delineate water use such as kitchen water use, pool or water feature water use, and process water use (Figure 7-1).

The multiple retrofit isolation approach requires the following:

a. The baseline data should span the normal full range of all independent variables under normal facility operations.
b. Regression modeling should be applied to each separate retrofit meter historical reading minus the estimated energy conservation measure flow reductions.
c. Reasons should be reported for data gaps, data eliminations, or estimation of any actual measured data in the baseline or postretrofit periods.
d. Actual data points that span the typical range of independent variables should be used for estimation of missing data.
e. Where multiple similar facilities of one owner are involved, uncertainty and confidence calculations should include the impact of any sampling techniques used.
f. The algorithm for savings determination should comply with the net determination bias test as defined in Section 4.2.10.
g. With each annual savings report, show at least the level of uncertainty and confidence interval in the savings determined during the postretrofit period.
h. The level of uncertainty must be less than 50% of annual reported savings at a confidence level of 68%.

7.6 Water Calculations

7.6.1 Leak Calculations. If the leak is observable, leaks from plumbing fixtures can be estimated by counting the drops over a ten-second period of time and finding the approximate leak rate shown in Table 7-1. Use Table 7-2 for leak calculations for leaking pipes.

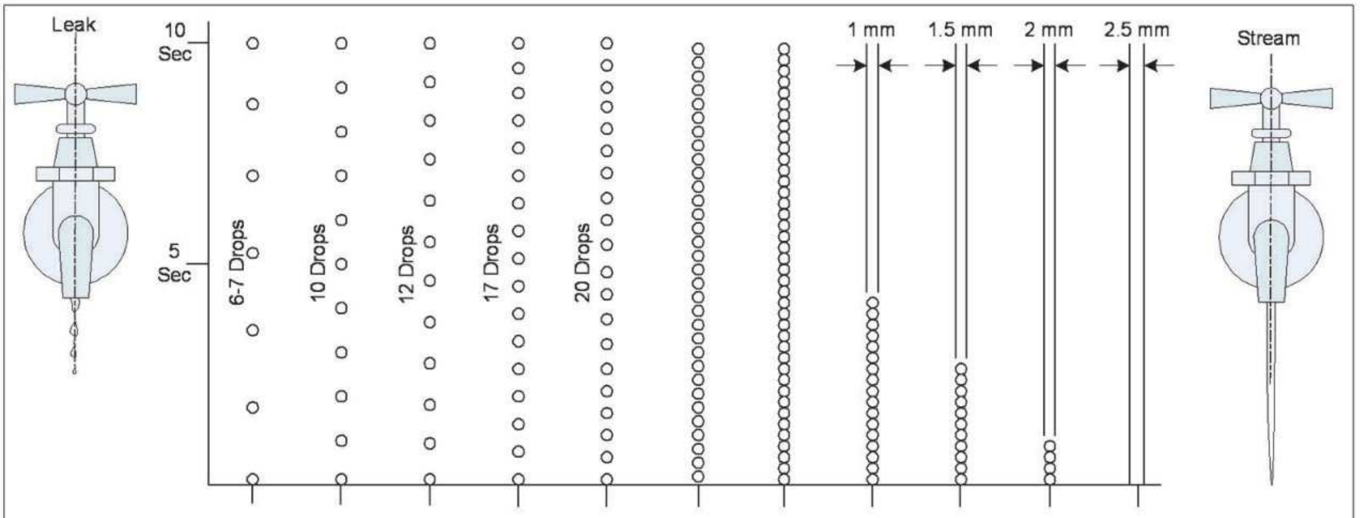
7.6.2 Plumbing Fixture Calculations. For total water flow, determine the number of full-time equivalent occupants by gender and calculate the average number of daily visitors. Using the information in Table 7-3, calculate water flow using the following formulas:

(Occupants by gender) × (Fixture flow per use) × (Uses per day) = gpd (L/d)

(Occupants by gender) × (Fixture flow) × (Uses per day) × (Average time per use) = gpd (L/d)

(Number of fixtures) × (Cleaning activities per day) × (Gallons [litres] per cleaning activity) = gpd (L/d)

TABLE 7-1 Water Losses from Leaking Fixtures
Association of German Engineers (2000)



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

TABLE 7-2 Water Losses at 5 Bar (72.5 psi) Pressure Due to Leaking Pipes[a,b]

Opening, mm	Opening, in.	L/s	GPM[c]	L/h	GPH[c]	m^3/day	GPD[c]	m^3/mo.	GPM	m^3/y	Acres ft/y
0.5	0.02	0.005	0.08	18	5	0.04	114	13	3,472	158	0.13
1.0	0.04	0.016	0.25	58	15	1.40	365	42	11,109	508	0.41
1.5	0.06	0.030	0.48	108	29	2.60	685	79	20,830	946	0.77
2.0	0.08	0.053	0.84	191	50	4.60	1,210	139	36,799	1,673	1.36
2.5	0.10	0.085	1.35	306	81	7.30	1,940	232	59,017	2,680	2.17
3.0	0.12	0.136	2.16	490	129	11.80	3,104	358	94,427	4,292	3.48
3.5	0.14	0.188	2.98	677	179	16.00	4,291	487	130,532	5,842	4.81
4.0	0.16	0.247	3.92	889	235	21.30	5,638	649	171,496	7,787	6.32
4.5	0.18	0.304	4.82	1,094	289	26.30	6,939	799	211,073	9,583	7.77
5.0	0.20	0.372	5.90	1,339	354	32.10	8,492	978	258,286	11,730	9.51
5.5	0.22	0.434	6.88	1,562	413	37.50	9,907	1,104	301,334	13,683	11.10
6.0	0.24	0.500	7.93	1,800	476	43.20	11,413	1,314	347,159	15,768	12.78
6.5	0.26	0.567	8.99	2,041	539	49.00	12,943	1,490	393,678	17,879	14.50
7.0	0.28	0.655	10.38	2,358	623	56.60	14,952	1,722	454,778	20,659	16.75

a. Association of German Engineers (2000).
b. Correction factors used for different pressures are as follows.

0.5 Bar (7.25 psi)—Multiply by 26%
1.0 Bar (14.5 psi)—Multiply by 45%
2.0 Bar (29.0 psi)—Multiply by 63%
3.0 Bar (43.5 psi)—Multiply by 77%
4.0 Bar (58.0 psi)—Multiply by 89%
5.0 Bar (72.5 psi)—Values are correct 100%
6.0 Bar (87.0 psi)—Multiply by 108%
7.0 Bar (101.5 psi)—Multiply by 118%
8.0 Bar (116.0 psi)—Multiply by125%
9.0 Bar (130.5 psi)—Multiply by 132.5%
10.0 Bar (145.0 psi)—Multiply by 140%

c. GPM = gallons per minute; GPH = gallons per hour; GPD = gallons per day.

TABLE 7-3 Water Use Standard (I-P)

	Water Flow					Use								
Item	**Std Pre-1990**	**Std**	**Energy Policy Act 1997**	**Low Post-2000**	**Unit[a]**	**Male Use**	**Female Use**	**Male Visitor Use**	**Female Visitor Use**	**Unit[a]**	**Cleaning**	**Unit[a]**	**Time (min)**	**Units**
Symbol		**S**	**L**	**VL**		**M**	**F**	**MV**	**FV**		**C**		**T**	
Sanitation														
Water closet tank type	4.5[b]	3.5[b]	1.6[b]	1.0[b]	GPF	1.0[c]	3.0[c]	0.1[c]	0.5[c]	FPDPP	1	FPD		
Water closet dual flush tank type (low flush)		1.6[b]	1.1[b]	0.8	GPF	1.0[c]	2.0	0.1[c]	0.5[c]	FPDPP	1	FPD		
Water closet flush valve	4.5[b]	3.5[b]	1.6[b]	1.0[b]	GPF	1.0[c]	3.0[c]	0.1[c]	0.5[c]	FPDPP	1	FPD		
Water closet flush valve dual flush type (low flush)		1.6[b]	1.1[b]	0.8	GPF	1.0[c]	2.0	0.1[c]	0.5[c]	FPDPP	1	FPD		
Urinal	3.5[b]	1.5[b]	1.0[b]	0	GPF	2.0[c]		0.4[c]		FPDPP	1	FPD		
Urinal (high efficiency)		1.0	1.0[b]	0.5	GPF	2.0[c]		0.4[c]		FPDPP	1	FPD		
Lavatory faucet (cold water [CW] only)	6.0[b]	4.0[b]	2.5[b]	0.5[b]	GPM	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	0.5	GPD	0.15[c]	MPU
Lavatory faucet (tempered CW component)	3.0	2.0	1.25	0.25	GPM	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	0.5	GPD	0.15[c]	MPU
Lavatory faucet automatic (CW only)		1.0	0.25[b]	0.25[b]	GPV	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	0.5	GPD	0.15[c]	MPU
Lavatory faucet automatic (tempered CW component)		0.5	0.13	0.13	GPV	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	0.5	GPD	0.15[c]	MPU
Sink faucet (CW only)	2.5	2.5	1.0	1.0	GPM	1.0[c]	1.0[c]			UPD	0.5	GPD	0.25[c]	MPU
Sink faucet (tempered)	1.25	1.25	0.5	0.5	GPM	1.0[c]	1.0[c]			UPD	0.5	GPD	0.25[c]	MPU
Shower (CW only)	6.5[b]	3.5[b]	2.5[b]	1.5[b]	GPM	0.1[c]	0.1[c]			UPD	0.5	GPD	5.0[c]	MPU
Shower (tempered)	3.25	1.75	1.25	0.75	GPM	0.1[c]	0.1[c]			UPD	0.5	GPD	5.0[c]	MPU
Trap primer	4.0[d]	0.5[e]	0.5[e]	0.5[e]	GPD									
Hot Water														
Lavatory faucet (hot water [HW] only)	6.0[b]	4.0[b]	2.5[b]	0.5[b]	GPM	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	0.5	GPD	0.15[c]	MPU
Lavatory faucet (tempered HW component)	3.0	2.0	1.25	0.25	GPM	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	0.5	GPD	0.15[c]	MPU
Lavatory faucet automatic (tempered HW component)		0.5	0.13	0.13	GPV	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	0.5	GPD	0.15[c]	MPU
Sink faucet (HW only)	2.5	2.5	1.0	1.0	GPM	1.0[c]	1.0[c]			UPD	0.5	GPD	0.25[c]	MPU
Sink faucet (tempered HW component)	1.25	1.25	0.5	0.5	GPM	1.0[c]	1.0[c]			UPD	0.5	GPD	0.25[c]	MPU
Shower	6.5[b]	3.5[b]	2.5[b]	1.5[b]	GPM	0.1[c]	0.1[c]			UPD	0.5	GPD	5.0[c]	MPU
Shower (tempered HW component)	3.25	1.75	1.25	0.75	GPM	0.1[c]	0.1[c]			UPD	0.5	GPD	5.0[c]	MPU
Clothes washer (residential)		50	45	25	GPU	1.0	1.0			UPD				
Dishwasher (residential)		13	13	6	GPU	0.2	0.2			UPD				

a. GPF = gal/flush; FPDPP = flush/day/person; FPD = flushes/day; GPM = gal/min; UPD = uses/day; GPD = gal/day; MPU = min/use; GPV = gal/visit; GPU = gal/use
b. DOE (2002)
c. USGBC LEED Standards WE
d. ASHRAE (2009a) Figure 5.1 (1 drop/s)
e. ASHRAE (2009a) Figure 5.1 (1 drop/8 s)
f. Tempered water calculated as 50% HW to 50% CW

TABLE 7-3 Water Use Standard (SI)

Item	Water Flow					Use								
	Std Pre-1990	Std	Energy Policy Act 1997	Low Post-2000	Unit[a]	Male Use	Female Use	Male Visitor Use	Female Visitor Use	Unit[a]	Cleaning	Unit[a]	Time (min)	Units
Symbol		S	L	VL		M	F	MV	FV		C		T	
Sanitation														
Water closet tank type	17.03[b]	13.25[b]	6.06[b]	3.79[b]	LPF	1.0[c]	3.0[c]	0.1[c]	0.5[c]	FPDPP	1	FPD		
Water closet dual flush tank type (low flush)		6.06[b]	4.16[b]	3.03	LPF	1.0[c]	2.0	0.1[c]	0.5[c]	FPDPP	1	FPD		
Water closet flush valve	17.03[b]	13.25[b]	6.06[b]	3.79[b]	LPF	1.0[c]	3.0[c]	0.1[c]	0.5[c]	FPDPP	1	FPD		
Water closet flush valve dual flush type (low flush)		6.06[b]	4.16[b]	3.03	LPF	1.0[c]	2.0	0.1[c]	0.5[c]	FPDPP	1	FPD		
Urinal	13.25[b]	5.68[b]	3.79[b]	0	LPF	2.0[c]		0.4[c]		FPDPP	1	FPD		
Urinal (high efficiency)		3.79	3.79[b]	1.89	LPF	2.0[c]		0.4[c]		FPDPP	1	FPD		
Lavatory faucet (cold water [CW] only)	0.38[b]	0.25[b]	0.16[b]	0.03[b]	LPS	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	1.89	LPD	0.15[c]	MPU
Lavatory faucet (tempered CW component)	0.19	0.13	0.08	0.02	LPS	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	1.89	LPD	0.15[c]	MPU
Lavatory faucet automatic (CW only)		3.79	0.95[b]	0.95[b]	LPV	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	1.89	LPD	0.15[c]	MPU
Lavatory faucet automatic (tempered CW component)		0.5	0.13	0.13	LPV	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	1.89	LPD	0.15[c]	MPU
Sink faucet (CW only)	0.16	0.16	0.06	0.06	LPS	1.0[c]	1.0[c]			UPD	1.89	LPD	0.25[c]	MPU
Sink faucet (tempered)	0.08	0.08	0.03	003	LPS	1.0[c]	1.0[c]			UPD	1.89	LPD	0.25[c]	MPU
Shower (CW only)	0.41[b]	0.22[b]	0.16[b]	0.09[b]	LPS	0.1[c]	0.1[c]			UPD	1.89	LPD	5.0[c]	MPU
Shower (tempered)	0.21	0.11	0.08	0.05	LPS	0.1[c]	0.1[c]			UPD	1.89	LPD	5.0[c]	MPU
Trap primer	15.14[d]	1.89[e]	1.89[e]	1.89[e]	LPD									
Hot Water														
Lavatory faucet (hot water HW] only)	0.38[b]	0.25[b]	0.16[b]	0.03[b]	LPS	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	1.89	LPD	0.15[c]	MPU
Lavatory faucet (tempered HW component)	0.19	0.13	0.08	0.02	LPS	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	1.89	LPD	0.15[c]	MPU
Lavatory faucet automatic (tempered HW component)		0.5	0.13	0.13	LPV	3.0[c]	3.0[c]	0.5[c]	0.5[c]	UPD	1.89	LPD	0.15[c]	MPU
Sink faucet (HW only)	0.16	0.16	0.06	0.06	LPS	1.0[c]	1.0[c]			UPD	1.89	LPD	0.25[c]	MPU
Sink faucet (tempered HW component)	0.08	0.08	0.03	0.03	LPS	1.0[c]	1.0[c]			UPD	1.89	LPD	0.25[c]	MPU
Shower	0.41[b]	0.22[b]	0.16[b]	0.09[b]	LPS	0.1[c]	0.1[c]			UPD	1.89	LPD	5.0[c]	MPU
Shower (tempered HW component)	0.21	0.11	0.08	0.05	LPS	0.1[c]	0.1[c]			UPD	1.89	LPD	5.0[c]	MPU
Clothes washer (residential)		50	45	25	LPU	1.0	1.0			UPD				
Dishwasher (residential)		13	13	6	LPU	0.2	0.2			UPD				

a. LPF = L/flush; FPDPP = flush/day/person; FPD = flushes/day; LPS = L/s; UPD = uses/day; LPD = L/day; MPU = min/use; LPV = L/visit; LPU = L/use
b. DOE (2002)
c. USGBC LEED Standards WE
d. ASHRAE (2009a) Figure 5.1 (1 drop/s)
e. ASHRAE (2009a) Figure 5.1 (1 drop/8 s)
f. Tempered water calculated as 50% HW to 50% CW

7.6.3 Hot-Water Generation Energy Calculations. For hot-water energy use, determine the average water temperature differential between inlet and outlet water, and use the following formulas to determine the energy used.

For Electric Water Heaters

$$\text{kWh} = [(\text{Gallons used}) \times 8.33 \times (\Delta T\text{°F})]/3412$$

For Gas Water Heaters

$$\text{Therms} = [(\text{Gallons used}) \times 8.33 \times \Delta T\text{°F})]/(\text{Eff.}(0.80) \times 100{,}000)$$

Note that 8.33 lb/gal is the density of water at 70°F. The value of 8.33 lb/gal of water is a standard value at 70°F temperatures. If a value is required at a different temperature, adjust the standard value to a different temperature by using Table A-6 density divided by 7.48.

7.6.4 Cooling Tower Water Use Calculations. From the total HVAC load, determine the average condenser water flow in gallons per minute (gpm) and the average differential temperature between the inlet and outlet water. From design or use records, determine average cycles of concentration. Use the formulas in the following subsections (taken from www.eng-tips.com/register.cfm) to determine water use.

7.6.4.1 In Inch-Pound (I-P) Units

M = makeup water, gpm

C = circulating water, gpm

D = draw-off water, gpm

E = evaporated water, gpm

W = windage water losses, gpm

X = concentration of any completely soluble salts, usually chlorides, parts per million by weight, ppmw

X_M = concentration of chlorides in M, ppmw

X_C = concentration of chlorides in C, ppmw

Cycles = cycles of concentration = X_C/X_M

A water balance around the entire system is given by

$$M = E + D + W$$

Because E has no salts, a chloride balance around the system is given by

$$M(X_M) = D(X_C) + W(X_C) = X_C(D + W)$$

and therefore

$$X_C/X_M = \text{Cycles} = M/(D + W) = M/(M - E) = 1 + \{E/(D + W)\}$$

From a simplified heat balance around the cooling tower, we get

$$(E = (C)(\Delta T)(c_p)/H_V$$

where

H_V = latent heat of vaporization of water = ca. 1000 Btu/lb

ΔT = water temperature difference from tower top to tower bottom, °F

c_p = specific heat of water = 1 Btu/lb/°F

W, in the absence of manufacturer's data, may be assumed to be

a. 0.3% to 1.0% of C for a natural draft cooling tower,
b. 0.1% to 0.3% of C for an induced draft cooling tower, and
c. about 0.01% of C if the cooling tower has windage drift eliminators.

Concentration cycles in HVAC cooling towers usually range from 2.5 to 3.5 but may be higher depending on the chemical treatment or filtering programs. Savings from higher cycles of concentration declines as cycles are increased.

Informative Note: Draw-off and blowdown are synonymous. Windage and drift are also synonymous.

7.6.4.2 In International System (SI) Units

M = makeup water, m^3/h

C = circulating water, m^3/h

D = draw-off water, m^3/h

E = evaporated water, m^3/h

W = windage water losses, m^3/h

X = concentration of any completely soluble salts, usually chlorides, ppmw

X_M = concentration of chlorides in M, ppmw

X_C = concentration of chlorides in C, ppmw

Cycles = cycles of concentration = X_C/X_M

A water balance around the entire system is given by

$$M = E + D + W$$

Because E has no salts, a chloride balance around the system is given by

$$M(X_M) = D(X_C) + W(X_C) = X_C(D + W)$$

and therefore

$$X_C/X_M = \text{Cycles} = M/(D + W) = M/(M - E) = 1 + \{E/(D + W)\}$$

From a simplified heat balance around the cooling tower, we get

$$E = (C)(\Delta T)(c_p)/H_V$$

where

H_V = latent heat of vaporization of water = ca. 2260 kJ/kg

ΔT = water temperature difference from tower top to tower bottom, °C

c_p = specific heat of water = 4.184 kJ/kg/°C

W, in the absence of manufacturer's data, may be assumed to be

a. 0.3% to 1.0% of C for a natural draft cooling tower,
b. 0.1% to 0.3% of C for an induced draft cooling tower, and
c. about 0.01% or less of C if the cooling tower has windage drift eliminators.

TABLE 7-4 Landscape Factors[a]

	Species Factor (K_s)			Density Factor (K_D)			Microclimate Factor (K_{MS})		
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
Ground covers	0.2	0.5	0.7	0.5	1.0	1.1	0.5	1.0	1.2
Mixed trees, shrubs, groundcovers	0.2	0.5	0.9	0.6	1.1	1.3	0.5	1.0	1.4
Turf grass	0.6	0.7	0.8	0.6	1.0	1.0	0.8	1.0	1.2

a. USGBC (2005)

TABLE 7-5 Irrigation Type

Type	Irrigation Efficiency, %	Controller Efficiency Dry Climate, %	Controller Efficiency Wet Climate, %
Sprinkler	0.625[a]	0.25	0.5
Drip	0.90[a]	0.25	0.5

a. USGBC (2005)

E is calculated from the total rejected heat from the connected load, and *D* and *W* are derived from *C*. The rejected load is converted to pounds of water evaporated by using the latent heat of evaporation of water, which is approximately 970.4 Btu/lb (2255.6 kJ/kg). Exact enthalpy values can be obtained from a steam table enthalpy of water at system temperature and pressure values.

7.6.5 Landscape Water Use Calculations. Obtain the local evapotranspiration rate (ET_o) from local meteorological sources; determine vegetation types and the plant species factor (K_S), plant species density factor (K_D), and microclimate factor (K_{MS}); determine the reference evapotranspiration rate (ET_L); and using the equations below, determine the landscape water use. The value of ET_o is available from local weather data, which are used by farmers and landscapers to predict required irrigation requirements. NASA also has produced a worldwide map of average ET_o values, but it is less accurate than local data.

K_S is separated into low water use, medium water use, and high water use; K_D is the factor for shading of the planting area and is also separated into low, medium, and high. A low density factor is where trees and plantings shade 60% of the ground, average density factor is where trees and plantings shade 90% to 100% of the ground, and high density is where a tree canopy shades plantings that shade the ground.

K_{MS} is for areas that allow sun or wind to increase the evaporation rate of the soil. Areas rated “high” for K_{MS} include parking lots; west sides of buildings; and west and south sides of slopes, meridians, and areas exposed to wind tunnel effects. Areas rated “low” include shaded areas; areas protected from the wind; north sides of buildings, courtyards, and slopes; and areas shaded by building overhangs.

$$ET_L = ET_o \times K_L$$

(Use Table 7-4 for K_L [landscape factors] information.)

$$K_L = K_S \times K_D \times K_{Ms}$$

Using information in Table 7-5, calculate the baseline case for landscape water use with the following equations:

$$\text{Total water applied}_{[gal]} = \text{Area}_{[ft^2]} \times (ET_{L[in.]}/IE) \times CE \times 0.6233_{[gal/ft^2/in.]}$$

$$\text{Total potable water applied}_{[gal]} = \text{Total water applied}_{[gal]} - \text{Reuse water}_{[gal]}$$

Calculate post retrofit case and calculate percent savings.

8. ELECTRIC DEMAND

8.1 Electric Demand Modeling Using a Two-Step Method. To calculate electric demand savings, a two-step method can be used that utilizes the ASHRAE Diversity Factor Toolkit (RP-1093) and ASHRAE Inverse Model Toolkit (IMT) (RP-1050).

In the first step, the preretrofit and postretrofit data are identified and separated into two data files along with the corresponding hourly ambient temperature. Figure 8-1 shows the whole-building data from the example building. Twenty-four-hour weekday-weekend profiles are then calculated for each group of data using the ASHRAE Diversity Factor Toolkit (RP-1093) as shown in Figure 8-2.

In the next step, the maximum kilowatt use (90th percentiles) from a month of postretrofit period was compared against the maximum kilowatt use from the same month of preretrofit period to calculate the demand savings for that month. For periods of missing data in the preretrofit period for a building, in order to compare the months of postretrofit period against the same months of preretrofit period, ASHRAE's IMT can be used to fill in or extend the demand prediction from the 1093-RP demand savings analysis to months where no demand data were available. To accomplish this, the maximum monthly demand (90th percentile profile) is plotted against the maximum average daily temperature of the month for the preretrofit period. In the example building, this is shown in Figure 8-3. Similar procedures can be used if data are missing in the postretrofit period.

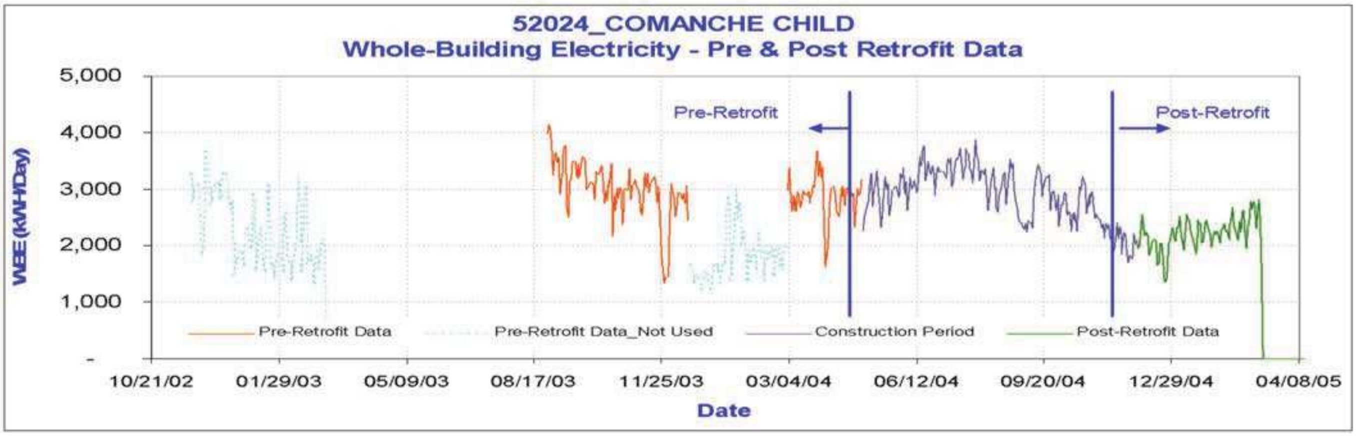


FIGURE 8-1 Preretrofit and postretrofit whole-building hourly data from example building.

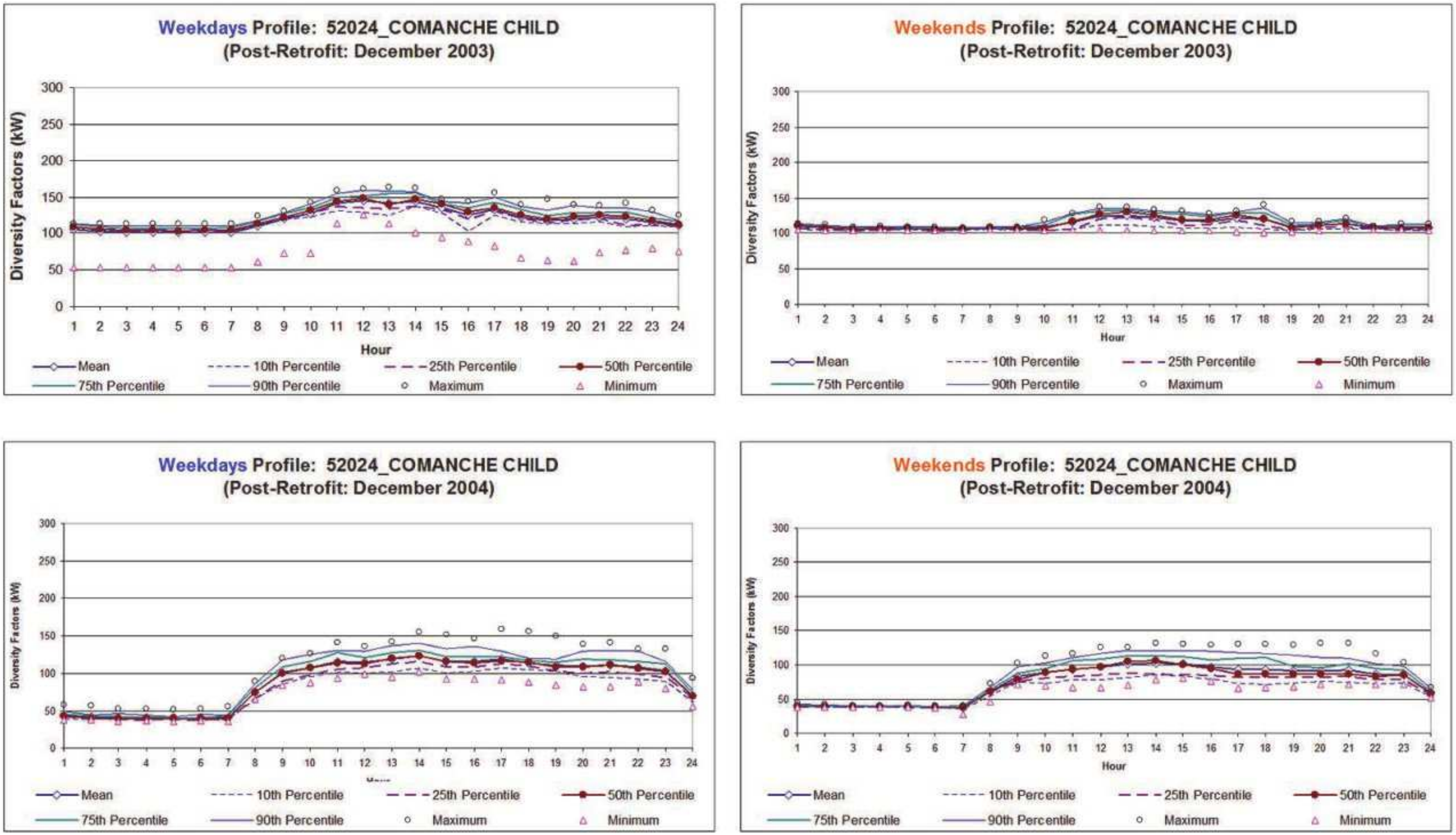


FIGURE 8-2 Twenty-four-hour weekday/weekend profiles generated with ASHRAE Diversity Factor Toolkit (RP-1093).

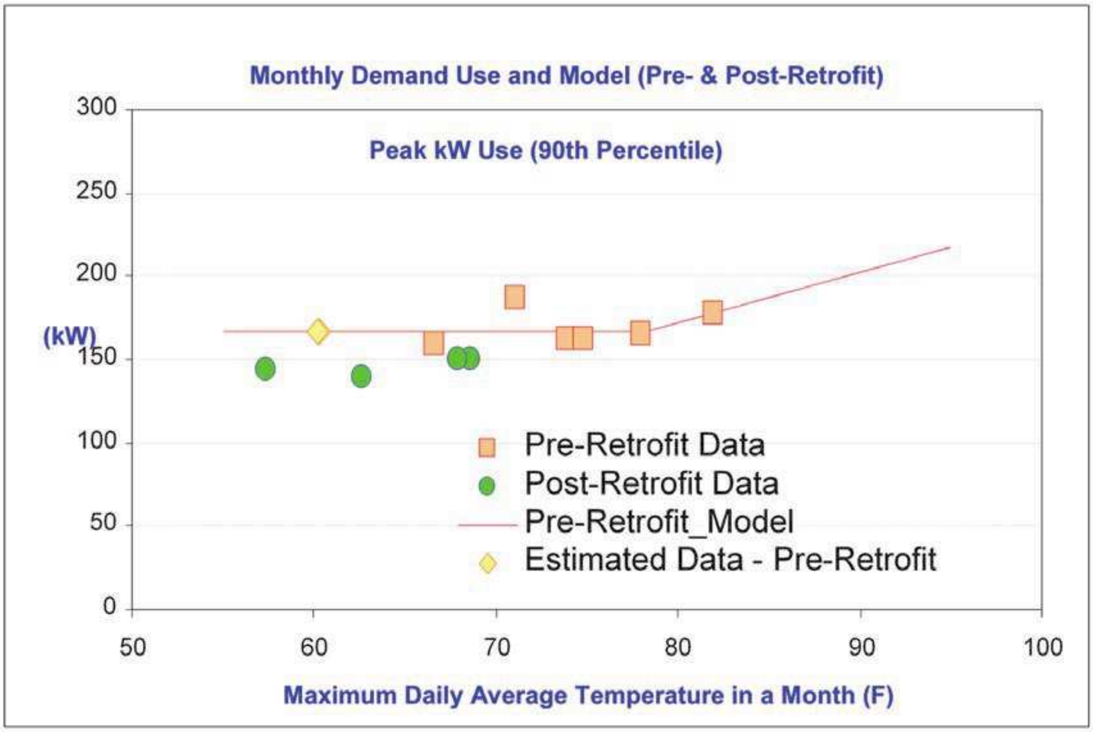


FIGURE 8-3 Electrical demand in the preretrofit period predicted with ASHRAE's Inverse Model Toolkit 3P model.

9. MEASUREMENT AND VERIFICATION (M&V) FOR RENEWABLE ENERGY TECHNOLOGIES

9.1 Overview. A protocol for measuring performance is required if renewable energy technologies are to be recognized for their potential. These technologies make use of sustainable energy sources that are regenerated in nature, and they include solar, wind, biomass (e.g., sustainably harvested food crops, organic wastes, and landfill gas), geothermal, small hydroelectric, ocean thermal, wave, and tidal energy. Renewable energy projects are installed all over the world in numerous projects funded by governments, private companies, organizations, and third-party financiers.

Whether a renewable energy system is integrated into a larger energy delivery system or is a stand-alone system, a method of measuring and verifying performance is needed. Project financing, emissions credits, and emissions trading will all benefit from a standardized, widely accepted measurement and verification (M&V) approach that serves the needs of all renewable energy project partners.

All renewable energy technologies supply energy rather than reduce the energy consumed. Measuring this energy supply can often serve as a simplified approach to measuring system performance. The energy production of a renewable energy system that is not connected to a utility is directly linked to the amount of energy consumed by the connected load. An M&V strategy must be able to differentiate between an increase in renewable energy supply and a reduction in the load (such as that caused by an efficiency measure or a curtailment of the load).

In addition, the performance of some renewable energy systems is very much a function of environmental conditions such as solar radiation or wind speed. These conditions are outside the control of project developers and should be taken into account in any M&V approach. An M&V objective always includes a measurement of savings in purchased fuel or electricity but rarely includes other factors that may be equally important to a project, including savings in first cost (solar photovoltaics are often the least-cost option for small remote loads), reductions in atmospheric emissions, reductions in risk of transporting fuels (fuel spills), using community industry rather than importing fuel, avoiding fuel supply interruptions or price fluctuations, or other externalities.

An M&V strategy for renewable energy may need to differentiate between a reduction in fossil fuel use caused by renewable energy delivery as opposed to one caused by a reduction in the load (by efficiency measures or curtailment).

Renewable energy projects are frequently capital intensive, often requiring a longer investment term than that of energy efficiency projects. Therefore, an M&V program for renewable energy may need to verify that benefits are sustained over a long period of time. This situation favors M&V approaches that may cost more initially but have lower annual operating costs.

9.2 Objectives. From the earliest stages of project development through operation of a completed renewable energy system, M&V may actually have several objectives, including the following:

a. Measure existing daily, weekly, and annual demand and/or consumption load profiles to establish the energy use baseline and to ascertain the size of the system, energy storage requirements, and other design characteristics of a project. These load profiles also provide information needed to establish project feasibility.
b. Serve as a commissioning tool by confirming that systems were installed and are operating as intended.
c. Serve as the basis for payments to a project developer or energy service company over the term of a performance contract. Payments can be directly tied to measured performance. Alternatively, or perhaps in addition, M&V results could be used to verify a minimum level of performance guaranteed in a contract.
d. Provide data that can be used as diagnostics, which continually help to sustain system performance and benefits over time.
e. Increase customers' confidence and reduce transaction costs by using a defined, accepted, and proven M&V approach to facilitate negotiations during financing and contract development.
f. Secure the full financial benefits of emissions reductions, such as emissions trading. To verify compliance with emissions reduction targets, regulating bodies will need to adopt a protocol for measuring emissions reductions. A protocol common to all projects is required to claim and trade emissions credits.
g. Help certify a "green power" program. Although the certification of green power programs, which offer power generated from renewable energy systems to utility customers, is beyond the scope of the International Performance Measurement and Verification Protocol (IPMVP), the protocols presented here could be used in such a certification process.

For project developers, financing entities, and large customers (such as governments), additional M&V objectives extend beyond the scope of an individual contract:

a. Validate or improve computer simulations or other predictions of system performance, thus reducing project risk and increasing investors' confidence in predictions of project benefits.
b. Provide developers, investors, lenders, and customers with more confidence regarding the value of future projects than engineering estimates do.
c. Provide a means to pool projects for financing based on their M&V characteristics.

Some general issues unique to renewable energy are involved in the establishment of a baseline of energy use and costs for M&V purposes. These include the fact that renewable energy systems deliver energy rather than simply reduce consumption, as noted, and that renewable energy systems are often located in remote areas not served by utilities.

Because renewable energy technologies are used in an energy delivery system, there is no need for a baseline if performance claims are based on delivery rather than savings. However, the M&V options described here can be applied to measure either the energy delivered by a renewable energy system or the resulting utility energy savings for a facility as a whole. It is important to state that these two may not be exactly the same and to specify whether performance claims are based on delivery or on savings.

Metering of delivered energy without a baseline is often the recommended M&V approach for renewable energy systems because it is very accurate, moderate in cost, and measures elements of project performance over which the developer has some control. For example, a solar water heating system may deliver a certain amount of heat, but utility energy savings for the facility would be the amount delivered by the solar system divided by the efficiency of the original water heater. In this case, the developer of the solar project would not have control over the efficiency of the existing water heater, so it is more appropriate to base performance claims on energy delivery rather than on savings.

Renewable energy systems are often cost effective as the only source of power in remote locations where utility power is unavailable. A baseline based on the utility or another type of on-site generation could be arbitrary and rather meaningless in such situations. Nevertheless, savings could be determined from a baseline computed as the energy use or cost that would have been incurred without the renewable energy system.

For additional information, refer to the IPMVP volume on measurement and verification for renewable energy technologies (EVO 2012).

10. NORMATIVE REFERENCES AND BIBLIOGRAPHY

10.1 Normative References

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(This informative annex is not part of this guideline. It is provided for informational purposes only.)

INFORMATIVE ANNEX A PHYSICAL MEASUREMENTS

A1. INTRODUCTION

In situ field testing will require measurements of various physical characteristics of the equipment in question. 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 it. This annex provides a review of techniques applicable to measurement of run time; electric demand and energy use; temperature; liquid, air, and steam flow; thermal energy; psychometric properties (humidity); pressure; and outside weather conditions.

Commissioning and calibration of metering devices are the processes that contribute to the proper installation and provision of adjustments necessary to generate accurate meter data. The accuracy and reliability of the data obtained from meters largely depends on whether they are properly installed and calibrated. Installation details must strictly follow the meter manufacturer's instructions. Once a meter is properly installed, a process must be conducted to confirm accuracy and calibration.

Accuracy is the ability of a measurement to match the actual value being measured. Calibration is the act of checking or adjusting the accuracy of the meter by comparing it with a known standard. The known standard in the case of most meters can be a portable meter of greater accuracy with calibration traceable to the National Institute of Standards and Technology (NIST). A list of calibration procedures, provided in the references, includes Baker and Hurley (1984), EEI (2002), Huang (1991), Hyland and Hurley (1983), Hurley and Schooley (1984), Hurley (1985), ISA (1976), Kulwicki (1991), and Ramboz and McAuliff (1983).

Proper installation must be verified in detail by a commissioning process containing checklists of all items and processes necessary to ascertain compliance to the installation criteria provided by the meter manufacturer. Different types of meters have very specific installation requirements that are necessary for proper function. The meter manufacturer installation procedures and recommendations should be followed in detail. Meters should be installed by factory qualified contractors under the supervision of the project commissioning agent, the project inspector, the project manager, and the engineer of record.

Because NIST traceable accuracy validation may be impractical, expensive, or unnecessary for certain applications, a more practical approach should be implemented, as discussed below, followed by a formal approach for cases that require a formal traceable calibration process. It is at times more practical to require that meters be factory calibrated rather than field calibrated, as the necessary instrumentation and test rigs are readily available in the factory. This is particularly true of flowmeters because field calibration is often impractical if not impossible due to the lack of a good location to mount a temporary meter (it is hard enough finding a good location for the permanent meter) and because finding a sufficiently accurate temporary meter may not be practical. Still, a check must be made to ensure that the meter and transmitter were properly configured. For instance, a flowmeter can be checked by causing the entire flow to go through a device with a flow measurement capability (however accurate) or with a known flow and pressure drop relationship (e.g., a chiller). This test will allow the meter to be checked for the appropriate order of magnitude reading to ensure proper configuration, but it cannot be used for actual calibration; the factory calibration must be relied upon. It is ultimately the responsibility of the project team to ensure that the data produced by a meter are sufficiently reliable for the given application. For applications requiring a very high degree of assured accuracy, a more formal process should be followed.

Formally, the definition of calibration traceability that has achieved global acceptance in the metrology community is contained in the *International Vocabulary of Metrology—Basic and General Concepts and Associated Terms* (BIPM 1998):

> The property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons, all having stated uncertainties.

It is important to note that traceability is the property of the result of a measurement, not of an instrument or calibration report or laboratory. It is not achieved by following any one particular procedure or using special equipment. Merely having an instrument calibrated, even by NIST, is not enough to make the measurement result obtained from that instrument traceable to realizations of the appropriate SI unit or other stated references. The measurement system by which values are transferred must be clearly understood and under control. In other words, traceable measurements or meter data must follow a traceable calibration protocol involving proper instruments and certified calibration professionals.

Therefore, a thorough review of the installation process and requirements for each meter needs to be conducted. This process must address proper installation, calibration, verification, and traceability to a known established standard. Usually, manufacturer installation manuals furnish specific information on the proper installation of meters and related devices. Test equipment used for testing and calibration of field devices shall be at least twice as accurate as the respective field device. For example, if a field device is ±0.5% accurate, test equipment shall be ±0.25% accurate over the same range.

Table A-1 (I-P and SI units) lists the instrumentation requirements for accurate measurement for various equipment functions per generally recommended industry practice.

A2. METERING DEVICES

A2.1 Electric Power Measurement. Real power, power that has the ability to perform work, can be measured directly using watt transducers, devices that determine power from voltage and current sensors, making the necessary internal calculations to account for power factor and to eliminate any bias in the measurement. Watt-hour transducers, devices that inte-

TABLE A-1 Minimum Instrumentation Requirements (I-P)

Function/Instrument Type	Minimum Range	Accuracy	Resolution	Calibration Interval
Rotation measurement/ digital rotational speed— dual functions	0 to 5000 rpm	±2%	±5 rpm	12 months
Temperature measurement/ digital thermometers:				
Air	–40°F to 240°F	±1% of reading	0.2°F	12 months
Immersion	–40°F to 240°F	±1% of reading	0.2°F	
Contact	–40°F to 240°F	±1% of reading	0.2°F	
Electrical measurement/ digital true root-mean-square (RMS) multimeter:				
Volts AC	0 to 600 VAC	±2% of reading	V	12 months
Amperes	0 to 100 A	±2% of reading	0.1 A	
Air pressure measurement/ digital manometer	0 to 10.00 in. wg	±2% of reading	0.01 < 1 in. wg 0.1 > 1 in. wg	12 months
Air velocity measurement (not for Pitot tube traverses)	50 to 250 fpm	±5% of reading	20 fpm	12 months
Humidity measurement/ digital hygrometer	10% to 90% rh	2% rh	1%	12 months
Direct reading hood/ digital airflow multimeter	100 to 2000 cfm	±5% of reading ±5 cfm	1 cfm	12 months
Hydronic pressure measurement/ digital hydrometer	–30 in. Hg to 60 psi 0 to 100 psi 0 t0 200 psi	±2% of reading ±2% of reading ±2% of reading	0.5 psi 1.0 psi 2.0 psi	12 months
Hydronic differential pressure measurement/digital hydrometer	0 to 100 in. wg 0 to 1000 ft wg	±2% of reading ±2% of reading	1.0 in. wg 1.0 ft wg	12 months
Data loggers—temperature	–4°F to 150°F	0.5°F @77°F	0.2°F	12 months
Data loggers—humidity	10% to 90% rh	2.5% rh	1%	12 months
Data loggers—CO_2	0 to 2500 ppm	±50 ppm	1 ppm	12 months
Data loggers—CO	0 to 2000 ppm	±5 ppm	1 ppm	12 months
Data loggers—lighting levels	0 to 3000 fc	±10 fc	2 fc	12 months
Data loggers—electrical	0 to 600 VAC 0 to 100 A	±2% of reading ±4% of reading	1.0 V 0.5 A	12 months
Data loggers—static pressure:				12 months
Low range	0 to 0.25 in. wc	±1% of reading	0.01 < 1 in. wg	
High range	0 to 6.00 in. wc	±1% of reading	0.1 > 1 in. wg	
Data loggers—water pressure				12 months
Differential pressure	0 to 100 ft	±2% of reading	psi	
Hydrostatic pressure	0 to 100 psi	±2% of reading	1.0 psi	
Thermal (infrared) thermometer	0°F to 900°F	±3°F ±1% of reading	0.2°F	12 months

TABLE A-1 Minimum Instrumentation Requirements (SI)

Function/Instrument Type	Minimum Range	Accuracy	Resolution	Calibration Interval
Rotation measurement/ digital rotational speed— dual functions	0 to 5000 rpm	±2%	±5 rpm	12 months
Temperature measurement/digital thermometers: Air Immersion Contact	 –40°C to 115°C –40°C to 115°C –40°C to 115°C	 ±1% of reading ±1% of reading ±1% of reading	 0.1°C 0.1°C 0.1°C	12 months
Electrical measurement/ digital true root-mean-square (RMS) multimeter: Volts AC Amperes	 0 to 600 VAC 0 to 100 A	 ±2% of reading ±2% of reading	 1 V 0.1 A	12 months
Air pressure measurement/ digital manometer	0 to 2500 Pa	±2% of reading	2.5 < 250 Pa 25 > 250 Pa	12 months
Air velocity measurement (not for Pitot tube traverses)	0.25 to 12.5 m/s	±5% of reading	0.1 m/s	12 months
Humidity measurement/ digital hygrometer	10% to 90% rh	2% rh	1%	12 months
Direct reading hood/ digital airflow multimeter	50 to 1000 L/s	±5% of reading ±5 cfm	1 cfm	12 months
Hydronic pressure measurement/ digital hydrometer	–760 mm Hg to 400 kPa 0 to 700 kPa 0 to 1400 kPa	±2% of reading ±2% of reading ±2% of reading	3.3 kPa 6.7 kPa 16.7 kPa	12 months
Hydronic differential pressure measurement/digital hydrometer	0 to 25 kPa 0 to 300 kPa	±2% of reading ±2% of reading	 250 Pa 3.0 kPa	12 months
Data loggers—temperature	–20°C to 65 °C	±0.25°C	0.1°C	12 months
Data loggers—humidity	10% to 90% rh	2.5% rh	1%	12 months
Data loggers—CO_2	0 to 2500 ppm	±50 ppm	1 ppm	12 months
Data loggers—CO	0 to 2000 ppm	±5 ppm	1 ppm	12 months
Data loggers—lighting levels	0 to 32,000 lux	±100 lux	20 lux	12 months
Data loggers—electrical	0 to 600 VAC 0 to 100 A	±2% of reading ±4% of reading	1.0 V 0.5 A	12 months
Data loggers—static pressure: Low range High range	 0 to 60 Pa 0 to 1500 Pa	 ±1% of reading ±1% of reading	 2.5 < 250 Pa 25 > 250 Pa	12 months
Data loggers—water pressure Differential pressure Hydrostatic pressure	0 to 300 kPA 0 to 700 kPA	±2% of reading ±2% of reading	2 kPa 5 kPa	12 months
Thermal (infrared) thermometer	0°C to 500°C	±1.5°C ±1% of reading	0.1°C	12 months

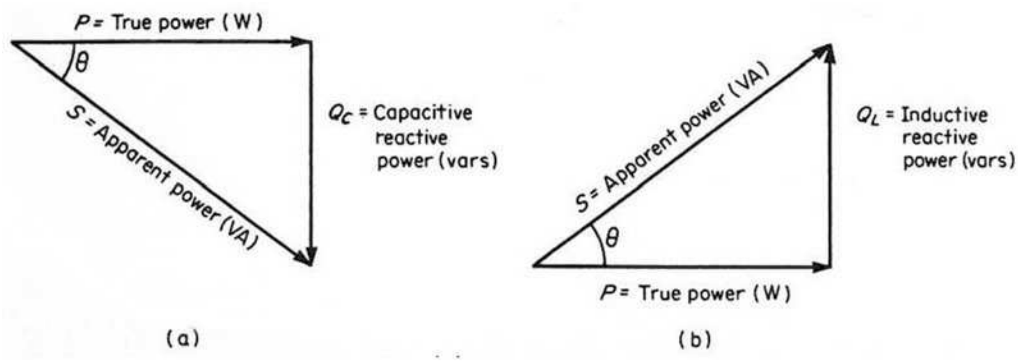

FIGURE A-1 Power triangles for (a) capacitive and (b) inductive circuits.

grate power over time, are available to give the engineer real energy use data and eliminate the error inherent in assuming or ignoring power factor. Stand-alone watt-hour transducers are available to produce pulses representative of some number of watt-hours. These pulses are typically input to a pulse-counting data logger for storage and later retrieval and analysis.

An alternate technology involves combining the metering and data logging functions into a single piece of hardware. This integrated metering approach incorporates virtual digital watt-hour meters into a single solid-state device capable of monitoring individual phases of three-phase power circuits. Whereas pulse-counting technology makes kilowatt and kilowatt-hour information available to the user, the integrated approach allows access to much more information. In addition to kilowatts and kilowatt-hours, each individual phase of power can be monitored to provide information on voltage, current, apparent power in kilovolt-amperes, kilovolt-ampere hour, and power factor. Many integrated meters have the ability to perform wave-form analysis, capturing harmonic information for both voltage and current wave-forms. Power metering devices should only be installed by qualified personnel and in compliance with the National Electric Code (NFPA 2014), state, and local codes.

A2.1.1 Metering Fundamentals. Electric power measurements and calculations for alternating current (AC) circuits are made in terms of root-mean-square (RMS) values. Only true RMS responding meters should be used in electric power measurements.

Power in an AC circuit consists of apparent power (total power), true power (work), and reactive power (capacitive and inductive power) (see Figure A-1). Apparent power is the sum in quadrature of the true power and reactive power. Power factor is the ratio of true power divided by apparent power. Power factor is also the cosine of the phase angle between the voltage across the circuit (or load) and the current through the circuit (or load).

Metering electric energy use requires the measurement of several variables, including voltage (V), current (A), frequency (Hz), and phase angle between the voltage and current (θ).

Electric energy is measured for both magnitude (kW) and time (hour) and is metered as kilowatt-hours (kWh) where the constant "k" stands for "kilo" and is a multiplier of 1000. Electric energy billings typically consist of an energy consumption component (kWh), a demand component (kW), and a power factor (PF) or reactive power component (kilovolt-ampere reactive [kVAR]).

Electromechanical watt-hour-meter technology and nomenclature were developed and evolved during the twentieth century. The advent and application of solid-state technology to the watt-hour-meter has greatly enhanced the data processing capabilities of power meters. Electromechanical meters measured energy use and demand through rotation of an induction disk as a result of torque created by the applied voltage, current, and system frequency. A solid-state meter converts current and voltage inputs to digital signals through an analog-to-digital converter and measures power using microprocessor-based algorithms and calculations and an internal clock. The microprocessor-based meter is also capable of measuring harmonics, event capture, and estimating peak demand.

Electric energy parameters such as kilowatts (kW), kilovolt-amperes reactive (kVAR), kilovolt-amperes (kVA), and power factor (PF), can be calculated as follows:

Real Power, Single-Phase Loads

$$P(\mathrm{kW}) = \mathrm{PF} \times I(\mathrm{A}) \times V(\mathrm{V})/100$$

Real Power, Three-Phase Loads

$$P(\mathrm{kW}) = \mathrm{PF} \times I(\mathrm{A}) \times V(V)/1000$$

Reactive Power, Three-Phase Loads

$$S(\mathrm{kVA}) = \sqrt{3} \times I(\mathrm{A}) \times \mathrm{VL\text{-}L(V)}/1000$$

Apparent Power, Three-Phase Loads

$$\mathrm{kVA}_{3\varphi} = \sqrt{\mathrm{kW}_{3\varphi}{}^2 + \mathrm{kVAR}_{3\varphi}{}^2}$$

Power Factor

$$\mathrm{PF} = \frac{\mathrm{kW}}{\mathrm{kVA}} = \cos\theta$$

A2.1.2 Meter Types. The most basic energy meters provide energy and demand information. More sophisticated meters provide information on power quality, capture events, log and store data, display data through a local screen, and

TABLE A-2 Typical Meter Capabilities by Type

Capability	Revenue Grade Meter	Advanced Energy Meter	Submeter
Configuration	Utility socket, panel, switchboard	Utility socket, panel, switchboard	Panel, stand alone
Revenue accuracy	Yes	Yes	Not typical
Energy and demand	Yes	Yes	Yes
Power quality analysis	No	Yes	No
Data logging	No	Yes	Optional
Data output and communications	Pulse RS-232/485 Fiber optic Wireless Modem Ethernet TCP/IP Modbus, BACnet DNP 3.0	Pulse RS-232/485 Fiber optic Wireless Modem Ethernet TCP/IP Modbus, BACnet DNP 3.0	Pulse RS-232/485 Wireless Modem Ethernet TCP/IP Modbus, BACnet
Alarm and control	No	Yes	No
Programmable input connections	No	Yes	No
Graphic display	No	Yes	Not typical
Current transformers	CTs with 5 A secondary, ANSI metering class, ±0.3%	CTs with 5 A secondary, ANSI metering class, ±0.3%	
Cost	****	*****	***

communicate with or control other devices or systems. Meters can be grouped into several categories based on their capabilities: revenue grade meters, advanced energy meters, and submeters (Table A-2).

Meters can be installed as socket-mount, semiflush switchboard case style, or on panels in cabinets. Meters should be installed indoors in a dry, conditioned space, such as an indoor service entrance switchboard room, whenever possible. Other factors to consider include proximity to a data network gateway, Modbus, BACnet, or other network communication to a building management system; submeter locations; and other communication requirements.

Power meters are available in several ampere rating classes. The class designation denotes the maximum load capacities (in amperes) of the meter. Power measurements require measurements of current (amperes) integrated with the corresponding voltages. This can be accomplished directly with certain classes of data loggers that contain onboard digital watt transducers, or it can be accomplished with separate watt transducers that feed a digital pulse to the data logger. In general, voltage transformers are required for circuit applications where the voltage exceeds 600 V. Consult with the meter manufacturer or the meter specification data sheet for input requirements and limitations.

Power meters are rated in terms of accuracy. Metering accuracy should be a minimum of 1% where used for billing purposes. Meters with accuracy classifications better than 1% are readily available at reasonable cost. ANSI C12.1, *Code for Electricity Metering* (NEMA 2008), lists metering accuracy requirements and applications. However, revenue grade meters are readily available that are cost competitive with the non-revenue-grade type. Revenue grade and metering accuracy class instrument transformers should be specified for campus power distribution and building service entrance meters whenever possible. The total accuracy of any meter installation depends on the accuracy of the meter and also the accuracy of the instrument transformers.

A2.1.3 Instrument Transformers. All electric power meters, except Class 100 and 200, require inputs from current transformers (CTs), potential transformers (PTs), or both. Metering accuracy transformers with the proper burden ratings should be used for all installations. Instrument transformers complying with requirements and ratings stipulated in ANSI C57.13, *IEEE Standard Requirements for Instrument Transformers* (IEEE 2008) should always be specified. Relaying class instrument transformers are not suitable for use in metering circuits where billing and revenue accuracy are required. Split-core CTs should never be installed where revenue grade accuracy readings are desired.

A common problem with power meters after installation is data measurement errors or gaps in data due to insufficient current flow to the meter. This may be the result of the installation of CTs with a primary ratio that is too large for the actual load. This problem is avoided by specifying CTs that have primary ratios based on expected demand and that have a rating factor of RF2.0 (200% of the primary rating). Specifying metering class multiratio CTs is another option to address the ratio issue. For instance, a typical 2000 A switchboard will be manufactured with 2000:5 CTs. Consider specifying 1000:5 CTs with a rating factor RF2.0 for the metering circuit when the expected power demand is roughly half of the connected load.

All metering devices require the installation of voltage and current circuit disconnecting devices. These circuits should always include a properly rated (circuit voltage and interrupting rating) fused disconnect with rejection-type fuses and a CT shorting terminal block with safety ground.

A2.1.4 Calibration of Electric Power Meters. All revenue grade meters should have a calibration certificate indicating measurements traceable to the NIST or equivalent institution. Meter manufacturers and suppliers must provide the criteria for installed accuracy validation. Documentation affirming that the meter was properly installed and is providing accurate data should be specified to be a part of the commissioning process.

Listed below are the suggested procedures for minimum, optimal, and advanced calibration methods for electric metering devices:

a. **Minimum.** Verify the current and voltage by spot measurement. Conduct multiple-point through-system (end-to-end) calibration in the field.
b. **Optimal.** Instruments are provided with a qualitative multipoint factory calibration (including minimum, typical, and maximum). Multiple-point through-system (end-to-end) calibration is conducted in the field.
c. **Advanced.** Electric power meters are calibrated at a certified calibration laboratory. This calibration method is required for revenue grade meters and should be done once every three to four years. Verify the current and voltage by spot measurement. Conduct multiple-point through-system (end-to-end) calibration in the field.

A2.1.5 Standards for Electrical Power Meters

A2.1.5.1 ANSI C12.1-2008, *American National Standard Code for Electricity Metering.* ANSI C12.1 establishes acceptable performance criteria for new types of AC watthour meters, demand meters, demand registers, pulse devices, instrument transformers, and auxiliary devices. It states acceptable in-service performance levels for meters and devices used in revenue metering. It also includes information on related subjects, such as recommended measurement standards, installation requirements, test methods, and test schedules. This code for electricity metering is designed as a reference for those concerned with the art of electricity metering, such as utilities, manufacturers, and regulatory bodies.

Table A-3 provides descriptions of typical metering devices.

A2.2 Natural Gas

A2.2.1 Meter Types. There are numerous common types of meters that may be used to measure natural gas—diaphragm, rotary, turbine, and thermal gas mass flow.

a. **Diaphragm Meters.** Positive-displacement devices that have fixed-volume measurement compartments formed by a two-sided convoluted diaphragm. A small pressure drop across the meter causes it to cycle so these compartments alternately fill with gas at the inlet and then empty at the outlet. By counting the number of cycles, the meter provides a measure of gas volume.
b. **Rotary Meters.** These meters are positive-displacement measurement devices. In this case, a pair of impellers forms the fixed-volume compartments. When downstream demand initiates the flow of gas, the impellers rotate to receive a fixed volume of gas at the inlet and then discharge it at the outlet.
c. **Turbine Meters.** These meters have a rotor in the gas stream. As gas flows through the meter, the rotor turns at a speed that is proportional to the rate of gas. This type of meter is termed an "inferential meter."
d. **Thermal Mass Flowmeters.** These meters use a thermal sensing principle for direct mass measurement of the gas. These meters can be specified as insertion type or in-line type. The thermal mass flow sensor consists of two resistance temperature detectors (RTDs). The sensor elements are constructed of a reference grade platinum wire wound around mandrels usually inserted into stainless steel or Hastelloy tubes. The reference RTD measures the gas temperature. The instrument electronics heats the mass flow sensor to a constant temperature differential above the gas temperature and measures the cooling effect of the gas flow. The electrical power required to maintain a constant temperature differential is directly proportional to the gas flow rate.

Deciding which type of meter is the best choice for a particular application depends upon the following: the pressure of the gas being measured, the maximum flow rate to be measured, the minimum flow rate to be measured, and the cost of the meter. Table A-4 provides a comparison of the advantages and disadvantages of each meter type.

A2.2.2 Adjustment for Pressure and Temperature. Gas meters perform measurements at line conditions of pressure and temperature. This measurement is known as the "uncorrected volume." With many meters, it is necessary to convert uncorrected volume to the equivalent volume at standard conditions ("corrected volume"). At line pressures above the reference pressure (typically 14.73 psia [10356 kg/m^2], the corrected volume will be greater than the uncorrected volume. The effect of pressure can be calculated as

$$V_{SCF} = V_{ACF} \frac{P_A}{P_{ref}} = V_{ACF} \frac{(P_{atm} + P_g)}{P_{ref}}$$

where V_{SCF} is gas volume in "standard" cubic feet, V_{ACF} is the actual volume, P_a is absolute gas pressure, P_{ref} is the reference gas pressure, P_{atm} is atmospheric pressure, and P_g is the gas gage pressure (pressure relative to atmospheric pressure).

When actual flowing temperatures are above the reference temperature (60°F [15.6°C]), the corrected volume will be less than the uncorrected volume. Conversely, at temperatures below 60°F (15.6°C), the corrected volume will be greater than the uncorrected volume. The effect of temperature can be calculated as

$$V_{SCF} = V_{ACF} = \frac{(460 + T_{ref})}{(460 + T_g)}$$

where T_{ref} is the reference temperature and T_g is the actual gas temperature.

In actual practice, some type of correcting device is normally used with a meter to automatically convert to standard cubic feet (cubic metres). For diaphragm, rotary, and turbine

TABLE A-3 Measurement Methods for Electrical Use

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Existing energy meter	1%	1/2 h for instrumentation technician; zero maintenance	Read existing utility energy meter.	
Existing demand meter	1%	Instrumentation technician, 1/2 h; zero maintenance	Read existing utility demand meter.	
Portable wattmeter	1% to 5%	1/2 h for instrumentation technician, mainly to set up for measurement; normal maintenance	Use clamp-on wattmeter.	Reference voltage typically obtained by installing spring clips on electrical panel lugs. Should one of the clips become disconnected and go to ground in the process of obtaining a measurement, a potentially hazardous and damaging electrical failure will result.
Infrared pulse detector	2%	One person, 1 h maximum; normal maintenance	Install on face of utility meter with acrylic adhesive. Modulated infrared detector senses black rotation mark on meter. Requires utility permission because sensor will typically be installed on utility meter.	Does not require utility personnel for installation unless meter face must be removed to install rotation mark.
Current transformers (CTs) on secondaries and watt transducer	2%	1 h each for instrumentation technician and electrician; normal maintenance.	Split core, shunted CTs are installed on service entrance and connected to a data acquisition system (DAS).	Requires electrical service shutdown, coordination with facility, battery powered lights in work area, etc.
Portable recording wattmeter	1% to 2%	Analog output to dedicated DAS	This approach involves attaching clamp-on CTs and potential leads to a Dranatz or BMI type meter with data acquisition capability. The meter is connected to a load and operated for a specified period of time.	
Pulse splitter	1%	Included in sensor cost because installation is typically conducted by utility meter shop personnel. Requires up to 4 hr for one person; zero maintenance.	A pulse splitter is typically installed on an existing revenue meter. The retrofit is not complex.	Installation requires utility participation.

meters in an application where line pressure is stable, the meter can be supplied with an index that corrects for a constant pressure. Diaphragm and rotary meters can also be supplied with an integral continuous mechanical temperature-compensating device for temperature correction. For turbine meters and larger diaphragm meters, a correcting instrument is typically used.

A2.2.3 Calibration of Natural Gas Meters. All revenue grade meters should have a calibration certificate indicating measurements traceable to the NIST or equivalent institution. Meter manufacturers and suppliers must provide the criteria for installed accuracy validation. Documentation affirming that the meter was properly installed and providing accurate data should be specified to be a part of the commissioning process.

Listed below are the suggested procedures for minimum, optimal, and advanced calibration methods for natural gas metering devices.

a. **Minimum.** Verify the current and voltage by spot measurement. Conduct multiple-point through-system (end-to-end) calibration in the field.
b. **Optimal.** Instrumentation is provided with a qualitative multipoint factory calibration (including minimum, typical, and maximum). Multiple-point through-system (end-to-end) calibration is conducted in the field.
c. **Advanced.** Natural gas meters are calibrated at a certified calibration laboratory. This calibration method is required for revenue grade meters and should be done once every three to four years. Verify the current and voltage by spot measurement. Conduct multiple-point through-system (end-to-end) calibration in the field.

A2.2.4 Standards for Natural Gas Meters. Various organizations are involved in developing standards for natural gas measurement. Among them are the American Gas Association (AGA), the American Petroleum Institute, the Interna-

TABLE A-4 Natural Gas Flowmeter Comparison

Meter Type	Maximum Gas Pressure, psig	Maximum (Minimum) Capacity, scfh	Typical Accuracy/ Rangeability	Advantages	Disadvantages
Diaphragm	100	5000 (no minimum)	±1% 100:1	Inexpensive; good at measuring low flow rates	Mechanical components can become fouled and fail; temperature correction recommended.
Rotary	285	16,000 (1000 scfh min)	±1% 30:1 to 120:1	Good for commercial and industrial gas flow measurement	Mechanical components can become fouled and fail.
Turbine	300	150,000 (50,000 scfh minimum)	±1% of reading	Great for large gas flow rates, such as central heating plants; low pressure drop	Expensive—not good for measuring low flow rates
Thermal gas mass flow	300	384,000 (no minimum)	±1% +0.2% of full scale	Easy to install	Straight pipe is critical for accuracy and stability.

TABLE A-5 Measurement Methods for Natural Gas Use

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Existing meter	1%	1/2 h for instrumentation technician; zero maintenance	Read existing utility energy meter	
Combustion efficiency	2%	1 h for instrumentation technician	Probe inserted into combustion exhaust flue and measurements obtained. Approach may require drilling sampling port if one is not available.	Commonly overlooked performance evaluation technique
Pulse initiator	2%	One person, 1 h maximum; normal maintenance	A pulse head is normally installed on an existing meter by utility personnel. A meter change out may be required.	Does not require utility personnel for installation unless meter face must be removed to install rotation mark. Sensor can be misaligned on installation resulting in spurious data. Pulse output should be verified against dial meter reading.
Run-time sensor	1%	1 h each for field technician and electrician; normal maintenance	A run-time status is used to identify when a particular device is operating.	A status sensor and a one-time burner heat output measurement can be used as a proxy for use on natural gas fueled appliances with constant output while operating (furnaces, etc.).

tional Organization for Standardization, the Gas Processors Association, ANSI, and NIST. For more information, refer to the websites and publications of the various organizations. Table A-5 summarizes measurement methods for natural gas.

A2.3 Btu Meters

A2.3.1 Hot Water and Chilled Water. Thermal product energy use measurements refer to measurements taken after the energy fuel (e.g., electricity, natural gas) has been converted into thermal energy (e.g., hot water or chilled water), for example, hot water for heating, potable domestic hot water for human use, chilled water, and steam. It is recommended that such energy use measurements be designated separately (i.e., Btu, *t* or Joule, *t*) from energy fuel measurements (i.e., Btu, *f* or Joule, *f*) as the thermal product energy use measurements do not include the conversion efficiency.

Thermal product energy use measurements usually require a volumetric flow rate per unit time (m), a specific heat constant (e.g., at constant pressure), and a temperature difference (ΔT) (density would also be needed if measuring steam or air). Accurate thermal energy use measurements usually require calibrated flowmeters such as axial turbine meters, tangential paddle-wheel meters, target-type meters, pitot tubes, orifice meters, venturi meters, ultrasonic meters, magnetic meters, specific heats for the fluid being measured (e.g., water, antifreeze), and usually temperature measurements for the supply and return temperatures (assuming a loop configuration), or temperature rise measurements (for domestic water heaters) (Miller 1997).

TABLE A-6 Water Properties as a Function of Temperature

Property of Water	Units, I-P (SI)	Symbol	Temperature, °F (°C)				
			40 (4.4)	**60 (15.6)**	**80 (26.7)**	**100 (37.8)**	**200 (93.3)**
Specific heat	Btu/lbm·°F (kJ/kg·°C)	c_p	1.006 (4.211)	1.001 (4.19)	0.999 (4.182)	0.999 (4.182)	1.006 (4.211)
Density	lbm/ft^3 (kg/m^3)	ρ	62.42 (999.87)	62.36 (998.91)	62.21 (996.5)	61.99 (992.98)	60.12 (963.03)
Conversion constant	Btu·min/gal·°F·h (kJ·min/°C·h)	C	503.4 (252.6)	500.7 (251.2)	498.6 (250.1)	496.7 (249.2)	485.1 (234.4)

Metering building hot- and chilled-water energy use requires the measurement of three variables: entering water temperature (T_E, °F), leaving water temperature (T_L, °F), and flow rate (gpm).

From these, energy use, Q, in Btu/h, can be calculated as

$$Q = m \times \Delta h \approx c_p \times \rho \times \text{Flow} \times (T_L - T_E)$$

$$Q \approx C \times \text{gpm} \times (T_L - T_E)$$

This equation has the following sources of error:

a. The equation assumes water is an incompressible fluid. This is a good assumption for the pressures and temperatures commonly found in building hydronic systems.
b. The conversion constant 500 assumes a density and specific heat based on 68°F (20°C) water. The value is reasonably accurate for chilled water but a few percent off for hot water. This may or may not be significant in energy calculations, depending on how the energy data are used. If metering is for utility cost charge back, a more accurate calculation of this constant is probably warranted and can be interpolated from Table A-6 as a function of average fluid temperature.
c. Flow measurement can be quite inaccurate depending on the type of meter and calibration and how the meter is installed. (Flowmeters are discussed in Section A2.5.)
d. Temperature measurement accuracy also varies by sensor type and calibration. For nonrevenue metering of hot water, relatively inexpensive sensors can be used, as the temperature difference between entering and leaving water is generally large (>20°F [–6.67°C]). For chilled-water applications, sensor accuracy relative to entering and leaving water becomes significant as the temperature differences can be small (<10°F [–12.2°C]). For instance, if one sensor reads 1°F (0.556°C) high while the other is 1°F (0.556°C) low, the energy calculation can be 20% off. Temperature sensor types are discussed in more detail in Section A2.7.

The British thermal unit calculations in Table A-6 can be performed by a data acquisition system (DAS) capable of real-math calculations from flow and temperature sensors, or it can be done by a device called a "Btu meter." The Btu meter generally is configured to send calculated Btu data, optionally along with individual temperature and flow measurement data, to the DAS for monitoring. It may also have a display for manual reading of internally stored energy use data. The main advantage of the Btu meter is that temperature sensors are factory matched to minimize temperature difference calculation errors. With a stable specific heat constant and accurate sensors, these Btu meters offer accuracy better than 3%. Btu meters are recommended because of their improved temperature measurement accuracy and stability and ease of data collection, particularly if energy is being metered for revenue purposes (allocating costs of chilled- or hot-water use per building).

The temperature sensors are provided with Btu meters so that they can be factory matched and calibrated for improved accuracy. For the purpose of computing thermal loads in British thermal units per hour or tons of refrigeration, it is more important that the sensors be matched or calibrated with respect to one another than for their calibrations to be traceable to a standard. Optimally, they should be calibrated to indicate the same temperature within a tolerance of 0.15°F (0.08°C) over a range of 25°F to 75°F (–3.9°C to –23.9°C).

The flowmeter can be any type, depending on the desired accuracy (see flowmeter discussion below). The output of the Btu meter can be a pulse or analog output connected to a DAS. Modern Btu meters also include the ability to directly connect to common control networks such as BACnet/MSTP, Modbus/EIA485, LonWorks, and various proprietary networks. This allows, at low cost, not only the Btu data but also the flow and temperature data to be monitored by the DAS.

A2.3.2 Calibration of Hot-Water and Chilled-Water Btu Meters. The following are the suggested procedures for minimum, optimal, and advanced calibration methods for Btu metering devices.

a. **Minimum.** Verify the temperatures and flow rates by spot measurement. Conduct multiple-point through-system (end-to-end) calibration in the field.
b. **Optimal.** Calibrate Btu meters to NIST traceable standards for both liquid flow and temperature sensors. Testing should occur in-house at the manufacturer's facility. Each meter should be provided with a calibration certificate by the Btu meter manufacturer. Multiple-point through-system (end-to-end) calibration is conducted in the field.
c. **Advanced.** Btu meters are calibrated at certified calibration laboratories. Verify temperature and flow rates by spot measurement. Conduct multiple-point through-system (end-to-end) calibration in the field. Btu meters should be calibrated in accordance with ANSI/ASHRAE Standard 125, *Method of Testing Thermal Energy Meters*

TABLE A-7 Measurement Methods for Btu Meters

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Electronic Btu meter	2% to 5%	2 h for instrumentation technician; high maintenance	Temperature and flow sensor outputs connected to Btu meter. Signal cable routed from Btu meter to DAS.	Accuracy depends on accuracy of input sensors. Btu meters are available at a wide range of costs.
Data logger—real-time math	2% to 5%	2 to 4 h for instrumentation technician time to program data logger; normal maintenance	Conditional data logging capability (real-time mathematics) is used to calculate Btus from temperature and flow data.	Accuracy depends on accuracy of input sensors. Real-time mathematics capability is not available on all DAS.

for Liquid Streams in HVAC Systems (ASHRAE 2006). Testing should be done by an independent testing facility. Each Btu meter should be provided with a calibration certificate by the independent testing facility.

Informative Note: Adherence to ASHRAE Standard 125 is strictly on a voluntary basis.

A2.3.3 Standards for Hot-Water and Chilled-Water Btu Meters

A2.3.3.1 ANSI/ASHRAE 125-1992 (RA2006), *Method of Testing Thermal Energy Meters for Liquid Streams in HVAC Systems.* ASHRAE Standard 125 provides a method for testing factory-assembled thermal energy meters used to measure the thermal energy added to or extracted from a liquid stream supplying an HVAC system. The accuracy and precision requirements of temperature and flow measurements and test procedures are given to create plots of thermal meter error as a function of flow and temperature difference.

Informative Note: No manufacturers or independent laboratories use this standard to certify operation of water Btu meters.

Table A-7 describes common measurement methods for Btu meters.

A2.4 Steam. Thermal energy use measurements for steam can require steam flow measurements (e.g., steam flow or condensate flow), steam pressure, temperature, and feedwater temperature, where the energy content of the steam is then calculated using steam tables. In instances where the steam production is constant, this can be reduced to measurements of steam flow or condensate flow only (i.e., assumes a constant steam temperature-pressure and feedwater temperature-pressure).

Steam use can be metered in the following two ways:

a. Measuring steam vapor flow and converting to mass flow (lb/h [kg/h]) by adjusting for density variations based on steam temperature or pressure (if steam is assumed to be saturated) or based on temperature and pressure (if steam is superheated).
b. Measuring steam condensate flow and converting to mass flow (lb/h [kg/h]) by adjusting for density variations based on fluid temperature.

Historically, the latter approach was most popular because measuring liquid flow was much less expensive and it is accurate over a very wide flow range. Utility grade diaphragm meters were most commonly used, particularly for building submetering applications, but turbine meters are another option. However, condensate flow does not include processes for which no condensate is returned, such as steam used for humidification and some sterilizers. With the advent of more accurate gas flow measurement devices, direct measurement of steam is becoming the preferred metering approach.

The most common steam volumetric flow measuring device is the vortex shedding meter. It is accurate across a fairly wide flow range (at least 25:1 but as high as 150:1), but as with all meters, its accuracy drops off at very low flow rates. If the range is expected to vary widely and accuracy is required at low flow rates, consider splitting the steam service into two or more (e.g., one service for year-round low-flow steam use and another for high-flow winter heating and humidification loads), each with its own meter sized for the expected flow rate and range.

Steam vapor volumetric flow rate can be converted to mass flow rate using the following equation:

$$G = \frac{V}{\upsilon}$$

where G is the mass flow rate (lb/h [kg/h]), V is the volumetric flow rate (ft^3/h [m^3/h]) as measured by the flowmeter, and υ is the specific volume (ft^3/lb [m^3/kg]). To determine the specific volume for saturated steam, steam temperature or pressure must be measured from which specific volume can be determined from the steam tables (see *ASHRAE Handbook—Fundamentals* [ASHRAE 2005], Chapter 6) or equations approximating the table. For superheated steam, both temperature and pressure must be measured from which specific volume can be approximated by perfect gas laws or determined more accurately with empirical correlations with temperature and pressure. Typically, steam is not superheated by the time it reaches the meter from the steam boilers, so these more complex calculations are not required.

Many meters are available that make the volumetric to mass flow rate conversion using a built-in temperature or pressure sensor and conversion logic within the meter transmitter so that external conversion to mass flow rate is not required.

The output of the steam calculator (Btu meter) can be a pulse or analog output connected to a DAS. Modern steam calculators also include the ability to directly connect to common control networks such as Modbus-RTU and others. This allows

TABLE A-8 Hot-Water and Chilled-Water Flowmeter Comparison

Type	Configuration	Typical Accuracy/ Minimum Flow	Advantages	Disadvantages
Turbine (single for small pipes, dual for pipes 2.5 in. [0.064 m] and larger)	Insertion	±2% 0.5 fps (0.15 m/s)	Usually, least expensive insertion style allows easy retrofit (via hot tap) and removal for cleaning, replacement.	Can be fouled by contaminants in water; not recommended for open-circuit systems. Moving parts result in lower operating life, possibly degrading accuracy. Requires correct installation depth to be accurate. Sensitive to installation details—long straight inlet and outlet runs are required.
Full-bore magnetic	Flow tube	±0.5% 0.05 fps (0.015 m/s)	Most accurate meter. Lowest minimum flow rate. Least sensitive to installation problems and requires least amount of straight piping runs at inlet and discharge. Very little maintenance required; no moving parts. Long life with little calibration required.	Most expensive meter, and especially expensive for large pipes (>12 in. [0.305 m]). Cannot be removed without shutting off system or providing an expensive bypass.
Single-point magnetic	Insertion	±1% 0.2 fps (0.06 m/s)	Insertion style allows easy retrofit (via hot tap) and removal for cleaning, replacement. Very little maintenance required; no moving parts. Long life with little calibration required.	Relatively expensive for small pipe sizes. Requires correct installation depth to be accurate. Sensitive to installation details—long, straight inlet and outlet runs are required.
Vortex shedding	Insertion	±2% 1 fps (0.3 m/s)	Insertion style allows easy retrofit (via hot tap) and removal for cleaning, replacement.	Not accurate at low flows. Can be fouled by contaminants in water. Requires correct installation depth to be accurate. Sensitive to installation details—long straight inlet and outlet runs are required.
Transit time ultrasonic	External	±0.5% 1 fps (0.3 m/s)	External mount allows easy retrofit and replacement. No moving parts and no parts exposed to fluid so maintenance costs are low.	Relatively expensive for small pipe sizes. Not accurate at low flows or quick rate of change. Requires correct configuration to be accurate—sensitive to configuration details such as pipe dimensions and wall thickness. Sensitive to installation details—long straight inlet and outlet runs and precise mounting are required.

not only the Btu data but also the flow and temperature and any other data stored in the meter to be monitored by the DAS.

A2.5 Liquid Flow. Choosing a liquid flowmeter for a particular application requires knowledge of installation requirements (flange, tap, straight length, pipe size, etc.); accuracy required; fluid type and properties, including temperature, density, pressure, viscosity, turbidity (cleanliness of the fluid), corrosiveness, and levels of aeration; flow conditions the meter is to encounter, including the range of expected flow velocities and flow profile and turbulence at the point of measurement; pressure drop limitations; and available budget.

In general, flow sensors can be grouped into four different meter types:

a. Obstruction differential pressure-type flowmeters (e.g., nozzle, orifice plate meter, venturi meter, averaging pitot tube meter, wedge, flow tube).
b. Obstruction sampling-type flowmeters (e.g., variable-area meter, positive displacement meter, turbine meter, tangential paddle-wheel meter, target meter, vortex meter, insertion magnetic meter, hot-wire anemometer).
c. Noninterfering meters (e.g., ultrasonic meter, full-bore magnetic meter).
d. Mass flowmeters (e.g., Coriolis mass flowmeter, angular momentum mass flowmeter).

While there are specific applications for each of these metering technologies, this annex discusses the more common liquid flow measurement devices that are used in conjunction with temperature measurements to determine the thermal energy in a fluid flow. Table A-8 compares the features, advantages, and disadvantages of these meters, with application issues summarized in the subsections that follow.

A2.5.1 Nondifferential Pressure Obstruction Flowmeters. Several types of nondifferential pressure obstruction flowmeters have been developed that are capable of providing a linear output signal over a wide range of flow rates, often without the severe pressure-loss penalty that is incurred with an orifice plate or venturi meters. These include the variable-area meter, positive displacement meter, axial turbine meter, tangential paddle-wheel meter, target meter, vortex meter, and insertion magnetic meter. In general, these meters place a small target, weight, spinning wheel, or sensor in the flow stream to determine the velocity of the fluid. These instruments must be calibrated and installed with care to ensure that the sampled flow velocity can be accurately related to the average flow velocity.

a. **Axial Turbine Meters.** Axial turbine meters measure fluid flow by counting the rotations of a rotor that is placed in a flow stream. Axial turbine meters can be full-bore type or insertion type. Full-bore turbine meters have an axial rotor and a housing that is sized for a specific installation. Turbine insertion meters allow the axial turbine to be inserted into the fluid stream and use the existing pipe as the meter body. This type of meter can be hot-tapped into existing pipes through a valving system without having to shut down the system.

   The insertion turbine meter may have one or two turbines. The single turbine only samples the fluid velocity at a small cross-sectional area of pipe; therefore, total volumetric flow rate can only be accurately inferred if the meter location provides conditions consistent with the meter's calibration. This is typically used in fully developed and stable flow with minimal nonrotational or skewed components. Manufacturer specifications rely on these conditions being provided. These conditions are typically found in long, straight sections of pipe removed from internal turbulence.

   One dual turbine insertion meter offers the advantage of counter rotating turbines, thereby reducing the impacts of rotational flow while increasing the cross-sectional area sampled. Insertion meters can be used on pipe above 2 in. (5 cm) diameter with very low pressure loss. The rate of rotation of the turbines, driven by the fluid, provides an output linear with flow rate for turbulent flow. This output can usually be obtained either as a signal pulse representing a quantity of fluid flow or as a frequency or analog signal proportional to flow rate.

b. **Vortex Meters.** Vortex meters use the same basic principle that makes telephone wires oscillate in the wind between telephone poles. This effect is due to oscillating instabilities in a low field after it splits into two flow streams around a blunt object. Vortex meters have no moving parts and are suitable for gas, steam, and clean liquid flow measurements. They require minimal maintenance and have good accuracy and long-term precision. Vortex meters provide a linear digital (or analog) output. They are a point measurement and need to be calibrated. Vortex meter accuracy is of rate, not full scale.

c. **Insertion Magnetic Meters.** Insertion magnetic meters use Faraday's law of electromagnetic induction to facilitate the measurement of sampled flow. Insertion magnetic meters can be found with single or multiple sensors per probe. Greater accuracy can be obtained if multiple probes are used at each measurement location. They require an electrically conductive fluid. Insertion magnetic meters are now available that are very accurate (±1% of rate through a flow range of 1 to 15 fps [0.3 to 4.57 m/s]). They are equipped with insertion and removable hardware for hot-tap applications. Their cost and sizes above 10 in. (0.254 m) pipe are appreciably less than full-bore magnetic meters.

A2.5.2 Noninterfering Flowmeters. In all of the previously described meters, some interference with the flow stream is necessary to extract a measurement. Recently, a relatively new class of meters has been developed that is able to extract a measurement without placing an obstruction into the fluid stream.

a. **Ultrasonic Flowmeters.** Transit-time ultrasonic flowmeters (UFMs) measure fluid velocities by detecting small differences in the transit time of sound waves that are shot at an angle across a fluid stream. Various designs have been developed that use multiple-pass, multiple-path configurations. Clamp-on UFMs have been developed that now facilitate convenient measurement of fluid velocities in pipes of varying sizes. Typical manufacturers' stated accuracies vary from 1% to 3% of actual flow to 2% of full scale. The ability to achieve these accuracies is largely dependent on installation technique and field conditions.

   Doppler UFMs measure fluid velocities by sensing the velocity of small particles or air bubbles entrained in the fluid with sound waves that are shot at an angle across a fluid stream. Such meters require a certain number of particles and air bubbles in the fluid to reflect the signal back to the receiver. Doppler-effect meters are available with accuracies between 2% and 5% of full scale and are normally less expensive than the standard transit time-effect ultrasonic devices. Meter cost is independent of pipe size.

   It should be noted that UFMs are difficult to field calibrate. These meters are velocity-dependent devices and are highly vulnerable to errors caused by poor pipe and flow conditions and improper installation technique, as are the obstruction types of flowmeters. Using the manufacturer's stated accuracy for field applications can be risky.

b. **Full-Bore Magnetic Meters.** Full-bore magnetic flowmeters use Faraday's law of electromagnetic induction to measure the average flow velocity in a pipe. Magnetic coils surround the flow, using a pulsed direct current (DC) or AC-generated field to produce a signal. The signal is proportional to the average velocity in the pipe and is nearly unaffected by flow profile. Manufacturers of pulsed DC-excited magnetic flowmeters have a stated flow uncertainty of 1% within a 10:1 turndown if flow velocity is greater than 0.5 fps (0.15 m/s). The AC-excited magnetic flowmeters have a stated flow uncertainty of 1% to 2% full scale. They require an electrically conductive fluid.

   Magnetic meters are becoming the flowmeter of choice for custody transfer energy-based liquid flow measurement. They offer many advantages such as 0.25% to 1% accuracy, high precision, and wide operating ranges under limited restrictions at increasingly reduced costs. Advancements in approaches, such as pulsed DC and dual frequency excitation offer excellent long-term stability and greatly reduce the need for recalibration. Full-bore magnetic flowmeters come in a variety of installation formats. While they are very accurate, they are also somewhat expensive.

A2.5.3 Minimum Installation Requirements

A2.5.3.1 Location Specification. Flowmeters that are sensitive to flow conditions (dynamic flow, severe rotational velocities, or high spatial variation in velocities) should be located a minimum of 20 diameters upstream and 10 diameters downstream of straight-run piping, clear of any flow disturbances. More than 20 diameters of upstream straight-run piping are preferred if multiplane close-coupled elbows are present upstream. If insertion-type flowmeters are used, the hot tap should be oriented in the plane of the outside radius of the first upstream elbow. The length of straight pipe before and after the meter should be specified by the meter manufacturer to achieve the accuracy stated for the meter.

A2.5.3.2 Use of Flow Straightening Devices. If the minimum installation requirements cannot be met or severe flow conditions exist, a flow straightening device should be used.

A2.5.4 Calibration of Flowmeters. Field calibrations of flow measurement systems are both complex and costly. Use of portable UFMs to calibrate a permanent liquid flowmeter is not recommended. Their use as a transfer standard to known accuracy requires sophisticated procedures that are extremely expensive and time consuming to apply. The accuracy of a single measurement is highly suspect, but they are very helpful in establishing the flow profile within the pipe. UFMs are velocity dependent devices and are highly vulnerable to variations in flow profile and installation error. They should be considered 5% devices at best for pipe diameters 12 in. (0.305 m) and under. UFM flow profile compensation assumes a fully developed flow profile at the calculated Reynolds number. Even at 10 diameters downstream of an elbow, significantly altered flow profile will occur. It is suggested that flow profile compensation be turned off and the acceptable deviation between the measuring flowmeter and the UFM be restricted to 5% for applications with less than 10 pipe diameters of straight length pipe upstream of the UFM.

Because field calibrations can be difficult and expensive, it is recommended that an appropriate device be selected that is the least vulnerable to field conditions. It should provide the accuracy required and be laboratory calibrated. If the device selected is vulnerable to field conditions, efforts should be made to ensure stable flow conditions in the field. In long-term monitoring applications, the device should be inspected and cleaned and provided with laboratory recalibration on a periodic basis. In lieu of field calibrations, the flow profile should be thoroughly documented and alternative measures used to ensure the accuracy of the measurement point. For differential pressure devices, the associated differential pressure (and pressure if measuring vapor state) instruments should be calibrated periodically.

A2.5.4.1 Fixed Flow Applications. For fixed flow applications, spot check flow using a portable UFM.

A2.5.4.2 Variable Flow Applications. For variable flow applications, spot check flow using a portable UFM at a range of flow conditions.

A2.5.4.3 Evaluation of Spatial Variation in a Liquid Flow Profile. One method to field-verify the accuracy of an installed flow sensor is to confirm that the installed flow conditions in the field are consistent with the flow conditions that existed during laboratory calibration. If the laboratory calibration was done properly, the flow sensor was calibrated under flow conditions that provided centered and stable flow conditions over the range of flow velocities the sensor would see when installed. If the flow profile at the point of measurement is centered and stable, the laboratory calibration can be considered to apply to the field installation. One method of verifying that the flow stream is centered and stable is to evaluate its spatial variation.

Spatial variation can be determined by sampling the flow profile at a number of radial points across the pipe cross section at the measurement location with one channel of a two channel UFM. The second channel is required as a control to correct the sample average due to variations of flow in time. The suggested method using an ultrasonic flowmeter to determine spatial variation uncertainty is as follows:

a. Use a two-channel UFM system whose function has been verified by an independent laboratory other than the manufacturer.
b. At the proposed measurement location do the following:
    1. Determine pipe parameters: diameter, wall thickness, material, temperature, presence and condition of lining.
    2. Determine fluid parameters: temperature, sonic velocity, viscosity.
    3. With channel 1, take flow readings at orientations of 0, 45, 90, and 135 degrees (from the top of the pipe on horizontal pipes) while simultaneously taking readings with channel 2 at 90 degrees nearby.
    4. Use the reflect (2 path) mode. If the flowmeter has a flow profile compensation feature, this compensation should be turned off.
    5. The flow profile should be verified at least at the minimum, typical, and maximum expected flow rates.
c. The UFM is an excellent diagnostic tool, useful for identifying variations in the flow profile. But using the UFM's average measured flow as a calibrated flow reading is not recommended. This requires a sophisticated procedure outside the scope of this annex.
d. Spatial variation for each expected flow rate can be calculated as follows:

    Spatial Variation, % = (t-statistic) × (Standard deviation of measurements corrected for variations due to time)/(Number of measurements)$^{1/2}$/(Average of the corrected measurement) × 100

e. For dynamic applications that yield multiple ranges of typical flow rates, spatial variation is then equal to the standard deviation of the spatial variations for each expected flow rate (such as minimum, typical, and maximum expected) divided by the square root of the number of expected flow rates observed. It is also possible to weight each expected flow rate by the expected frequency of occurrence.

This procedure was developed for ASHRAE Standard 150, *Method of Testing the Performance of Cool Storage Systems* (ASHRAE 2004). A sample calculation is found in Standard 150 Annex D, "A Method of Determining Spatial Variation in a Liquid Flow Stream." An accurate UFM is as expensive as an insertion magnetic meter. Its accuracy is dependent on a very careful installation, recognizing the specific needs for laying lengths above and below the flowmeter. The pitot tube traverse is a much better device. Further, the insertion magnetic meter described above is a much better meter to use because it can be extracted and tested in a certified laboratory.

A2.5.5 Standards for Flowmeters. There are several applicable standards for liquid flow measurement, depending on the instrumentation. In each case, the standards describe procedures and techniques for the specific class of instruments. The following standards may be appropriate for in situ flow testing. The main concerns for field applications are accuracy, cost, installation and retrieval methods, ease of measurement, and degree of intrusion.

a. ANSI/ASHRAE Standard 41.8, *Standard Methods of Measurement of Flow of Liquids in Pipes Using Orifice Flowmeters*
b. ANSI/ASME MFC-2M-1983 (R1988), *Measurement Uncertainty for Fluid Flow in Closed Conduits*
c. ANSI/ASME MFC-5M-1985 (R1989), *Measurement of Liquid Flow in Closed Conduits Using Transit-time Ultrasonic Flow Meters*
d. ANSI/ASME MFC-6M-1998, *Measurement of Fluid Flow in Pipes Using Vortex Flow Meters*
e. ANSI/ASME MFC-8M-2001, *Fluid Flow in Closed Conduits- Connections for Pressure Signal Transmission Between Primary and Secondary Devices*
f. ANSI/ASME MFC-9M-1988, *Measurement of Liquid Flow in Closed Conduits by Weighing Method*
g. ANSI/ASME MFC-10M-1988, *Method for Establishing Installation Effects on Flowmeters*
h. ANSI/ASME MFC-11M-2006, *Measurement of Fluid Flow by Means of Coriolis Mass Flowmeters*
i. ASME PTC 19.5-2004, *Part II of Fluid Meters—Interim Supplement on Instruments and Apparatus*

Table A-9 summarizes measurement methods for various flowmeters.

A2.6 Temperature. Most commonly used temperature sensing devices use one of four basic methods for measuring temperatures: RTDs; thermoelectric sensors (thermocouples); semiconductor-type resistance thermometers (thermistors); and junction semiconductor devices, which are also called integrated circuit (IC) temperature sensors. Measurement accuracy is depends on the type of sensor, the sensor method of measurement (direct insertion, thermowell, or surface temperature), the absolute temperature, the vibration level of the measurement location, the distance and routing between the sensor and the data logging device, and the data logging device's method of reading the sensor input.

A2.6.1 Resistance Temperature Detectors. RTDs are metallic devices whose resistance changes with temperature. They are among the most accurate, reproducible, stable, and sensitive thermal elements available. These devices are economical and readily available in configuration packages to measure indoor and outdoor air temperatures as well as fluid temperatures in chilled water or heating systems. Considering their overall performance, the most popular RTDs are 100 and 1000-ohm platinum devices in various packaging, including ceramic chips, flexible strips, and thermowell installations in either two-, three-, or four-wire configurations, with or without current transmitters.

a. Four-wire RTDs all but eliminate lead length and path issues, and a data logging device with a pulsed constant current source (to reduce self-heating effects) can measure temperatures to within 0.01°F (0.056°C) if properly calibrated.
b. Three-wire RTDs moderately reduce the effect of the long leads in an appropriately designed bridge circuit (0.25°F [0.139°C]).
c. Two-wire RTDs must be field calibrated to compensate for lead length and should not have lead wires exposed to conditions that vary significantly from those that are being measured (0.5°F [0.278°C]).

Factory matched and calibrated sensors with current transmitters can be used with data logging devices that do not have four-wire RTD measurement capability to improve accuracy (0.1°F [0.056°C]). These also reduce lead wire effects. Most data logging equipment allows for direct connection of RTDs by providing internal signal conditioning and the ability to establish offsets and calibration coefficients. Some types of RTDs tend to be more prone to failure at high temperatures or under high vibration.

A2.6.2 Thermocouples. In thermocouple thermometry, the magnitude of the voltage is dependent on the type of material and the temperature difference. The most commonly used thermocouple materials are platinum-rhodium (Type S or R), chromel-alumel (Type K), copper-constantan (Type T), and iron-constantan (Type J). Though thermocouples are economical and reasonably accurate (though less accurate than RTDs), they require cold junction compensation, and their output signal is weak, making them sensitive to electrical noise and requiring the use of amplifiers and wide spans. They are also vulnerable to stress and vibration. Once a thermocouple has been placed in service, it is, in effect, never the same. Thermocouples are used in the laboratory for fast response averaging or differential temperature thermal arrays or in the field when accurate temperatures are required at high temperatures and high vibrations. Thermocouples are usually cheaper than RTDs.

A2.6.3 Thermistors. Thermistors are semiconductor devices whose resistance changes with temperature. They offer high sensitivity and fast linear response. At high resistance, they can be very accurate over narrow ranges. One of the primary differences between thermistors and RTDs is that

TABLE A-9 Measurement Methods for Flowmeters

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Portable ultrasonic flowmeter	5%	1 h for instrumentation technician; normal maintenance	Meter sensor is adjustable to fit a variety of pipe diameters.	Proper application and installation are critical. Potentially useful for in-field sensor verification.
In-line or insertion flowmeter	2%	4 h for instrumentation specialist; high maintenance	Flowmeter is inserted into pipe through weldolet. Signal cable is routed to a DAS.	Includes welding and hot-tap costs. Various flowmeter types are available. Routine recalibration is important.
Accumulating flowmeter	1% to 2%	1 h each for plumber and instrumentation technician	Hot-water rated accumulating water meter installed on water line to be measured.	Requires licensed plumber for installation. Visual reading of accumulating register.
Pulse flowmeter	2%	1 h for plumber, 1 h for instrumentation technician; normal maintenance	A utility-grade pulse initiating water meter is installed in the water line to be measured. Signal wire is routed to the DAS.	A licensed plumber will typically be required for installation.

thermistors have a very large negative resistance change with temperature. Thermistors are not interchangeable and their temperature-resistance relationship is very nonlinear. They are fragile devices and require the use of shielded power lines, filters, or DC voltage.

A2.6.4 Integrated Circuit Temperature Sensors. Certain semiconductor diodes and transistors also exhibit reproducible temperature sensitivities. Such devices are usually ready-made IC sensors and can come in various shapes and sizes. These devices are occasionally found in HVAC applications where their low cost and strong linear output over a narrow range are requirements. They are typically found in averaging or multipoint temperature sensors and in some Btu meters. IC temperature sensors have a moderately good absolute error, but require an external power source, are fragile, and are subject to self-heating errors.

A2.6.5 Calibration of Temperature Sensors. The following methods can be used to calibrate temperature sensors.

a. Single-point verification/calibration in the field using physical standards: Ice bath, 32°F (0°C); gallium cell, 84.59°F (29.22°C).
b. Multipoint verification/calibration in the field at various points in the operating range (including minimum, typical, and maximum) using a Dewar flask; include physical standards whenever possible.
c. Laboratory and field multipoint verification/calibrations using cold block, hot-block cell, or regulated fluid bath that has been calibrated by a NIST-traceable device or uses a secondary standard as reference; include physical standards whenever possible.

A2.6.6 Standards for Temperature Measurement. Table A-10 describes some typical temperature measurement procedures.

A2.6.6.1 ANSI/ASHRAE 41.1-1986 (RA2006), *Standard Method for Temperature Measurement*. ASHRAE Standard 41.1 describes procedures intended specifically for use in testing HVAC equipment and components. The standard applies to temperature measurements in air, water, brine, and volatile or nonvolatile refrigerants, under both steady state and transient conditions between −40°F and 400°F (–40°C and 204°C). This standard has general measurement techniques as well as specific techniques for liquid-in-glass thermometers, thermocouples, and electric resistance thermometers (including thermistors). Recommended accuracy, precision, and test tolerances are given for air dry bulb, air wet bulb, water, and refrigerant temperatures. Limits of error of thermocouples and extension wires are given for different types of thermocouples. The general guidelines of this standard apply to field and laboratory measurements, while the accuracy recommendations need to be compared to the requirements for field performance testing. Investigations are required to test whether the accuracy recommendations can be achieved at reasonable costs in field applications.

A2.6.6.2 ANSI/ASME PTC 19.3-2010 (R-2010), *Temperature Measurement*. ASME Performance Test Code (PTC) 19.3 is a summary discussion of temperature measurement and basic sources of error for radiation thermometers, thermocouples, resistance thermometers, liquid-in-glass thermometers, and others. The code goes into greater detail than ASHRAE Standard 41.1 on the theory and principles of operation, materials of construction, and characteristics of the various types of thermometers. The limits of error for thermocouples listed in the two codes are identical. PTC 19.3 details extensive laboratory calibration methods for the various types of thermometers. While this code is an excellent reference, it has limited application and installation details that could apply to in situ measurements. The standard includes a list of advantages and disadvantages for each type of thermometer, which could be helpful in choosing measurement techniques for particular projects.

A2.7 Psychrometric Properties. Obtaining accurate, affordable, and reliable humidity measurement has always been a difficult and time-consuming task. Recently, such measure-

TABLE A-10 Measurement Methods for Temperature

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Portable electronic thermometer	2%	15 min for an instrumentation technician; normal maintenance	A handheld digital thermometer is used to record interior temperatures at specified locations.	Care must be taken to select representative locations for temperature measurement. Substantial spatial variation in indoor temperature often exists. Be aware of outdoor "heat island" effects. Take care not to obtain readings near furnace flues or exhaust air outlets.
Portable recording electronic thermometer	2%	1 h for instrumentation technician; normal maintenance	Temperature sensors provide analog output to a dedicated DAS. RTDs, thermistors, and thermocouples are all commonly used as sensors.	A simple and easy-to-use approach when only temperature data are required.
Surface-mounted electronic temperature sensor	2%	2 h for instrumentation technician; normal maintenance	Temperature sensor is cemented to outside surface of metal pipe. Signal wire is routed to DAS.	Thermal contact between temperature sensor and pipe is critical.
Electronic temperature sensor and thermowell	1% to 2%	1 h for instrumentation specialist; 1 h for plumber; normal maintenance.	Thermowell is installed in plumbing system. Temperature sensor is installed in thermowell. Signal wire is routed to DAS.	A licensed plumber is typically required for sensor installation.

ments have become more important in HVAC applications for purposes of control, comfort, system diagnosis, and performance evaluation. The amount of moisture in the air can be described by several interchangeable parameters, including relative humidity, humidity ratio, dew-point temperature, and wet-bulb temperature.

A2.7.1 Relative Humidity Sensors. Typically, relative humidity sensors are available in the following accuracies: 5%, 2%, and 2% (NIST certified). For monitoring or control of building spaces (i.e., rooms), temperature and humidity sensors are often contained in a single device, allowing one device to be used to measure both space conditions. The sensor can use a bulk polymer sensing element. The advantages of the bulk polymer sensor technology are small size, low cost, and fast response times (on the order of 1 to 120 s for 64% change in relative humidity); and good accuracy over the full range, including the low end, where most devices lose their accuracy.

A2.7.1.1 Calibration of Relative Humidity Sensors. The following can be used to calibrate relative humidity sensors.

a. Single point calibrator, 3%, that has been calibrated by a NIST traceable device.

b. Portable environmental chamber that has been lab calibrated with an NIST traceable dew-point monitor, 3%.

c. Laboratory calibration in a salt bath or in an environmental chamber controlled by a calibrated NIST traceable dew-point monitor, 3%. Salt baths are not recommended outside of the laboratory. They do not transport well and their accuracy is greatly affected by the unstable environmental conditions usually found in the field.

d. Field calibration using a single-point calibrator or portable environmental chamber that has been lab calibrated with an NIST traceable dew-point monitor (Turner et al. 1992).

A2.7.2 Dew-Point Sensors. The condensing (chilled mirror) dew-point sensor is an accurate and reliable instrument over a wide humidity range. Typical accuracy is ±1°F (±0.5°C) with the dew point being measured over a range of −40°F to +136°F (−40°C to +58°C). This sensor works by using a cooled mirrored surface; when the surrounding air reaches the dew-point temperature, it condenses on the mirrored surface. The condensate is detected by optical techniques. The measured surface temperature is then the dew-point temperature. The temperature of the mirror is read by a precision (100 ohm, four-wire) platinum RTD embedded beneath the mirror's surface.

A2.7.2.1 Calibration of Dew-Point Sensors. The following can be used to calibrate dew-point sensors. Table A-11 describes typical humidity measurement techniques.

a. Single-point calibrator
b. Portable environmental chamber that has been laboratory calibrated
c. Laboratory calibration

A2.8 AirFlow. Airflow is measured with many of the same measurement techniques used for liquid flow. Sensor selection is also dependent upon the measurement application, although cooling-coil face velocity, fume hood ventilation airflow, and compressed airflow may all be measured by the same sensor type. Airflow offers an even greater challenge

TABLE A-11 Measurement Methods for Psychrometric Measurement

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Sling psychrometer	2%	15 min for instrumentation technician; normal maintenance	Sling psychrometer is rotated and visual reading of wet- and dry-bulb temperatures is obtained.	Still in common use for one-time measurements. Can be used both indoors and outdoors. Not accurate above 80% relative humidity. Avoid operating in direct sunlight.
Portable electronic relative humidity (rh) meter	2% to 5%	15 min for instrumentation technician; normal maintenance	Read handheld instrument.	Instrumentation cost depends on accuracy requirements. Usable both indoors and outdoors.
Electronic rh sensor	2% to 5%	1 to 2 h for instrumentation technician; 1 h for electrician may be required for installation of sensor power supply.	Sensor is typically installed on interior wall, often in association with temperature sensor.	Sensors typically require separate low-voltage power supply for operation. Electronics cannot operate in a condensing environment.
Electronic dew-point sensor	2%	2 to 4 h for instrumentation technician; requires monthly maintenance		Requires meteorological enclosure.

than liquid due to the extensive size or lack of a clearly defined cross-sectional area. Also prevalent are unpredictable flow profiles, low velocities, and the presence of moisture that complicate the measurement.

Typical sensor types include the pitot tube, rotameters, and vane and hot-wire anemometers. Pitot tubes can be single port or multiple port. Hot-wire anemometers and pitot tubes can be employed in area averaging arrays to obtain a more accurate measurement in fume hood and duct applications. Some sensor systems incorporate upstream flow straightening vanes. Orifice plates and nozzles are also used, especially in industrial applications. Pitot tubes, orifice plates, and nozzles utilize a differential pressure transducer or transmitter across the sensor to interpret the measured flow velocity. To determine mass flow, the pressure and temperature also need to be recorded.

A2.8.1 Calibration of Airflow Measurement. Calibration of airflow measurement systems in the field is often more difficult than for liquid flow, because of large and complex ductwork and the difficulty of using clamp-on ultrasonic instrumentation to measure airflow. While ultrasonics can be used to determine flow profile of liquid flows, and with great care for calibration, the clamp-ons have a poor coupling to the flow if used with air. Whether or not a calibration should be performed depends on the installed flow system. If the flow system is inherently accurate, such as with an array of pitot tubes or a flow nozzle or orifice with adequate flow conditioning, then inspection of the array for damage or deposits and a calibration of the differential pressure sensor should be adequate. The differential pressure and pressure sensors should be calibrated periodically, such as every six months to one year if high accuracy is required. If the flowmeter system has greater potential inaccuracy, then a field calibration may be necessary (e.g., if the system cannot be sent to a calibration laboratory).

Field calibrations of airflow can be performed under steady state conditions by pitot tube or propeller anemometer traverses in at least two planes. These devices require laboratory calibration for the field calibration to be valid. Where the field conditions will vary under normal operation, calibrations should be checked over a range of at least five flow rates.

If the flow measurement accuracy is not critical, a rough check can be made by performing a flow and/or an energy balance with another system that has good flow measurement instrumentation.

A2.8.1.1 Fixed-Flow Applications. Inspect flowmeter for damage, deposits, or plugging, and repair if necessary. Calibrate differential pressure and static pressure instruments. Check flow by performing a flow or energy balance with other measurements. Perform a multiplane pitot tube or anemometer traverse at the expected flow rate.

A2.8.1.2 Variable-Flow Applications. Inspect flowmeter for damage, deposits, or plugging, and repair if necessary. Calibrate differential pressure and static pressure instruments. Check flow by performing a flow or energy balance with other measurements under several flow conditions. Perform a multiplane pitot tube or anemometer traverse under at least five flow conditions across the range of expected flows.

A2.8.2 Airflow Standards

A2.8.2.1 ASHRAE 41.2-1987 (RA 1992), *Standard Methods for Laboratory Airflow Measurement.* ASHRAE Standard 41.2 sets forth recommended practices for airflow measurement for consistency in procedures and for reference in other ASHRAE Standards. The standard describes procedures to calculate flow rates from measurements of pressure differential across a flow nozzle or from measurements of velocity pressure obtained by a pitot traverse. The general practices outlined in this standard apply to both laboratory and field measurement of airflow. The obtainable accuracies can be used to help determine if the techniques in this standard are appropriate for a particular application.

A2.9 Pressure. Selecting a pressure measurement device for an application entails consideration of

a. accuracy and stability required;
b. pressure range;
c. reference pressure (gage, absolute, or differential);

TABLE A-12 Measurement Methods for Airflow Measurement

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Flow hood	2% to 5%	1/2 h instrumentation technician; normal maintenance	Flow hood placed over register or grille is to be measured.	Flow hoods are used to measure airflow through supply and return air registers and grilles.
Pressurization depressurization test	3% to 5%	1 h for instrumentation technician; normal maintenance	Measurement system is connected to single register; other registers in duct system are sealed.	Measurement system consists primarily of a variable-speed fan that can be connected directly to a duct system to pressurize or depressurize a forced air distribution system. Very accurate measurements of duct leakage can be obtained with careful measurement.

d. desired signal output (0 to 5 VDC; 4–20 mA, digital);
e. special features of the device's electronics, such as flexibility of scaling, digital communications/remote access, or fast response;
f. ease of use; and
g. available budget.

For industrial applications, the main categories of pressure measurement instruments include

a. manometers;
b. local indication, gage type;
c. transducers; and
d. transmitters.

Each category includes many different mechanical designs. This annex discusses the more common designs and the applications for which they would be useful.

A2.9.1 Manometers. The most common types of manometers include visual (U-tube, well, inclined, and micro) and digital/electronic (float, capacitance, sonar detector). They can handle static or differential pressure spans from 0.1 in. to about 60 psid (34.5 to 42,184 kg/m^2, with a maximum design pressure of about 6000 psig (4,218,400 kg/m^2). Visual manometers can be read to about 0.01 in. (3.45 kg/m^2), and micromanometers can be read to about 0.002 in. (0.69 kg/m^2). Manometers are most useful for temporary instrumentation setups when readings are to be taken manually. They are fundamental instruments and do not require independent calibration equipment, as they can be zeroed manually. For improved accuracy, their readings should be adjusted for temperature and gravity to standard conditions. Accuracy is also affected by capillary effects in the tube and by the method used to read the liquid level.

Manometers rely on a liquid level, so they are sometimes difficult to read if the pressure is not steady because the liquid level will oscillate. Thus, they are less suitable for obtaining accurate readings under unsteady conditions. They also require some maintenance to keep them clean so that they can be read easily, so that their inner diameter does not change, and to keep them free of air bubbles. It is very important to ensure all air is bled out of the whole instrument system when manometers are used. There are also safety issues that need to be considered because manometers can break, or their fluid (sometimes mercury) can blow over into the process or leak into the environment.

The main advantages of manometers are their high accuracy, low cost, and simplicity. Their accuracy is based on how accurately they can be read and on the adjustments that are made to standard conditions. There are some safety concerns and maintenance requirements.

A2.9.2 Gages. The most common types of pressure indicating gages include bellows, Bourdon tube, and diaphragm designs. They are available in many ranges, from vacuum to 10,000 psig (7,030,696 kg/m^2). Dial sizes can vary from 2 to 6 in. (690.6 to 2071.9 kg/m^2). The accuracy tends to vary with dial size, ranging from 0.25% for large dials to 2% for small dials. These instruments are easier to set up and use than manometers, but because they are not "fundamental" instruments, they may need calibration if accuracy is required. Accuracy can be affected by temperature and mechanical damage due to corrosion or vibration. Some gages are filled with glycerin to dampen the vibration of the pointer and to eliminate condensation within the gage.

As with other pressure measurement devices, it is important to bleed the instrument lines of air to maintain a known water leg up to the gage. Gages should be mounted in the same position that they were calibrated in to maintain accuracy. Because they are usually installed in a vertical position, air may tend to collect below the gage, which would affect its water leg correction and the accuracy of the reading. If they are to be used with corrosive liquid or vapor, they should be isolated from the process with a seal (e.g., chemical, diaphragm, or volumetric) or purge. Pointers can be fitted with a maximum pointer to indicate the maximum pressure reached in the system.

The advantages of gages are their low cost and simplicity. The disadvantages are that they need to be read manually and they need calibration for good accuracy.

A2.9.3 Pressure Transducers. These pressure measurement devices come in a variety of types, including strain gage, capacitive, potentiometric, piezoelectric, and optical. Most of these types can measure pressures from somewhere in the vacuum range to at least 10,000 psig (7,030,696 kg/m^2). Potentiometric and optical transducers are not designed to measure vacuum. Most transducers can be accurate to 0.1% of span or to 0.25% of full scale, but the piezoelectric and potentiometric may only be accurate to 0.5% to 1.0% of full scale. To obtain 0.1% accuracy, transducers should be calibrated. They are also affected by temperature, and their readings would need to be corrected to maintain better than 0.1% accuracy. Temperature is typically compensated for in the more "intelligent" transmitter designs.

The most popular designs are the strain gage and capacitive types. Transducers (without transmitters) typically need signal conditioning to amplify their output for measurement by a data collection system. They are less expensive than transmitters. They usually respond faster to pressure fluctuations than transmitters but are less flexible in terms of being able to adjust their spans and output, and they do not compensate their output for temperature or static pressure (which can affect differential pressure transducers). They are better than manometers and dial gages for long-term installations or where a large number of measurement points need to be recorded and linked to a data measurement system.

A2.9.4 Transmitters. Most transducer types are available with either a conventional or intelligent transmitter. Conventional transmitters condition the output of the transducer and typically provide a 4 to 20 mA output signal. They usually have potentiometers for zeroing and ranging. The more intelligent transmitter also provides adjustments to the output signal for temperature and static pressure (for some differential pressure transmitters). The output signal can be made proportional to the square root of the pressure. Transmitters can also provide filtering of the output signal to reduce the noise in the reading (by providing a running average for output). An intelligent transmitter can be communicated with remotely to perform such things as diagnostics, resetting, rescaling, or calibration. Some can also transmit data digitally over a single twisted-pair cable that can handle more than one sensor output.

Like pressure transducers, pressure transmitters should be calibrated to attain accuracies of about 0.1%. However, they will maintain their accuracy over a wider range of conditions because of their temperature (and pressure) compensation. They are more expensive, but they are easier to use with a data collection system and more convenient to configure, calibrate, and maintain.

A2.9.5 Minimum Installation Requirements. For static pressure measurements to be accurate, instrument taps should be located on straight piping runs, and they should be smooth, with no burrs, along the inside of the pipe. Instrument tubing should slope downward to the sensor location when the lines will fill with liquid, so that air (or vapor) can rise out of the tubing. ASME PTC guidelines recommend 1/2 in. (1.27 cm) tubing, but many installations use 1/4 in. (0.635 cm) tubing for convenience. Where the reading's accuracy can be significantly affected by air in the tubing (such as differential pressure measurements under a vacuum), larger tubing and shorter, steeper tubing runs are recommended where possible. For vacuum measurements of vapor, the tubing should slope upward to the sensor location so that condensate can drain out of the tubing toward the process. Sometimes a very small air bleed can maintain a clear line without affecting the measurement. Transmitters should be conveniently located to allow for calibration and maintenance.

Pressure sensors should be mounted as recommended by the manufacturer (typically horizontally for many transducers and transmitters and vertically for gages and manometers), with enough rigidity to minimize vibration, which could affect reading accuracy and damage equipment. If necessary, the process should be isolated from the sensor to avoid corrosion. Dampeners may be used to reduce significant pressure fluctuations. Bleed lines should be installed to enable convenient bleeding of air out of the sensor lines, up to the sensor. Some sensors are equipped with bleed plugs on their bodies. On the most critical measurements (such as fuel flow), consider redundant sensors to improve accuracy and reliability.

A2.9.6 Calibration of Pressure Sensors. The accuracy to which pressure-sensing instrumentation is to be calibrated depends on the required accuracy of the process measurement. For example, differential pressure and pressures used to determine flow rate typically require the highest accuracy, pressures used to determine state point require good accuracy, and pressures used by operations for checking processes may require less accuracy. The frequency of the calibration will depend on the stability of the instrumentation and the accuracy requirements. For very high accuracy, calibrations at installation and every six months to one year are recommended. For good accuracy, calibration at installation and then every two years may be sufficient. For lower accuracy requirements, a loop test at installation and then a calibration when there appears to be a problem should suffice.

The most accurate calibration would entail a through-system calibration, where a known pressure is maintained at the transmitter and compared with the reading at the direct digital control system or digital readout. It is preferred that the transmitter be calibrated after it is mounted and installation is complete. Where an intelligent transmitter communicates digitally with a control system, it may be possible to take the reading at the transmitter, although a through-system calibration is still the preferred method.

The pressure source for the calibration can be a deadweight tester or an electronic pressure calibrator for ranges above atmosphere and an accurate digital pressure gage for ranges below atmosphere. The accurate calibration should cover the entire expected operating pressure range of the process, with at least five calibration points. The correction can be applied either within the sensor or in the control system. After the correction is applied, another set of calibration points should be run to check that the correction was applied properly. A record of calibrations for each instrument should be maintained. If after several calibrations, the drift is found to be very small, then the calibration interval can be increased.

The reference pressure should be adjusted for temperature, local gravity, and static pressure if required by the deadweight tester or electronic calibrator. These adjustments correct the reading to reference conditions, such as 68°F (20°C) or the acceleration of gravity at 45 degrees latitude at sea level. The adjustments should be made to the reference pressures before the calibration corrections are applied to the instrument.

A2.9.6.1 Static Pressure. Gage pressure calibrations can be performed with deadweight testers (inaccuracies are less

TABLE A-13 Measurement Methods for Pressure Measurement

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Pressure transmitter	1% to 5%	2 to 4 h instrumentation technician; normal maintenance		Installation costs and requirements will vary with specific sites. Leakage must be avoided.
Pressure transducer	1% to 5%	2 to 4 h instrumentation technician; normal maintenance		Installation in retrofit applications may be complex.

than 0.05%) or electronic pressure calibrators (inaccuracies are about 0.1%). If the pressure sensor is set up to read absolute pressure, an atmospheric pressure gage will be needed to add ambient pressure to the applied reading. Calibrate at a minimum of five points, including the low and high ends of the instrument range. Depending on what the data system accepts, the corrections could be a linear curve representing the calibration points that encompass the expected process readings, or if all five calibration points are reasonable, they can be entered in the data system as discreet points.

Vacuum range pressures can be attained with a vacuum pump, with an atmospheric pressure gage as the reference using, the following procedure:

a. Draw a vacuum on the transmitter.
b. Use a 0 to 1000 μm vacuum gage to verify that 0 psia has been reached, if it is one of the calibration points.
c. Zero the reference gage if necessary.
d. Gradually bleed air into the system, and at each calibration point, stop the bleed and record the calibration data.

A2.9.6.2 Differential Pressure. Differential pressure transmitters are calibrated by applying a known pressure to their high-pressure side. Pressure can be applied by a deadweight tester or electronic calibrator. The calibration results are applied in the same way as for static pressure transmitters. This method of calibration is acceptable for high line pressure applications if the transmitters have static pressure compensation. If the transmitters do not compensate for line pressure, and high accuracy is required, the calibration source can be a special deadweight tester that applies both a differential pressure and a static pressure. If the line pressure is predictable, the differential pressure calibration points can be applied at a single static pressure. If the static pressure varies, the calibration points can be applied at a range of static pressures, and the calibration corrections can be interpolated.

A2.9.6.3 Very Low Differential Pressure. Very low differential pressure instruments (such as draft range transmitters) can be calibrated in comparison to a very sensitive manometer, such as a micromanometer or digital manometer. The manometer must be zeroed. A hand pump/bleed valve setup can be used to apply the small pressures required to the high sides. The manometer is adjusted and the instrument readings are compared at each point. The temperature of the manometer fluid should be used to adjust its readings to the standard temperature conditions of the transmitter.

A2.9.7 Pressure Standards

A2.9.7.1 ANSI/ASHRAE 41.3-1989, *Standard Method for Pressure Measurement.* ASHRAE Standard 41.3 presents practices for accurately measuring steady-state, nonpulsating pressures. The scope of the standard covers type of pressure, range of applications, accuracy, and installation and operation techniques. Devices covered include differential pressure (head) meters, elastic element gages, manometric gages, pressure spring gages, and pressure transducers. The limits of accuracy and calibration techniques for these devices are discussed. Examples of measurement applications for HVAC ductwork and hydronic systems are given. Once the required pressure measurement accuracies are determined, this standard can be used to help choose appropriate pressure measuring devices.

A2.9.7.2 ANSI/ASME PTC 19.2-1987 (R2004), *Pressure Measurement Instruments and Apparatus.* ASME PTC 19.2 describes the various types of instruments and methods of measurement likely to be prescribed by other codes and standards. Details that will determine their range of application are given, such as the limits and sources of error, methods of calibration, and precautions. Static, differential, absolute, gage, and velocity pressure are defined. Guidelines for pressure connections to systems are detailed along with potential sources of error. For liquid level gages, tables are supplied for corrections due to meniscus height, capillary depression, temperature, and gravity variations. Other types of instruments described are deadweight gages, elastic gages, and low-pressure measurement devices.

Table A-13 summarizes measurement methods for two of the device types discussed here.

A2.10 Thermal Fuel Energy Use Measurements. Thermal fuel energy use measurements refers to measurements of the fuel that is being consumed by the energy conversion device, including coal, wood, biomass, natural gas, oil, and various forms of liquid petroleum. For any of the fuel types the higher heating value (HHV) of the fuel must be known. These values are usually measured by the fuel supplier or can be obtained by sending a sample of the fuel for analysis. The thermal fuel energy use is then calculated by multiplying the mass (kilograms or pounds) of the fuel and the HHV. Coal weight or gallons (litres) of oil may need to be obtained from shipping invoices. (See ASHRAE [2007], Table 5.1.)

A2.11 Run Time. Measurement and verification (M&V) of energy savings often involves little more than an accurate accounting of the amount of time that a piece of equipment is operated or "on." Constant-load motors and lights are typical of this category of equipment that doesn't need to be metered with full-featured RMS power metering equipment to establish energy use. Self-contained battery-powered monitoring devices are available to record equipment run time (and in some cases, time-of-use information). This equipment provides a reasonably priced, simple to install solution to energy

TABLE A-14 Measurement Methods for Run-Time Measurement

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Status sensor	2%	1 h each for electrician and instrumentation technician; normal maintenance	Status sensor is installed on control circuitry of device being monitored. Sensor is opened or closed depending on operating status of device	Often required for evaluating the performance of devices with multiple operating conditions, such as heat pumps and refrigeration systems

savings calculations. Run-time measurements are typically applied to dedicated single circuit devices. Table A-14 describes one simple run-time measurement device.

A2.12 Ventilation and Ventilation Standards

A2.12.1 ANSI/ASHRAE Standard 129-1997 (RA2002), *Measuring Air Change Effectiveness.* Standard 129 defines a method of measuring air-change effectiveness in mechanically ventilated buildings or spaces. The method involves the age-of-air approach to air-change effectiveness and uses tracer gas procedures to measure the age of the air. The age of air at a given location is the average amount of time that has elapsed since the air molecules at that location entered the building. The definition of air-change effectiveness is based on the comparison of the age of the air in the occupied portions of the building to the age of air that would exist under conditions of perfect mixing of ventilation air.

Table A-15 describes several common ventilation measurement devices/techniques.

A2.13 Weather Data. Building energy use is often dependent on variables other than temperature and relative humidity. In locations where complete weather data are not available from the National Weather Service, additional measurements such as solar radiation and wind speed may need to be taken. Table A-16 summarizes the recommended additional weather measurements.

A3. EQUIPMENT TESTING STANDARDS—FACTORY

A3.1 Equipment Testing Standards—Chillers. The theoretical aspects of calculating chiller performance are well understood and documented. Chiller capacity and efficiency are calculated from measurements of water flow, temperature difference, and power input (Figure A-2). Calculations can also be checked by a heat balance performed on the entire system. These calculations and measurement techniques are detailed in the following subsections. In addition to these, there are few engineering articles in the literature specifically oriented toward the field testing of chillers. Chiller efficiency and amount of refrigeration produced can be calculated in real time using the energy management and control system (EMCS). These calculations require measurements of flow rate and temperature difference that can be recorded and used to calculate the thermal energy flows by the EMCS. Anderson and Dieckert (1990) discuss a method of testing chillers that could be accomplished without machine interruption. A graph of heat rate error as a function of mass flow rate error and temperature differential points to the importance of sensor accuracy for heat rate evaluations. The authors used IC temperature sensors and dual-rotor insertion flowmeters. Because field tests could not be done at rated conditions, data were compared to the expected values as determined from manufacturers' specifications.

For chiller testing, relative temperature measurement precision is more important than true accuracy because chiller capacity is related to the temperature difference. Relatively simple testing can be used to determine whether a chiller has a clean condenser and is performing satisfactorily by comparing a single test against the manufacturer's published performance curves (Harmon 1984).

A3.1.1 ARI Standard 550-92, *Centrifugal and Rotary Screw Water-Chilling Packages.* ARI Standard 550 establishes definitions and nomenclature for centrifugal and rotary screw chillers. It also defines the standard full- and part-load rating conditions for these types of chillers so that published ratings will have a consistent basis. Equations for calculation of allowable deviation tolerances from rated conditions are also given for full and part load. ARI Standard 590 (ARI 1992b) establishes similar conditions for the rating of chillers using positive displacement compressors.

A3.1.2 AHRI Standard 550/590-2003, *Performance Rating of Water-Chilling Packages Using the Vapor Compression Cycle.* AHRI Standard 550/590 combines two previously separate standards: ARI Standard 550-92 for centrifugal and rotary screw water-chilling packages, and ARI Standard 590-92 for positive displacement compressor water-chilling packages. Primary and confirming test methods are prescribed, along with test procedures detailing operational limits of the measured parameters, data to be recorded, and calculation of results.

A3.1.3 ASHRAE Standard 30-1995, *Methods of Testing Liquid Chilling Packages.* ASHRAE Standard 30 prescribes a method for testing liquid-chilling packages but does not specify the test conditions under which the system must operate. Primary and confirming test methods are prescribed, along with test procedures detailing operational limits of the measured parameters, data to be recorded, and calculation of results. Instruments and measurement techniques refer to other existing standards.

A3.2 Equipment Testing Standards—Fans. The theoretical aspects of calculating fan performance are well understood and documented. Fan capacity and efficiency are calculated from measurements of static pressure, velocity pressure, flow rate, fan speed, and power input (Figure A-3). The difficulties involved in standardizing in situ performance measurement are the wide variety of fan installations and system configurations. Measurement techniques and calculations are detailed in the following subsections. In addition to the standard measurement procedures listed in the standards below, several

TABLE A-15 Measurement of Mechanical Ventilation

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Tracer gas (SF_6)		3 h for instrumentation technician; zero maintenance	Technician initiates the dispersion of SF_6 gas, then collects periodic air samples over a 2 h period. Gas chromatograph or infrared spectrometer is required for analysis.	Substantial training is required to properly conduct test. Measurement produces total ventilation rate. Nonmechanical ventilation is computed by subtracting mechanical ventilation from this total. See electricity use measurement type for mechanical ventilation measurement protocols.
Perfluorocarbon tracer (PFT) test (4 zones), including analysis	5% to 10%	2 h for instrumentation technician; 1 h for deployment; 1 h for retrieval; zero maintenance	PFT sources and samplers are deployed in building per protocol.	PFT test is temperature dependent. Measurement produces "average" ventilation rate. Nonmechanical ventilation is computed by subtracting mechanical ventilation from this total. See electricity use measurement type for mechanical ventilation measurement protocols.
Blower door	5%	2 h for instrumentation technician; normal maintenance	Blower-door test protocol is followed. Computer-controlled fan with digital micromanometer pressurizes/depressurizes the building.	A trained technician is required for measurement. Measurement produces estimated ventilation rate. Nonmechanical ventilation is computed by subtracting mechanical ventilation from this total. See electricity use measurement type for mechanical ventilation measurement protocols.

TABLE A-16 Measurement of Additional Weather Data

Measurement Device	Accuracy	Sensor Installation and Maintenance	Measurement Procedures	Comments
Pyrheliometer—solar radiation	1% to 5%	4 h for instrumentation technician; normal maintenance	Pyrheliometer is mounted on a flat surface that has direct unshaded solar exposure during all hours of the year. Tracker is operated by a computer controlled motor. Signal cable is routed from the unit to a DAS.	Expensive instrumentation is typically used for research purposes.
Pyranometer—solar radiation	2% to 5%	2 h for instrumentation technician; high maintenance	Pyranometers are typically mounted on a horizontal exterior surface. Signal cable is routed to the DAS.	Horizontal solar radiation data can be converted by algorithm to incident radiation at any other surface angle. A multipyranometer array may be required for accurate measurements.
Wind speed recording anemometer	5%	2 to 4 h for instrumentation; high maintenance	Cup anemometer is installed on mast in representative location. Signal cable is routed to DAS.	Measurement error increases at low wind speeds. Wind speeds below 5 to 7 mph are often not recorded.
Wind speed meteorological grade recording anemometer	2%	4 to 8 h for instrumentation technician; high maintenance	Cup anemometer is mounted on mast in representative location. Signal cable is routed to DAS.	This level of accuracy is often not required in building measurement experiments.

articles have been published in *ASHRAE Transactions* (Stevenson 1976; Clarke 1976; Myers 1976; Zaleski 1976) that describe the basis for what was to become AMCA Publication 203, *Field Performance Measurement of Fan Systems*. Performance ratios, such as the Specific Fan Power (fan power/design airflow rate), can be used to characterize the possibilities of air systems to deliver low annual energy use (Jagemar 1994).

For example, measurements and handbook data show that for variable-speed drives (VSDs),

$$\text{Fan power} = (\text{Flow rate})^n$$

where

n = 2.0 to 2.5 for return fans

n = 1.5 to 2.0 for supply fans providing static pressure (Jagemar 1994)

A3.2.1 ANSI/ASHRAE Standard 51-2007 (AMCA210-2007), *Laboratory Methods of Testing Fans for Rating.* This standard establishes uniform methods for laboratory testing

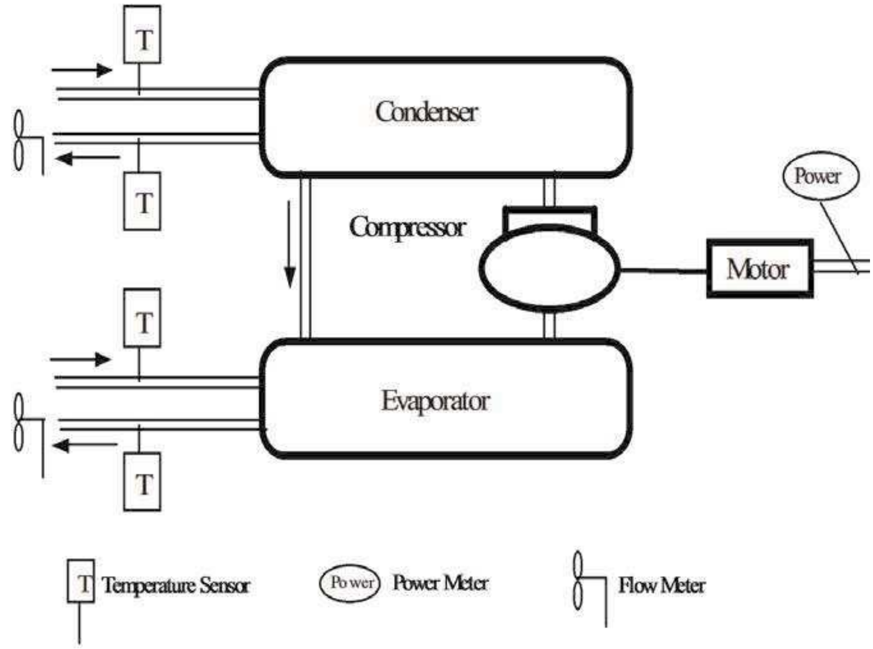

FIGURE A-2 Typical chiller with minimum required instrumentation.

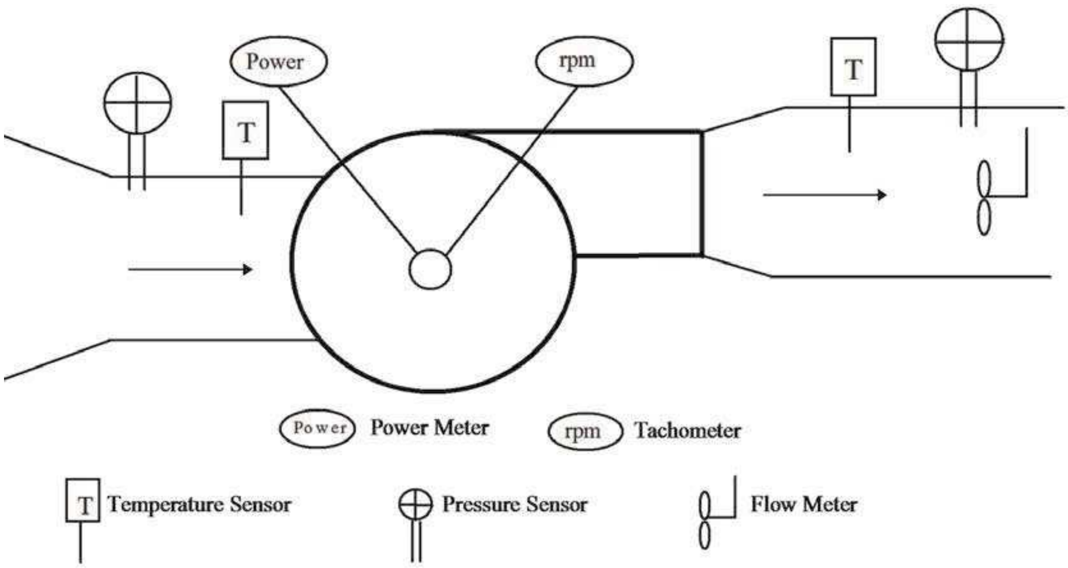

FIGURE A-3 Typical centrifugal fan with minimum required instrumentation.

of fans to determine performance in terms of flow rate, pressure, power, air density, speed of rotation, and efficiency. The units of measurement, definitions, instruments and methods of measurement, and calculations all have some validity for field testing. However, the laboratory equipment setups in this standard are generally precluded for field use because the prescribed duct configurations would require extensive alterations to installed systems.

A3.2.2 AMCA Standard 803-02 (R2008), ***Site Performance Test Standard for Power Plant and Industrial Fans.*** This standard establishes uniform methods for measuring the performance of large power plant or industrial fans under actual operating conditions on the site. The standard applies only to fans where the system effect is insignificant. This is determined by the calculation of minimum allowable deviations in the flow velocity profiles and duct geometry. If the installation does not meet the requirements of this standard, AMCA Publication 203-90, *Field Performance Measurement of Fan Systems* (see Section A3.2.3), should be consulted to deal with the system effects.

A3.2.3 AMCA Publication 203-90 (R2011), ***Field Performance Measurement of Fan Systems*****, and AMCA Publication 201-02 (R2011),** ***Fans and Systems.*** These two standards together provide guidance for the measurement of fan systems in the field. The major difficulty of field testing fan systems is the difficulty of finding appropriate locations for the required

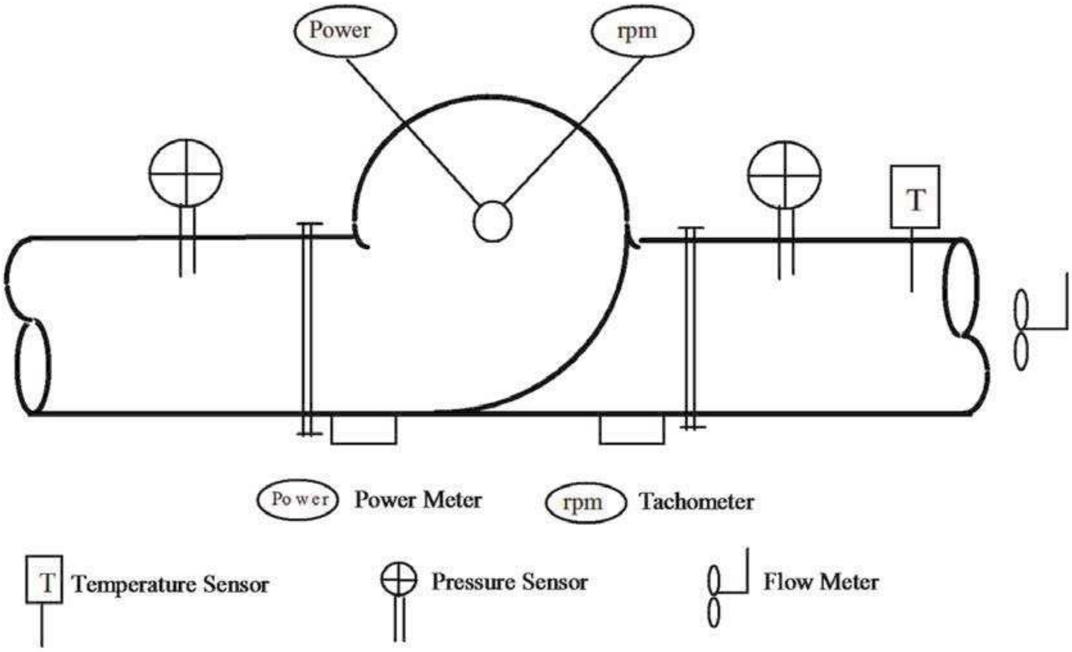

FIGURE A-4 Typical centrifugal pump with minimum required instrumentation.

measurements. The major restriction in the choice of traverse planes is the uniformity of the velocity profile. Because of the variety of fans and installations, they are necessarily somewhat general.

A3.2.4 ASME PTC 11-2008, *Fans*. ASME PTC 11 provides standard procedures for testing fans under actual operating conditions. Two approaches are included, one using mass flow rate and fan specific energy and the other (more common in HVAC applications) using volume flow rate and pressure. The methods in PTC 11 are based on measurements sufficiently close to the fan boundaries that correction for losses between traverse planes and fan boundaries are not required. The code specifies the velocity traverse method as the primary method for flow measurements and simple arithmetic summing to calculate the average flow. Traverse plane limitations are similar to AMCA Publication 203 (see Section A3.2.3). To account for varied velocity distributions, this code specifies a relatively large number of traverse points and requires the use of directional velocity probes. This method determines a single operating point for the fan in question. Separate tests are required for multiple operating points.

A3.3 Equipment Testing Standards—Pumps. The theoretical aspects of calculating pump performance are well understood and documented. Pump capacity and efficiency are calculated from measurements of pump head, flow rate, and power input (Figure A-4). These calculations and measurement techniques are detailed in the following standards.

A3.3.1 ASME PTC 8.2-1990, *Centrifugal Pumps*. ASME PTC 8.2 establishes rules for conducting pump tests under specified conditions to determine pump head, pump capacity, power input, efficiency, and net positive suction head requirements. The types of pumps in HVAC applications are a limited subset of the pumps covered in this standard. Two sets of testing procedures are described with differing uncertainty and accuracy requirements. The requirements of a particular project will determine which of the procedures is most appropriate. The standard is organized by guiding principles, instruments and method of measurement, and computation of results. Various configurations for the measurement of pump pressure are given. Capacity measurement is referred to other standards, with the applied limitations of the calibration and accuracies in this standard. For field application, the recommended accuracies should be compared to the requirements of the project in question and the limits of the available measurement techniques.

A3.3.2 Hydraulic Institute, Centrifugal Pump Test Standards. The Hydraulic Institute test standards apply to centrifugal, vertical turbine, mixed flow, and axial flow pumps and provides limiting conditions for measurement of capacity, head, speed, and input power. The tests are intended for rated and or specified conditions only and do not include provisions for part load performance. Calculations and examples are included for all performance characteristics and for methods of measuring pressure, capacity, speed, and shaft power.

Pellet (1974) gives advice on field performance measurement of pumps, stressing good engineering practice and practical solutions to common problems. Measuring techniques for pump head, capacity, and power are covered. Pump flow can be calculated from a pump curve using a measured pressure differential across the pump. Although the accuracy of this method depends on the shape of the pump curve, this method may still have applications such as check against other flow measurements. Advances in measuring and recording technology have made many of the technical aspects of this article obsolete, but the recommended practices and troubleshooting techniques are valid. Pump energy conservation in HVAC systems is often oversimplified toward comparisons of pump efficiencies. The type of system and its control strategy are essential for accurate estimation or calculation of annual energy use. A broad range of energy use can occur with various schemes for the same system (Rishel 1983).

A3.4 Equipment Testing Standards—Motors. These standards are included for completeness. In this project, the motors are considered a part of the equipment being tested. In addition, these motor-testing standards are not applicable in most in situ applications because they depend on shaft loading procedures that usually require disconnection of the motor in question.

a. ANSI/IEEE Standard 112-2004, *Standard Test Procedures for Polyphase Induction Machines*
b. ANSI/IEEE Standard 113-1985, *Standard Test Procedures for Direct Current Machines*
c. ANSI/IEEE Standard 115-2009, *Standard Test Procedures for Synchronous Machines*

In addition to the above-mentioned standards for motors, several engineering papers have been published for calculating efficiencies for the chillers, fans, and pumps requiring accurate testing of the driving motors. Hoshide (1994) describes utilizing the nearly linear relationship between motor slip and load for checking motor load. With motor load calculated and input power measured, motor efficiency is easily calculated.

Lobodovsky et al. (1989) describe a utility pilot project for field testing of electric motor efficiencies and determination of economically viable alternatives. The procedure used for field measurements was the IEEE 112 Method E/F. Required measurements for this procedure are load and no-load voltages, amperes, power factor (or power), shaft rpm, and stator resistance. Field experience is documented for the testing of 60 industrial motors noting difficulties especially in the no load measurements because of the need to uncouple the motor in question.

An Arizona program for replacement of HVAC motors discovered that the slip method of motor testing is prone to large errors because of the effects of incorrect nameplate data, motor temperature, operator error, operating voltage, and motor rewinding effects (Jowett 1994). A simple amperage test can determine motor loading above 50% with reasonable accuracy, while lower motor loading requires more involved tests as documented by Lobodovsky et al.

In recent years, the use of VSDs to control fans, pumps, compressors, and other equipment has risen steadily. Their use increases the efficiency of equipment at part load or flow. The fan or pump affinity laws predict that reductions in flow reduce the input power requirements according to a cube function. However, system interactions, such as static pressure, are not accounted for in the affinity laws, and experience has indicated that the actual system curve using VSD equipment will follow a square function, rather than the theoretical cube function (Stebbins 1994). Englander and Norford (1992) propose analysis of VSD applications on the basis of energy use characteristics or system characteristics. Five distinct categories are identified. Simplified general expressions for pump or fan power as a function of flow and pressure offset for throttled and VSD control are presented.

A3.5 Equipment Testing Standards—Boilers and Furnaces. There are two principal methods for determining boiler efficiency, the input-output method and the heat loss method, also known as the "direct method" and the "indirect method," respectively. Both are recognized by the American Society of Mechanical Engineers (ASME) and are mathematically equivalent. They would give identical results if all the required heat balance factors were considered and the corresponding boiler measurements could be performed without error. ASME has formed committees from members of the industry and developed ASME PTC 4.1a, *Steam Generating Units* (ASME 1974), which details the procedures for determining boiler efficiency by the two methods mentioned above. The following discussion has been extracted from Wei (1997).

Boiler efficiency is defined as the percentage of heat input to the boiler that is absorbed by the working fluid. The general practice in the United States is to base boiler efficiency on the HHV of the fuel, whereas in most countries using the metric system it is customary to use the lower heating value of the fuel (Aschner 1977). Practical design considerations limit the boiler efficiency that can be achieved. Typically, boiler efficiencies range from 75% to 95% for utility boilers (Stallard and Jonas 1996). For industrial and commercial boilers, the average efficiency ranges from 76% to 83% on gas, 78% to 89% on oil, and 85% to 88% on coal (Payne 1985).

The input-output method is the easiest way to determine boiler efficiency. It was standard for a long time, but is little used now (Gill 1984). In this method, the heat supplied to the boiler and the heat absorbed by the water in the boiler in a given time period are directly measured. Thus, the efficiency of a nonreheat boiler is given by

$$\eta_b = \frac{Q_a}{Q_i} \times 100 \tag{A-1}$$

where

Q_a = heat absorbed (Btu/h) = $\sum m_o h_o - \sum m_i h_i$

$m_o h_o$ = mass flow-enthalpy products of working fluid streams leaving the boiler envelope, including main steam, blowdown, soot blowing steam, etc

$m_i h_i$ = mass flow-enthalpy products of working fluid streams entering the boiler envelope, including feedwater, desuperheating sprays, etc.

Q_i = heat inputs (Btu/h [kJ/h]) = $V_{fuel} \times \text{HHV} + Q_c$

V_{fuel} = volumetric flow of fuel into the boiler, scf/h (m^3/h)

HHV = fuel higher heating value, Btu/scf (kJ/m^3)

Q_c = heat credits, Btu/h (kJ/h)

Heat credits are defined as the heat added to the envelope of the steam generating unit other than the chemical heat in the fuel as fired. These credits include quantities such as sensible heat in the fuel, the entering air, and the atomizing steam. Other credits include heat from power conversion in the pulverizer or crusher, circulating pump, primary air fan, and recirculating gas fan.

For an abbreviated test (ASME 1974), heat credits can be ignored and the efficiency can be evaluated by using the results of only seven measurements (fuel flow rate, steam flow rate, steam and feedwater pressure and temperature, and HHV of the fuel). The trouble with this method is that the accuracy of these measurements, especially the flow rates, is sometimes an issue. To ensure that accurate readings are obtained, the measuring device should be inspected and the transducers calibrated. However, in normal practice, often only the transducer is taken out for calibration, and the measuring device is left untouched as its inspection requires the teardown of some equipment or a major plant outage. This is exactly what happened in the case study central utilities plant. Haberl et al. (1993b) pointed out this problem in a study of the A&M central utilities plant and noted that it must be resolved to implement an operational optimization program. However, it was not discussed in a previous boiler testing program in this plant (Dukelow 1991). As a consequence, even though a meter is newly calibrated, the readings it provides may not be accurate. Methods that can identify inaccurate meters without interrupting the plant's normal operation are needed.

Aside from the drawback mentioned, the direct method is also limited in that it only gives the efficiency of the boiler and does not indicate where the losses occur and the way to minimize them. Generally, the best method for efficiency determination is the heat loss method. Boiler efficiency equals 100% minus the losses. The heat loss method concentrates on determining the heat lost from the boiler envelope or the heat not absorbed by the working fluid. The method determines boiler efficiency as

$$\eta_b = \frac{Q_a}{Q_i} \times 100 = \frac{Q_i - Q_{loss}}{Q_i} \times 100$$

$$\eta_b = 100 - L_{df} - L_{fh} - L_{am} - L_{rad} - L_{conv} - L_{bd} - L_{inc} - L_{unacct} \tag{A-2}$$

where

Q_{loss} = heat losses, Btu/h (kJ/h)
L_{df} = dry flue gas heat loss, %
L_{fh} = fuel hydrogen heat loss, %
L_{am} = combustion air moisture heat loss, %
L_{rad} = radiation heat loss, %
L_{conv} = convection heat loss, %
L_{inc} = uncombusted fuel loss, %
L_{bd} = blowdown heat loss, %
L_{unacct} = unaccounted for heat losses, %

The heat losses include the flue gas loss (sensible and latent heat), radiation and convection loss, fuel loss due to incomplete combustion, blowdown loss, and losses that are unaccounted for. The flue gas loss is the major loss and is generally determined by a flue gas analysis; it varies with flue gas exit temperature, fuel composition, and type of firing (Aschner 1977). The radiation and convection loss can be taken from the standard American Boiler Manufacturers' Association curve (Babcock and Wilcox 1992).

For a boiler fired with solid fuel, an unaccounted loss of 1.5% is commonly used; for a gaseous or liquid fuel boiler, the commonly used value is 1% (Dukelow 1991). Blowdown is sometimes considered a loss (Witte et al. 1988; Aschner 1977). Although it is not a useful heat output, it is not considered a loss in the ASME PTC because the boiler has properly transferred the heat from the fuel to water. The dependence of these losses on boiler load is an important boiler characteristic and is the major factor considered in boiler load management (Payne 1985; Peters 1992; Shane 1981; and Yaverbaum 1979).

In the procedures used to calculate the heat losses, the two accepted methods are the "weight" method and the "mole" method. The weight method is used in the heat loss method of the ASME PTC, in which a combined standard mean specific heat of 0.24 Btu/lb/°F (0.56 kJ/kg) is used for the dry flue gas. With the mole method, the combustion chemistry formulas are used to determine the number of moles of each flue gas constituent, and the individual specific heat of each constituent is also used. For this reason, the mole method is slightly more precise than the standard ASME method.

Accuracy or uncertainty in boiler efficiency calculations is a function of the quantities measured and the method used to determine the efficiency. Using the input-output method, these quantities are related to overall efficiency. For example, if the measured boiler efficiency is 80%, then an error of 1% in one of the quantities measured will result in a 0.8% error in the efficiency. However, for the heat-loss method, the measured and determined parameters are related to net losses. Therefore, for the same boiler of 80% efficiency, a measurement error of 1% in any quantity would affect the overall efficiency by only 0.2% at most (1% of the measured losses of 20%). As a result, the heat-loss method is inherently more accurate than the input-output method for boilers with efficiencies above 50%.

The term "combustion efficiency" is often encountered in the literature describing boiler performance. Combustion efficiency is a measure of the fraction of fuel-air energy that becomes available during the combustion process (Thumann 1988). It is given by

$$\eta_c = \frac{|h_p| - h_f + h_a}{Q_i} \times 100 \tag{A-3}$$

where

η_c = combustion efficiency, %
h_p = enthalpy of products, Btu/lb (kJ/kg)
h_f = enthalpy of fuel, Btu/lb (kJ/kg)
h_a = enthalpy of combustion air, Btu/lb (kJ/kg)

If the products of combustion were cooled to the temperature of the entering fuel and combustion air before leaving the boiler, a 100% combustion efficiency could be achieved. However, this is impractical because it would require infinite heat transfer surface and would cause corrosion at the boiler cold ends as a result of moisture condensation. Generally, flue gas leaves the boiler at an elevated temperature, causing the combustion efficiency to drop. Fuels of higher hydrogen content produce combustion gases that have high specific heats;

thus, the flue gas loss tends to be greater and the combustion efficiency is lower. The relationship between boiler efficiency and combustion efficiency can be expressed by the following equation (Garcia-Borras 1983):

$$\eta_b = \eta_c - L_{rad} - L_{conv} - L_{unacct} \qquad \text{(A-4)}$$

Generally, the loss terms on the right-hand side of the above equation are small for a well-insulated boiler. Therefore, the combustion efficiency is about equal to the boiler efficiency. This equality is *not* valid, however, for boilers with poor insulation, poor blowdown control, or both of these faults.

There are well-proven empirical methods for estimating the stack loss (L_{df}, L_{fh}, and L_{am}) (Aschner 1977), radiation loss (L_{rad}), and convection loss (L_{conv}) and losses unaccounted for (L_{unacct}) (Fryling 1966); there are also statistical data for the other losses (Aschner 1977; Payne 1985). Combustion efficiencies for different types of fuels under various combustion conditions are available in tabular form (Dyer and Maples 1981; Taplin 1991; and Dukelow 1991). Their application and comparison with test results are used to investigate the influence of boiler design and operation on efficiency and fuel use.

The methods mentioned above can be readily applied to heat-recovery steam generators (HRSGs), provided that heat content in the entering gas stream can be determined and the rate of supplementary firing, if any, is known. Instructions for testing an HRSG are also described in the ASME PTC.

A3.5.1 In Situ Boiler Performance Evaluation. In situ boiler performance monitoring and evaluation is important to the overall efficiency of a power plant, which directly impacts operating cost. Boilers and their auxiliaries also account for the largest loss of thermodynamic availability in power plants (Gorzelnik 1985).

Various techniques are available for in situ boiler performance evaluation. Chernick (1985) described three approaches for determining how well in situ electric power generating units perform and discussed the advantages and applications of each. These approaches are the (a) self-referent method, (b) comparative method, and (c) absolute method. Other methods include the entropy method and the exergy method.

In the first method, the self-referent method, each unit's performance can be determined by a self-referent standard based on the unit's past performance. This self-referent method is easy to apply, but it does not usually produce fair and even-handed standards. It is inherently stricter for those units with good performance histories than for those with poor past performance.

In the second method, the comparative method, standards are based on comparative analyses, which aggregate the experience of other units. However, it is difficult to justify direct comparisons between units due to vintage, age, operating pressure, size, fuel type, etc.

In the third approach, the absolute method, standards are to be based on absolute measures of proper performance. They do not depend on actual performance data. The unit's performance is compared with its design performance.

Traditionally, the performance of a boiler is evaluated by its efficiency, which is based on the first law of thermodynamics. This approach is essentially an energy balance between the various inputs, outputs, and losses. It can be applied to determine the thermal efficiency of individual components as well as the overall plant. The drawbacks are that it does not indicate whether an energy conversion process is possible, the direction of the process, or the conditions under which it may occur. Despite its limitations, this method is widely accepted for its simplicity and ease of use.

Two other approaches for boiler performance evaluation that are based on the first and second laws of thermodynamics have gained academic popularity recently. They are the entropy method and the exergy method. The entropy method calculates the availability losses and the exergy method calculates the thermodynamic availability. They are both essentially an exergy balance and reveal the losses due to irreversibility during the energy conversion process. Niu (1992) used a second-law analysis in his boiler model to simulate and analyze a power system. The model can be applied to different power systems with different configurations. The analyses included the combustion heat flux, gas temperature distribution, feedwater heater and boiler unit performance, and effects of major operational parameters.

Al-Bagawi (1995) carried out a full energy and exergy analysis to identify the potential for improving power plant performance. The exergy analysis showed a detailed breakdown of exergy losses of the different components in the plant. Liu (1994) investigated the exergy destruction in a conventional steam power plant. Efficiencies based on the first law and second law of thermodynamics were calculated for a number of components and for the plant. The results showed that high first law efficiency did not necessarily mean high second law efficiency.

Although second law analysis offers greater insights into the performance of a thermal system, the problem is how to develop a practical means of applying the second law. Horn and Lang (1992) presented the fuel consumption index (FCI) for this purpose. The FCI indicates why and where in the system fuel is being consumed. It points out the contribution of each individual component to the electricity production or to thermodynamic losses in terms of fuel use. However, this approach requires accurate measurements of plant variables.

Ganapathy (1990) illustrated a simplified approach to predict the overall performance of HRSGs. Based on known or assumed pinch (the temperature difference between the flue gas and water as the flue gas cools to the point at which water starts to evaporate) and approach (the difference between the temperature of feedwater exiting the economizer and the temperature at which water starts to evaporate) points, a design is simulated, the gas/steam temperature profiles are determined, and the steam flow is obtained. The procedure may be used for both fired and unfired HRSGs. Kuppuraj (1986) presented a nomogram that can quickly estimate the performance of HRSGs under off-design conditions. Collins (1991), on the other hand, described a computer program that could execute off-design condition performance analyses of HRSGs. The HRSG is simply treated as a heat-transfer surface. Dechamps (1995) described a numerical method used to compute the transient performance of HRSGs.

Current technology makes it possible to perform calculations and equipment diagnoses in near real time (Harmon et al. 1992). Online performance monitoring systems provide plant operators, engineers, and management with real-time operating data. Continuous display of data enables the operator to alter the operating conditions and instantly view the benefit or consequence of his/her actions.

Boiler performance monitoring by itself provides little but an accumulation of numbers. It is only when this mass of raw data is validated and presented to the operator in a form suitable for his/her guidance that it gains meaning. However, data from one or more sensors may be inaccurate. Such problems become acute when using historical data to evaluate a boiler's performance and determine its characteristic curve. Hence, data validation is essential for any performance evaluation.

Although accurate data can be obtained by installing state-of-the-art instruments, budget constraints often prohibit the adoption of this practice. To remedy this problem, a broadly useful diagnostic method was developed by Wei (1997) to determine the in situ operating characteristics of power plant boilers when metered data are either missing or obviously erroneous. Wei's method can be used to analyze conflicting measurements, using analytic redundancy to deduce the measurement or measurements that are substantially in error without shutting down the plant and recalibrating all instrumentation. His work showed, through the case study power plant, that the method is quite robust in identifying faulty instruments in plants that possess a low degree of hardware redundancy. Once the malfunctioning meters are identified and the historical data are corrected, boiler characteristic curves are generated to guide the daily operation and assist future implementation of online optimal load allocation.

A3.6 Equipment Testing Standards—Thermal Storage

A3.6.1 ANSI/ASHRAE Standard 150-2000 (RA2004), *Method of Testing the Performance of Cool Storage Systems*. This standard was developed to provide a uniform method for evaluating the performance of cool-storage systems installed in buildings or central plants and is intended to be used by owners, operators, consultants, and others. The standard provides a method to determine the cooling performance of a given installation at the time of turnover to the owner or at any time during its useful life. It includes options for testing a system at times when less than the peak load is available and includes a method for defining test loads that enables the user to determine whether the cool-storage system would perform as expected when subjected to the actual peak load. The standard can also be used to determine the maximum performance of a new or existing system.

To perform the standard, the user is required to provide certain information about the system necessary to define the test conditions and requirements, including the following:

a. The load profile against which the storage device or system must be tested. The user should note that the usable storage capacity of a given storage device or system will vary depending on the load profile.
b. The tests that are to be performed. Users may elect to perform any number of the individual tests defined in the standard.
c. System parameters such as maximum usable discharge temperature, maximum usable cooling supply temperature, and criteria for determining the fully charged and fully discharged conditions.
d. For systems capacity tests, the boundaries of the system or portion of the system that is to be tested.

A3.7 Equipment Testing Standards—HVAC System (Air Side)

A3.7.1 ANSI/ASHRAE Standard 111-2008, *Practices for Measurement, Testing, Adjusting, and Balancing of Building Heating, Ventilation, Air-Conditioning, and Refrigeration Systems*. ASHRAE Standard 111 provides uniform procedures for measuring and reporting the performance of heating, ventilation, air conditioning, and refrigeration equipment in the field. It includes methods of air and hydronic measurements for flow, temperature, and pressure and recommendations for evaluating the validity of collected data considering system effects. Some system characteristics can be measured directly while others must be calculated from measured data. Equations for these calculations are included in this standard. Procedures are outlined for calculating flow rates using installed system balancing devices and using system components for which a rated valve constant is known. Accuracy requirements are given, but the standard does not provide detailed procedures for calibration of measuring techniques or assessment of measured data.

A3.7.2 ANSI/ASHRAE 130-2008, *Method of Testing Air Terminal Units*. ASHRAE Standard 130 specifies the instrumentation and facilities, test installation methods, and procedures for determining capacity and related performance of constant-volume and variable-volume air terminal units. This standard is required for compliance with ARI Standard 880.

A4. PERFORMANCE MONITORING

A4.1 ASHRAE Guideline 22-2008, *Monitoring Central Chilled Water Plant Efficiency*. The basic purpose of this guideline is to provide a method to monitor chilled-water plant efficiency on a continuous basis to aid the plant operating staff in the operations and improving chilled-water plant efficiency. The effort here is to improve individual plant efficiencies and not to establish an absolute efficiency that would serve as a minimum standard for all chilled-water-plants.

A4.2 ASHRAE (RP-1004,) *Performance Monitoring of Cool Storage Systems*. The purpose of ASHRAE RP-1004, *Determining Long-Term Performance of Cool Storage Systems from Short-Term Tests*, was to develop a generalized method for determining long-term performance of an existing cool-storage system based on short-term field measurements.

This involved development of an analysis method for determining energy and demand savings of the cooling plant due to the cool-storage system as compared to an otherwise identical one without such a cool-storage system. The analysis was to be based as much as possible on monitored data in contrast to conventional methods that rely on simplified calculations of "typical" days during summer and winter that are then extrapolated to the whole year.

RP-1004 also discusses formulating a short-term M&V plan, including issues such as what specific measurements to make, the time of the year in which to make them (i.e., how one season may be more suitable than another), and the duration of the short-term monitoring period. Additional information may be found in Elleson et al. (2002) and Reddy et al. (2002).

A4.3 ASHRAE (RP-1092), ***Procedures to Determine In Situ Performance of HVAC Systems*****.** The objective of ASHRAE RP-1092 was to develop a simplified model calibration procedure to allow building professionals to project annual cooling and heating energy consumption of buildings with multiple HVAC systems from short-term field measurement data. The following five major conclusions were reached in this research project:

a. The simplified model calibration procedure developed in the project can be used to accurately calculate long-term energy consumption using short-term field energy measurement data for different types of buildings with different systems.
b. Calibration must be performed to accurately determine the system performance, even if detailed field information is collected.
c. The short-term, hourly chilled-water consumption and heating-water consumption are the most critical energy data for model calibration. Hourly electric consumption has a limited effect on the accuracy of model calibration.
d. The general information on the building and systems are the most critical input parameters for the simplified model calibration.
e. The first-level calibration procedure is very important and can improve the model accuracy significantly.

(This informative annex is not part of this guideline. It is provided for informational purposes only.)

INFORMATIVE ANNEX B
DETERMINATION OF SAVINGS UNCERTAINTY

B1. SCOPE AND OBJECTIVE

Determining the uncertainty associated with estimates of energy, water, and demand savings requires techniques from statistics, measurement theory, sample survey theory, and other fields. These are complex topics that cannot be treated fully here. Uncertainty in savings can be attributed to errors in assumptions, sampling errors, measurement errors, and to prediction errors in the regression models. The scope of this annex is mainly limited to the last two sources only, with a pertinent discussion of sampling uncertainty. The objective is to present (a) the basic equations required to determine the uncertainty of savings estimates based on field-monitored baseline and postretrofit data and (b) the assumptions required to use these equations in practice.

Readers requiring a more in-depth understanding of the topic are directed to the *Guide to the Expression of Uncertainty in Measurement* (JCGM 2008) distributed by the Joint Commission for Guides in Metrology. This publication has been adopted by the International Organization for Standardization (ISO) as ISO/IEC Guide 98-3:2008. While not a standard in the precise sense, ISO/IEC 98-3:2008 is intended as the basis on which standards dealing with measurement and measurement accuracy are to be based.

B2. GENERAL EQUATION FOR UNCERTAINTY

Because savings in a retrofit project can rarely (if ever) be measured directly, savings must be estimated based on a mathematical model that is a function of quantities that can be measured (or in some cases, assumed). These quantities are called input quantities for the model. In general, the savings, E_{save}, is given by a model of the form

$$E_{save} = f(Y_1, Y_2, \ldots, Y_n) \quad \text{(B-1)}$$

where $Y_1, Y_2, \ldots, Y_n$ are the input quantities. If the input quantities are uncorrelated, then the uncertainty in E_{save}, denoted as ΔE_{save}, is related to the uncertainties in the input quantities by the following equation (Kirkup and Frenkel 2006):

$$\Delta E_{save} = \sqrt{\left(\frac{\partial f}{\partial Y_1}\right)^2(\Delta Y_1)^2 + \left(\frac{\partial f}{\partial Y_2}\right)^2(\Delta Y_2)^2 + \ldots + \left(\frac{\partial f}{\partial Y_n}\right)^2(\Delta Y_n)^2} \quad \text{(B-2)}$$

When the model is the sum (or difference) of several quantities $E_{save} = Y_1 \pm Y_2 \pm \ldots \pm Y_n$, Equation B-2 reduces to

$$\Delta E_{save} = \sqrt{(\Delta Y_1)^2 + (\Delta Y_2)^2 + \ldots + (\Delta Y_n)^2} \quad \text{(B-3)}$$

Likewise, when the measurement is the product of several quantities $E_{save} = Y_1 \times Y_2 \times \ldots \times Y_n$, Equation B-2 becomes

$$\Delta E_{save} = \sqrt{(Y_2 Y_3 \ldots Y_n)^2(\Delta Y_1)^2 + (Y_1 Y_3 \ldots Y_n)^2(\Delta Y_2)^2 + \ldots + (Y_1 Y_2 \ldots Y_{n-1})^2(\Delta Y_n)^2} \quad \text{(B-4)}$$

The uncertainty of a savings estimate must always specify the confidence level associated with it. An example might be, "At the 95% confidence level, the annual electricity savings associated with the project is 150,000 ± 1000 kWh," or equivalently, "A 95% confidence interval for the project's annual electricity savings is between 149,000 and 151,000 kWh." The conventional understanding of such a statement is that there is a 95% probability that the savings lies within the stated interval, but in a technical sense, this interpretation is not correct. The formal definition of the confidence interval is beyond the scope of this annex, but interested readers may refer to Draper and Smith (1998). In general, there is a direct relationship between the confidence level and the width of the confidence interval, i.e., a 95% confidence interval will be wider than a 68% confidence interval.

In order to specify a confidence level, the uncertainties defined in Equations B-3 and B-4 must be multiplied by the appropriate t-statistic. Formally, the uncertainty for the savings at the α confidence level is

$$E_{save} \pm t_{(1-\alpha)/2,\upsilon} \Delta E_{save} \quad \text{(B-5)}$$

where $t_{(1-\alpha)/2,\upsilon}$ is the upper $100(1-\alpha)/2$ percentage point of a t-distribution with υ degrees of freedom. The percentage points of the t-distribution are tabulated in numerous references, for example, Draper and Smith (1998). Most spreadsheet programs include this function as well.

B3. SAMPLING UNCERTAINTY

In retrofit projects that treat a large number of systems (e.g., a lighting retrofit project involving thousands of fixtures in a building), it may be costly or impractical to measure the savings from each one, so the savings estimate is often based on measurements of savings in a smaller, randomly selected subset of the total population. Suppose a project treats N identical systems, where N is large, and savings are measured for a random sample of size $n << N$. The sample results in a set of n savings measurements $E_{save,1}, E_{save,2}, \ldots, E_{save,n}$. The mean of the savings measurements is

$$\bar{E}_{save} = \frac{1}{n}\sum_{i=1}^{n} E_{save,i} \quad \text{(B-6)}$$

The standard deviation of the savings measurements is

$$s = \sqrt{\frac{\sum_{i=1}^{n}(E_{save,i} - \bar{E}_{save})^2}{n-1}} \quad \text{(B-7)}$$

The estimate for the total savings is

$$E_{save} = N\bar{E}_{save} \quad \text{(B-8)}$$

Assuming the savings of each system is uncorrelated with the savings of all other systems, the uncertainty in the savings estimate at the α confidence level is

$$\Delta E_{save} = t_{(1-\alpha)/2,\,n-1}\frac{Ns}{\sqrt{n}} \tag{B-9}$$

The fractional savings uncertainty—also called the "relative uncertainty" or "precision"—is found by dividing Equation B-9 by Equation B-8:

$$\frac{\Delta E_{save}}{E_{save}} = t_{(1-\alpha)/2,\,n-1}\frac{\text{CV}}{\sqrt{n}} \tag{B-10}$$

where CV is the coefficient of variance, defined as the standard deviation, s, divided by the mean $\bar{E}$.

When n is larger than about 30, the t-distribution is approximately equal to the normal distribution, and Equation B-10 can be rewritten as

$$\frac{\Delta E_{save}}{E_{save}} = z_{(1-\alpha)/2}\frac{\text{CV}}{\sqrt{n}} \tag{B-11}$$

where $z_{(1-\alpha)/2}$ is the 100(1 – α)/2 percentage point of a normal distribution.

It is often necessary to determine the sample size required to estimate the savings to within a specified precision at a given confidence level. For example, the goal of a 90-10 sample is to produce a savings estimate that has uncertainty less than 10% of the total savings at the 90% confidence level. The required sample size is determined by setting Equation B-11 equal to the desired precision and solving for n. Note that in this case, the standard deviation of the savings is assumed in advance, based on manufacturer's data, previous retrofit projects, and other information. Given a desired precision, e, a confidence level, α, and a standard deviation, s, the required sample size is

$$n = \frac{z^2_{(1-0.9)/2}\text{CV}^2}{e^2} \tag{B-12}$$

For more complicated survey designs, more complex formulas will apply. In general however, the uncertainty of the savings estimate is proportional to $1/(\sqrt{n})$. Thus, increasing the sample size by a factor of f will decrease the uncertainty by a factor of $\sqrt{f}$.

B4. UNCERTAINTY OF REGRESSION-BASED SAVINGS MODELS

B4.1 Calculation of Actual Savings. Conceptually, actual savings (as opposed to normalized savings) are calculated as follows:

a. In each of n baseline periods (usually covering at least one year), measure energy use and the values of one or more independent variables (e.g., average temperature, heating degree-days, occupancy, etc.) that affect energy use.
b. Use the baseline data to develop a (possibly nonlinear) regression equation $E_{base} = f(x_1, x_2, ..., x_p)$ relating energy use per period to the independent variables. Note that each x_i is assumed to be a 1-by-n column vector.
c. In each of m postretrofit periods, measure energy use and the values of the same independent variables measured in the baseline period.
d. Use the regression equation and the measured values of the independent variables to predict baseline energy use, $\hat{E}$, for each of the m postretrofit periods.
e. Sum the predicted values of energy use over the m postretrofit periods to determine the predicted total normalized baseline energy use, $\hat{E}_{base,\,m}$.
f. Sum the measured energy use over the m postretrofit periods to determine total measured postretrofit energy use, $E_{meas,m}$.
g. Subtract total measured postretrofit energy use from total normalized baseline energy use to determine savings.

Restated formally (Reddy et al. 1998) the method is

$$\sum_{j=1}^{m} E_{save,\,j} = \sum_{j=1}^{m}\hat{E}_{base,\,j} - \sum_{j=1}^{m} E_{meas,\,j} \tag{B-13}$$

$$E_{save,\,m} = \hat{E}_{base,\,m} - E_{meas,\,m} \tag{B-14}$$

With the assumption that model prediction errors and measurement errors are independent, the uncertainty in the savings is related to the uncertainties in the baseline and measured energy use as follows:

$$\Delta^2 E_{save,\,m} = \Delta^2\hat{E}_{base,\,m} + \Delta^2 E_{meas,\,m} \tag{B-15}$$

The fractional savings uncertainty is the ratio of the standard uncertainty to the savings. This is given by

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = \left[\frac{\Delta^2\hat{E}_{save,\,m}}{E^2_{save,\,m}} + \frac{\Delta^2 E_{meas,\,m}}{E^2_{save,\,m}}\right]^{1/2} \tag{B-16}$$

When the measurement error is small (for example, when measurements of electricity use come from utility bills), it can be neglected. With this simplification, the standard uncertainty in savings becomes

$$\Delta E_{save,\,m} = \Delta\hat{E}_{base,\,m} \tag{B-17}$$

and the fractional savings uncertainty becomes

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = \frac{\Delta\hat{E}_{base,\,m}}{E_{save,\,m}} \tag{B-18}$$

Three specific cases are now considered:

a. Weather-independent models, when, for example, lighting retrofits are being evaluated.
b. Weather-based regression models with uncorrelated residuals as assumed when analyzing monthly utility bills.
c. Weather-based regression models with serially correlated residuals, as is often encountered with models based on hourly or daily data (Ruch and Claridge 1993).

B4.2 Weather-Independent Models. When energy use is independent of weather and other variables, then baseline energy use per period can be modeled as an average value plus or minus some random variation. Suppose the average baseline energy use per period over n periods is found to be $\bar{E}$ with standard deviation s. The total baseline energy use normalized to the postretrofit period, $\hat{E}_{base,\,m}$, is then just $m\bar{E}$, and the uncertainty in this estimate is

$$\Delta\hat{E}_{base,\,m} = t_{(1-\alpha)/2,\,n-1} s m^{1/2} \tag{B-19}$$

where $t_{(1-\alpha)/2,\,n-1}$ is the 100(1 – α)/2 percentage point of a t-distribution with $n - 1$ degrees of freedom. Note that if measurement errors are assumed to be small, then $\Delta\hat{E}_{base,\,m} = \Delta E_{save,\,m}$, which gives

$$\Delta E_{save,\,m} = t_{(1-\alpha)/2,\,n-1} s m^{1/2} \tag{B-20}$$

The fractional savings uncertainty is given by

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = t_{(1-\alpha)/2,\,n-1} \frac{s m^{1/2}}{E_{save,\,m}} \tag{B-21}$$

It is often convenient to express the fractional uncertainty as a function of the fractional savings, F, defined as

$$F = \frac{\hat{E}_{base,\,m} - E_{meas,\,m}}{\hat{E}_{base,\,m}} = \frac{E_{save,\,m}}{\hat{E}_{base,\,m}} \tag{B-22}$$

Then given that $\hat{E}_{base,\,m} = m\bar{E}$ in this case, Equation B-21 can be written as

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = t_{(1-\alpha)/2,\,n-1} \frac{s}{m^{1/2} F \bar{E}} \tag{B-23}$$

Since $s/\bar{E}$ is the definition of the coefficient of variation, CV, Equation B-21 can also be written as

$$\frac{\Delta E_{save,\,m}}{E_{save,\,m}} = t_{(1-\alpha)/2,\,n-1} \frac{\mathrm{CV}}{m^{1/2} F} \tag{B-24}$$

B4.3 Weather Models with Uncorrelated Residuals. Reddy and Claridge (2000) presented a method for determining uncertainty in actual savings for cases where baseline energy use can be fit to a linear model dependent on weather and/or other variables. Note that the term "linear" in this case means a model that is linear *in the regression parameters*. Under this definition, a model such as $E(T) = a + bT + cT^2$ is linear, whereas a change-point model such as $E(T) = a + b(T - T_b)^-$ (where the parameter in parentheses equals $T - T_b$ if $T < T_b$, and zero otherwise) is nonlinear due to the discontinuity at $T = T_b$. For a linear equation, the regression equation can be written in matrix terms as

$$\boldsymbol{E} = \boldsymbol{Xb} \tag{B-25}$$

where $\boldsymbol{E}$ represents energy, $\boldsymbol{X}$ represents the independent variables, and $\boldsymbol{b}$ represents the regression parameters. The standard uncertainty in the estimate of the savings over m periods is then (Reddy and Claridge 2000)

$$\Delta E_{save} = t_{(1-\alpha)/2,\,n-p}\sqrt{\mathrm{MSE}[\mathbf{1}'(\boldsymbol{X}_{post}(\boldsymbol{X}'_{base}\boldsymbol{X}_{base})^{-1}\boldsymbol{X}'_{post} + \boldsymbol{I})\mathbf{1}]} \tag{B-26}$$

where

$t_{(1-\alpha)/2,\,n-p}$ = 100(1 – α)/2 percentage point of a t-distribution with $n - p$ degrees of freedom, with n equal to the number of periods in the baseline data and p equal to the number of parameters in the model

MSE = mean squared error of the regression model, i.e.,

$$\frac{1}{n-p}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2$$

$\boldsymbol{X}_{base}$ = n-by-p matrix of independent variables in the baseline period

$\boldsymbol{X}_{post}$ = m-by-p matrix of independent variables in the postretrofit period

$\boldsymbol{I}$ = m-by-m identity matrix

$\mathbf{1}$ = 1-by-m unit column vector. Premultiplying a matrix by a unit row vector and postmultiplying by a unit column vector is equivalent to summing the terms of the matrix.

Reddy and Claridge then developed an approximation to equation B-26 to eliminate the need for matrix algebra. One way of stating their approximation is:

$$\Delta E_{save} = 1.26\, t_{(1-\alpha)/2,\,n-p} \frac{\bar{E}_{base,\,m}}{\bar{E}_{base,\,n}}\left[\mathrm{MSE}\left(1 + \frac{2}{n}\right)m\right]^{0.5} \tag{B-27}$$

with $t_{(1-\alpha)/2,\,n-p}$ and MSE as defined in Equation B-26 and

n = number of periods in the baseline period

m = number of periods in the postretrofit period

$\bar{E}_{base,\,n}$ = mean energy use per period in the baseline period

$\bar{E}_{base,\,m}$ = mean of the predicted normalized baseline energy use in the postretrofit period, i.e., $\hat{E}_{base,\,m}/m$

Equation B-27 can be rewritten as follows to give the fractional savings uncertainty:

$$\frac{\Delta E_{save}}{E_{save}} = \frac{1.26\, t_{(1-\alpha)/2,\,n-p}}{m\bar{E}_{base,\,n} F}\left[\mathrm{MSE}\left(1 + \frac{2}{n}\right)m\right]^{0.5} \tag{B-28}$$

with MSE, m, n, and $\bar{E}_{base,\,n}$ as defined in Equation B-27 and F as defined in Equation B-22.

It is worth restating that Equations B-26 through B-28 apply only to problems where the baseline energy use can be fit to a linear model of weather and other independent variables. An example of a linear model would be one in which monthly gas use is modeled as a constant plus another constant times the monthly heating degree-days. For nonlinear change-point models of the type described in Informative Annex C of this guideline, Reddy and Claridge (2000) recommend ignoring the uncertainty in the change-point temperatures. This linearizes the regression models, allowing the use of Equations B-26 through B-28, but ignores the uncertainty associated with the change-point temperatures.

TABLE B-1 Baseline and Postretrofit Monthly Natural Gas Use and Monthly Average Temperature for a Hypothetical Retrofit Project

Baseline				**Postretrofit**		
$\bar{T}$	E_{meas}	$\hat{E}$	**Residual**	$\bar{T}$	E_{meas}	$\hat{E}$
30.8	376.	377.4	–1.4	38.3	294.	315.6
40.1	311.	300.8	10.2	43.8	244.	270.3
47.5	239.	239.8	–0.8	44.0	252.	268.6
53.3	186.	192.0	–6.0	57.0	148.	161.5
63.4	111.	108.7	2.3	66.6	86.	101.5
69.5	96.	101.5	–5.5	70.2	72.	101.5
74.7	99.	101.5	–2.5	77.4	73.	101.5
84.7	104.	101.5	2.5	78.9	77.	101.5
74.9	107.	101.5	5.5	77.2	91.	101.5
61.8	131.	121.9	9.1	69.4	85.	101.5
53.6	181.	189.5	–8.5	54.8	168.	179.6
53.3	187.	192.0	–5.0	40.1	285.	300.8
Total	**2128**				**1875**	**2105.4**

An example is now provided to illustrate the calculations. Table B-1 presents 12 months of baseline and postretrofit data on natural gas use and monthly average outdoor air temperature for a (hypothetical) building. Gas use is presented in unspecified units, which could be therms, cubic feet (cubic metres), etc. It is assumed that each monthly reading represents the same number of days. The data are plotted in Figure B-1.

The first step is to use ASHRAE's Inverse Model Toolkit to fit the baseline data to a three-parameter change-point model. The regression equation for the monthly baseline gas use is found to be

$$E = 101.51 - 8.244(T - 64.27)^{-} \tag{B-29}$$

where T is the monthly average temperature.

Next, the regression equation (Equation B-29) is used to predict the baseline energy use, $\hat{E}$, in each postretrofit month, given its average temperature. As seen in the table, the total baseline gas use normalized to the postretrofit period $\hat{E}_{base,\,m}$ is 2105.4 units. Since the measured postretrofit gas use is 1875 units, the savings E_{save} is (2105.4 – 1875) = 230.4 units, and the fractional savings, $F = E_{save}/\hat{E}_{base,\,m}$ is (2105.4 – 1875)/2105.4 = 10.9%.

In order to calculate the savings uncertainty, the mean square error (MSE) of the regression is required. This is as defined in Equation B-26, with n = 12 and p = 2. Note that although Equation B-28 contains three parameters, in order to use Equations B-26 through B-28, it is assumed that the change-point temperature is known, thereby reducing the number of parameters to two. Given this, the MSE is found to be 40.07.

Then, given the average gas use per month in the baseline period, $\bar{E}_{base,\,n}$ = 2128/12 = 177.3 units, and the average baseline monthly gas use normalized to the postretrofit period, $\bar{E}_{base,\,m}$ = 2105.4/12 = 175.5 units, the uncertainty of the savings at the 95% confidence level is calculated using Equation B-27 as

$$\Delta E_{save} = 1.26(2.634)\frac{175.5}{177.3}\left[40.07\left(1+\frac{2}{12}\right)12\right]^{0.5} = 77.8$$

Thus it could be stated that at the 95% level of confidence, the annual gas savings for the retrofit project of Table B-1 is 230 ± 78 units.

The fractional savings uncertainty at the 95% level of confidence is calculated using Equation B-28:

$$\frac{\Delta E_{save}}{E_{save}} = \frac{1.26(2.634)}{12(177.3)(0.109)}\left[40.07\left(1+\frac{2}{12}\right)12\right]^{0.5} = 34\%$$

Given that most spreadsheet programs are capable of performing matrix algebra, it is also possible to use Equation B-26 directly to calculate savings uncertainty. In this case, the matrices $\boldsymbol{X}_{base}$ and $\boldsymbol{X}_{post}$ are derived from the data in Table B-1 and the Equation B-29. The first column of each matrix is a column of 1s to account for the constant in Equation B-29. The second column of each matrix equals T – 64.27 if T < 64.27, and zero otherwise. The matrices are then as follows:

$$\boldsymbol{X}_{base} = \left|\begin{array}{cc} 1 & -33.47 \\ 1 & -24.17 \\ 1 & -16.77 \\ 1 & -10.97 \\ 1 & -0.87 \\ 1 & 0 \\ 1 & 0 \\ 1 & 0 \\ 1 & 0 \\ 1 & -2.47 \\ 1 & -10.67 \\ 1 & -10.97 \end{array}\right| \qquad \boldsymbol{X}_{post} = \left|\begin{array}{cc} 1 & -25.97 \\ 1 & -20.47 \\ 1 & -20.27 \\ 1 & -7.27 \\ 1 & 0 \\ 1 & 0 \\ 1 & 0 \\ 1 & 0 \\ 1 & 0 \\ 1 & 0 \\ 1 & -9.47 \\ 1 & -24.17 \end{array}\right|$$

Applying Equation B-26 gives ΔE_{save} = 81.7 units, which is within 5% of the value obtained using Equation B-27.

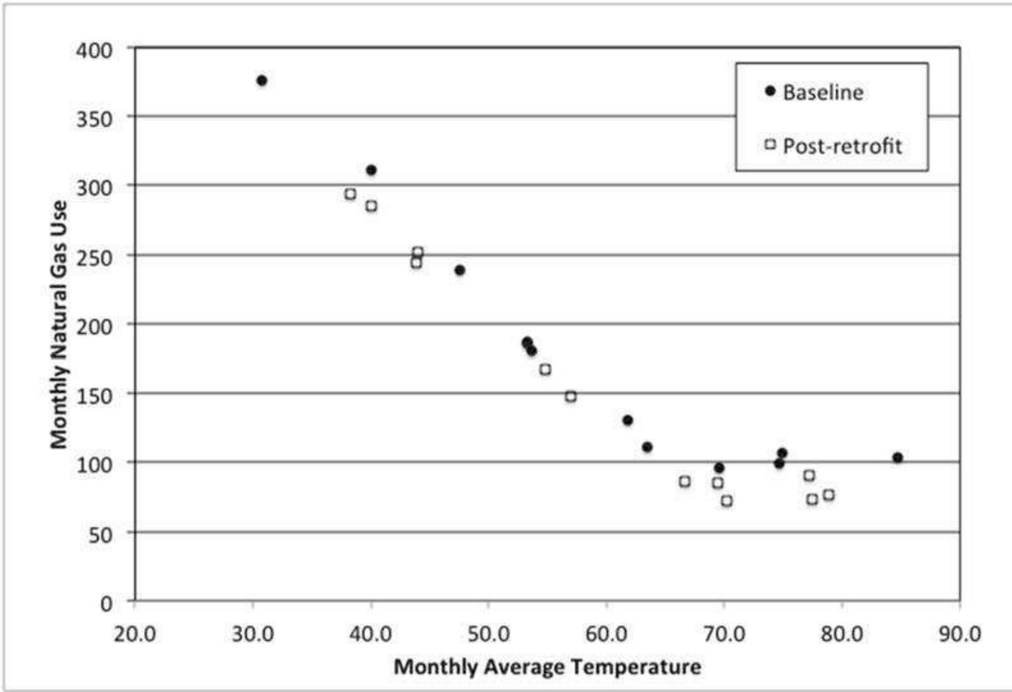

FIGURE B-1 Graphical representation of the Table B-1 data.

Recall that due to the nonlinearity of the regression model, both of these uncertainty estimates are approximations to the true value.

B4.4 Weather-Dependent Models with Correlated Residuals. Note that Equations B-26 through B-28 are appropriate for regression models without serial correlation in the residuals. This would apply to models identified from utility (e.g., monthly) data. When models are identified from hourly or daily data, previous studies (see, for example, Ruch et al. [1993]) have shown that serious autocorrelation often exists. These autocorrelations may be due to (a) "pseudo" patterned random behavior due to the strong autocorrelation in the regressor variables (for example, outdoor temperature from one day to the next is correlated) or (b) to seasonal operational changes in the building and HVAC system not captured by an annual model. Consequently, the uncertainty bands have to be widened appropriately. Accurate expressions for doing so have been proposed by Ruch et al., which are, unfortunately, mathematically demanding. A simplified approach proposed by Reddy and Claridge (2000) is presented here.

From statistical sampling theory, the number of independent observations, n', of n observations with constant variance but having a lag 1 autocorrelation equal to ρ is

$$n' = n \times \frac{1-\rho}{1+\rho} \tag{B-30}$$

By extension, a simplified and intuitive way of modifying Equation B-13 in the presence of serial autocorrelation is to correct the MSE by the new degrees of freedom, n', and to replace n by n'. Equation B-28 becomes

$$\frac{\Delta E_{save}}{E_{save}} = \frac{1.26 t_{(1-\alpha)/2,\, n'-p}}{m \bar{E}_{base,\, n} F}\left[\mathrm{MSE}'\left(1+\frac{2}{n'}\right)m\right]^{0.5} \tag{B-31}$$

where

$$\mathrm{MSE}' = \frac{1}{n'-p}\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2 \tag{B-32}$$

Whereas Equation B-31 defines the fractional uncertainty, the savings uncertainty itself can be written as

$$\Delta E_{save} = 1.26 t_{(1-\alpha)/2,\, n'-p} \frac{\bar{E}_{base,\, m}}{\bar{E}_{base,\, n}}\left[\mathrm{MSE}'\left(1+\frac{2}{n'}\right)m\right]^{0.5} \tag{B-33}$$

A short discussion on how to compute the autocorrelation coefficient of model residuals is provided here. The autocorrelation coefficient of a time-series data stream provides a measure of the extent to which an observation is correlated with its immediate successor. The coefficient ρ, which is usually at lag 1, is easily deduced by duplicating the time-series data of model residuals onto another column of your worksheet with the time stamp displaced by one time interval. The square root of the R-value between both these data streams is the coefficient ρ. Note that only for daily or hourly data series is there a need to make corrections to the uncertainty formulas presented below. In certain cases, this coefficient is so low (say, $\rho < 0.5$) that the effect of serial autocorrelation in the regression model residuals can be ignored.

B4.5 Normalized Savings. Up to this point, the uncertainty equations presented have applied only to so-called actual savings. In many cases, it is necessary to normalize the savings to a typical or average period (usually a year) at the site. It was shown in Section B4.3 that when measurement errors are negligible, the uncertainty in calculating *actual* savings using a weather-based regression is due to the error in normalizing the baseline energy use to the postretrofit period. *Normalized* savings requires two regression equations: one that correlates baseline energy use with baseline weather conditions and one that correlates postretrofit energy use with postretrofit weather conditions. The regressions are used to normalize both the baseline energy use and the postretrofit energy use to a typical year; normalized savings is then defined as the normalized baseline energy use minus the normalized postretrofit energy use. As shown by Effinger et al. (2009), the uncertainty in calculating the normalized savings can be approximated as the square root of the sum of the squared uncertainty of each regression.

When no autocorrelation is present in the regression residuals (as is usually the case with monthly data), the uncertainty in the normalized baseline energy use is given by

$$\Delta E_{base,\,norm} = 1.26 t_{(1-\alpha)/2,\,n-p} \frac{\bar{E}_{base,\,g}}{\bar{E}_{base,\,n}} \sqrt{\mathrm{MSE}\left(1+\frac{2}{n}\right)g} \tag{B-34}$$

where

n = number of periods in the baseline period

g = number of periods in the typical year

p = number of parameters in the baseline regression

$t_{(1-\alpha)/2,\,n-p}$ = $100(1-\alpha)/2$ percentage point of a t-distribution with $n-p$ degrees of freedom

MSE = mean squared error of the regression model, i.e.

$$\frac{1}{n-p}\sum_{i-1}^{n}(Y_i - \hat{Y}_i)^2$$

$\bar{E}_{base,\,n}$ = mean energy use per period in the baseline period

$\bar{E}_{base,\,g}$ = mean of the predicted normalized baseline energy use in the typical year, i.e., $\hat{E}_{base,\,g}/g$

Likewise, the uncertainty in the normalized postretrofit energy use is given by

$$\Delta E_{post,\,norm} = 1.26 t_{(1-\alpha)/2,\,m-r} \frac{\bar{E}_{post,\,g}}{\bar{E}_{post,\,m}} \sqrt{\mathrm{MSE}\left(1+\frac{2}{m}\right)g} \tag{B-35}$$

where

m = number of periods in the postretrofit period

g = number of periods in the typical year

r = number of parameters in the postretrofit regression

$t_{(1-\alpha)/2,\,m-r}$ = $100(1-\alpha)/2$ percentage point of a t-distribution with m-r degrees of freedom

MSE = mean squared error of the regression model, i.e.,

$$\frac{1}{m-r}\sum_{i-1}^{n}(Y_i - \hat{Y}_i)^2$$

$\bar{E}_{post,\,n}$ = mean energy use per period in the postretrofit period

$\bar{E}_{post,\,g}$ = mean of the predicted normalized baseline energy use in the postretrofit period, i.e., $\hat{E}_{post,\,g}/g$

The approximate uncertainty in the normalized savings is then

$$\Delta E_{save} = \sqrt{(\Delta E_{base,\,norm})^2 + (\Delta E_{post,\,norm})^2} \tag{B-36}$$

This formula is an approximation only, because $\Delta E_{base,norm}$ and $\Delta E_{post,norm}$ are not independent of one another; both are linear functions of the normalized weather conditions and thus will exhibit cross correlation. In practice, the effect is often small, and Equation B-36 is a reasonably accurate approximation of the uncertainty.

The same idea applies when autocorrelation is present in the residuals of the individual regressions. Using Equation B-31, the uncertainty in the baseline regression is given by

$$\Delta E_{base,\,norm} = 1.26 t_{(1-\alpha)/2,\,n'-p} \frac{\bar{E}_{base,\,g}}{\bar{E}_{base,\,n}} \sqrt{\mathrm{MSE}\left(1+\frac{2}{n'}\right)g} \tag{B-37}$$

where $n' = n \times 1 - \rho / 1 + \rho$, with n equal to the number of periods in the preretrofit period; ρ is the (lag-1) autocorrelation as defined in Section B4.4l and other variables are as defined for Equation B-33.

The uncertainty in the postretrofit regression is given by

$$\Delta E_{post,\,norm} = 1.26 t_{(1-\alpha)/2,\,m'-r} \frac{\bar{E}_{post,\,g}}{\bar{E}_{post,\,n}} \sqrt{\mathrm{MSE}\left(1+\frac{2}{m'}\right)g} \tag{B-38}$$

where $m' = m \times 1 - \rho / 1 + \rho$, with m equal to the number of periods in the postretrofit period; ρ is the (lag-1) autocorrelation in the residuals of the postretrofit regression as defined in Section B4.4; and other variables are as defined for Equation B-34.

The uncertainty in the normalized savings is then as given in Equation B-35.

Note that Equations B-33, B-34, B-36, and B-37 are written as generally as possible such that the number of periods in the baseline and postretrofit periods (n and m, respectively) may be different. In practice, it is found that the best results are obtained when the number of periods in the baseline and postretrofit periods are nearly equal to one another.

B4.6 Bayesian Analysis of Savings Uncertainty. As seen in the previous sections, savings uncertainty can only be determined exactly when energy use is a linear function of some independent variable(s). For more complicated models of energy use, such as changepoint models, and for data with serially autocorrelated errors, approximate formulas must be used. These approximations provide reasonable accuracy when compared with simulated data, but in general it is difficult to determine their accuracy in any given situation. One alternative method for determining savings uncertainty to any desired degree of accuracy is to use a Bayesian approach.

In Bayesian savings analysis, model parameters are assumed to have probability distributions, which in most cases can be specified exactly. Dedicated computer software is then used to draw a large number of random samples from the parameter distributions; each random draw of the parameters then defines a different possible value for the energy savings. The ensemble of savings values so generated defines the distribution of the savings, and from this distribution one can calculate the mean, median, 95% confidence interval, and the interval corresponding to any desired level of confidence. Although this is a numerical technique, the accuracy of the results can be controlled through the number of samples drawn.

As an example, consider a simple case where monthly preretrofit energy use is fit to a linear function of monthly heating degree-days, $E = a + b \times \text{HDD}$. An equipment retrofit is performed and we are given the energy use E_{post} for one postretrofit year, as well as the heating degree-days (H_1, H_2, …, H_{12}) that occur in each postretrofit month. Using Bayesian savings analysis, one would write down the joint probability distribution of the parameters a and b (this distribution is not given here but is provided in numerous textbooks; for example, Gelman et al. [2003]). A so-called "prior distribution" must also be specified. Specialized software is then used to draw samples from the joint distribution of a and b. Each random draw (a_i, b_i) is used to calculate a value of the savings:

$$S_i = 12a_i + b_i\left(\sum_{j=1}^{12} \text{HDD}_j\right) - E_{post} \tag{B-39}$$

The mean savings for n samples drawn from the distribution is

$$\bar{S} = \sum_{i=1}^{n} S_i \tag{B-40}$$

To determine the 95% confidence interval (also called a "Bayesian credible interval" in this case), sort the n savings values from smallest to largest. The lower limit is the $0.025 \times n$-th value in order, and the upper limit is the $0.975 \times n$-th value in order.

Shonder and Im (2012) have shown that for a diffuse prior distribution, the Bayesian values of the mean and 95% confidence interval for the simple linear case are identical to the analytical values when a sufficient number of samples are drawn. The referenced paper provides several examples of using Bayesian analysis for other more complicated problems and recommends software that can be used for the analysis.

(This informative annex is not part of this guideline. It is provided for informational purposes only.)

INFORMATIVE ANNEX C
DATA COMPARISON

C1. HOURLY DATA COMPARISON AND CALIBRATION TECHNIQUES

C1.1 Graphical Comparison Techniques. ASHRAE Guideline 14 discusses four different graphical techniques, including (a) weather-day-type 24-hour profile plots, (b) binned interquartile analysis using box-whisker-mean (BWM) plots, (c) three-dimensional (3D) surface plots, and (d) 3D color plots. Determination of which techniques to use for any given calibration is left to the judgment of the modeler. Additionally, the graphical presentation will often allow interested parties to review and comprehend these results.

C1.1.1 Weather-Day-Type 24-Hour Profile Plots. To produce hourly load profiles, measured power is divided into a few different day types, averaged by the hour, and then plotted against time. The day types should be selected to meet the project needs, but may include up to eight day types: winter peak weekday, winter average weekday, winter average weekend day/holiday, summer peak weekday, summer average weekday, summer average weekend day/holiday, spring average weekday, and fall average weekday.

Figure C-1 is an example of a weekday 24-hour weather day type BWM plot that shows the whole-building electricity use versus the hour-of-the-day for both the measured data and the simulated data in three weather-day types.

The weather-day types arbitrarily divide the measured data into groupings. For example, the summer peak weekday can be defined by selecting the five warmest nonholiday weekdays during June, July, and August using the actual weather data for the calibration period. The hourly load data for each of those identified days are then extracted from the utility data sets and the simulation output and compared. In a similar fashion, the summer average weekday data are prepared from the remaining weekday data (excluding the days used in determining the peak day data set) as are the other day types of interest (Bou-Saada 1994). Software provided with the diversity factor tool kit can also be used to produce similar statistical plots (Claridge et al. 2004).

Calibration criteria for this technique can be developed for energy use and demand profiles based on monthly, daily, and hourly agreement for each day type of interest. Acceptable calibration has been declared when models match to within ±2.5% monthly, ±10% daily, and ±20% for a minimum of 20 out of 24 hours for each day type.

In Figure C-1, weekday data are plotted in a fashion that includes a combination of vertical and horizontal juxtapositioning, temperature-based BWM bins, and superpositioning of the mean bin line in the lower right graph. Similar analysis can be performed with weekend and holiday data (Bou-Saada 1994; Haberl and Bou-Saada 1998). In the upper left graph, the hourly measured whole-building electricity use is plotted against hourly ambient temperature. In the upper right graph, the corresponding simulated electricity data for the same period are shown. Binned BWM plots are below each scatter plot. These plots show the whole-building electricity use as a function of outdoor temperature bins divided into 10°F (–12.2°C) segments. One final feature of these plots is that the measured data mean is superimposed as a dashed line onto the calibrated simulation data. The difference between mean lines in each bin provides a measure of how well the model is calibrated at a specific temperature bin. Likewise, the interquartile range (i.e., the distance between the 25th and 75th percentiles) represents the hourly variation in a given bin.

C1.1.2 Binned Interquartile Analysis Using Box-Whisker-Mean Plots. The superimposed and juxtaposed binned BWM plots display the maximum, minimum, mean, median, 10th, 25th, 75th, and 90th percentile points for each data bin for a given period of data. These plots eliminate data overlap and allow for a statistical characterization of the dense cloud of hourly points (scatter plots are still useful in showing individual point locations). The important feature to note about this plot is that the data are statistically binned by temperature. This feature allows for the bin-by-bin goodness-of-fit to be evaluated quantitatively and graphically. Using the BWM plot combined with a scatter plot also allows one to visualize the data as a whole while simultaneously seeing the effects of the outliers in specific situations. Both of these features are important to the efficiency with which the graph conveys an accurate and consistent message to the viewer (Tukey 1977; Cleveland 1985).

Figure C-2 is an example of a weekday 24-hour weather-day-type BWM plot that shows the whole-building electricity use versus the hour of the day for both the measured data and the simulated data in three weather-day types.

C1.1.3 Three-Dimensional Surfaces. In Figure C-3, comparative 3D surface plots show the monitored data in part (a), the simulated data in part (b), positive-only values of the measured data subtracted from the simulated data in part (c), and positive-only values of the simulated data subtracted from the measured data in part (d).

Individual hourly differences may be visually detected over the entire simulation period using these plots, which allows the user to recognize patterns in the comparisons such as the simulation program's overpredictions in the spring and fall mornings and afternoons and both overpredictions and underpredictions in the late evening throughout the year. An obvious benefit of such plots is their ability to aid in the identification of oversights such as a daylight savings shift or misalignment of 24-hour holiday profiles (Bronson et al. 1992; Haberl et al. 1993a). One drawback associated with these graphs is the difficulty in viewing exact details such as the specific hour or specific day on which a misalignment occurs.

C1.1.4 Three-Dimensional Color Plots. Three-dimensional color plots serve a similar purpose as surface plots but solve some of the latter's problems. Some model calibrators complain that surface plots obscure data that are behind "hills" or in "valleys." By substituting color for depth, some calibrators find they can more easily interpret the graphs. For further information, refer to the work of Christensen (1985) as well as Wright and Williams (2014).

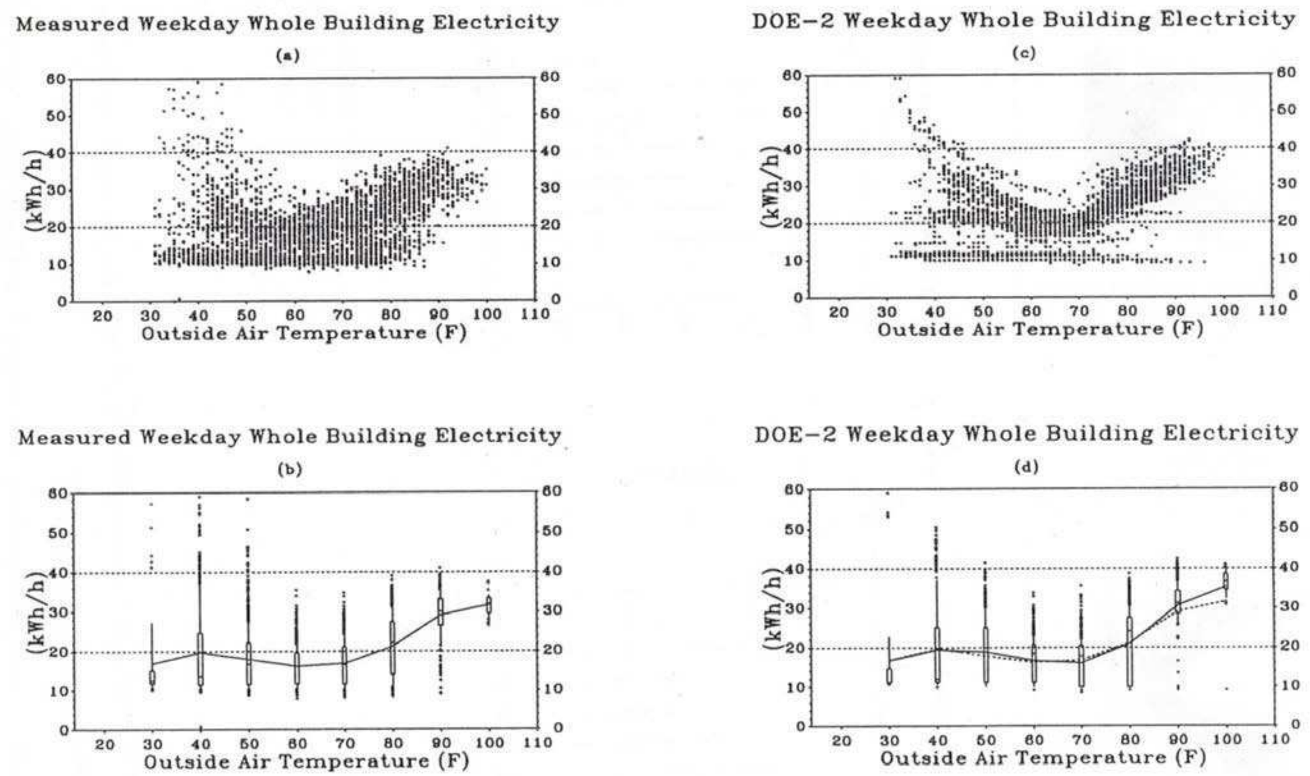

FIGURE C-1 Example weekday temperature bin calibration plots. This figure shows the measured and simulated hourly weekday data as scatter plots against temperature in the upper plots, (a) and (c), and as binned box-whisker-mean plots in the lower plots, (b) and (d) (Bou-Saada 1994).

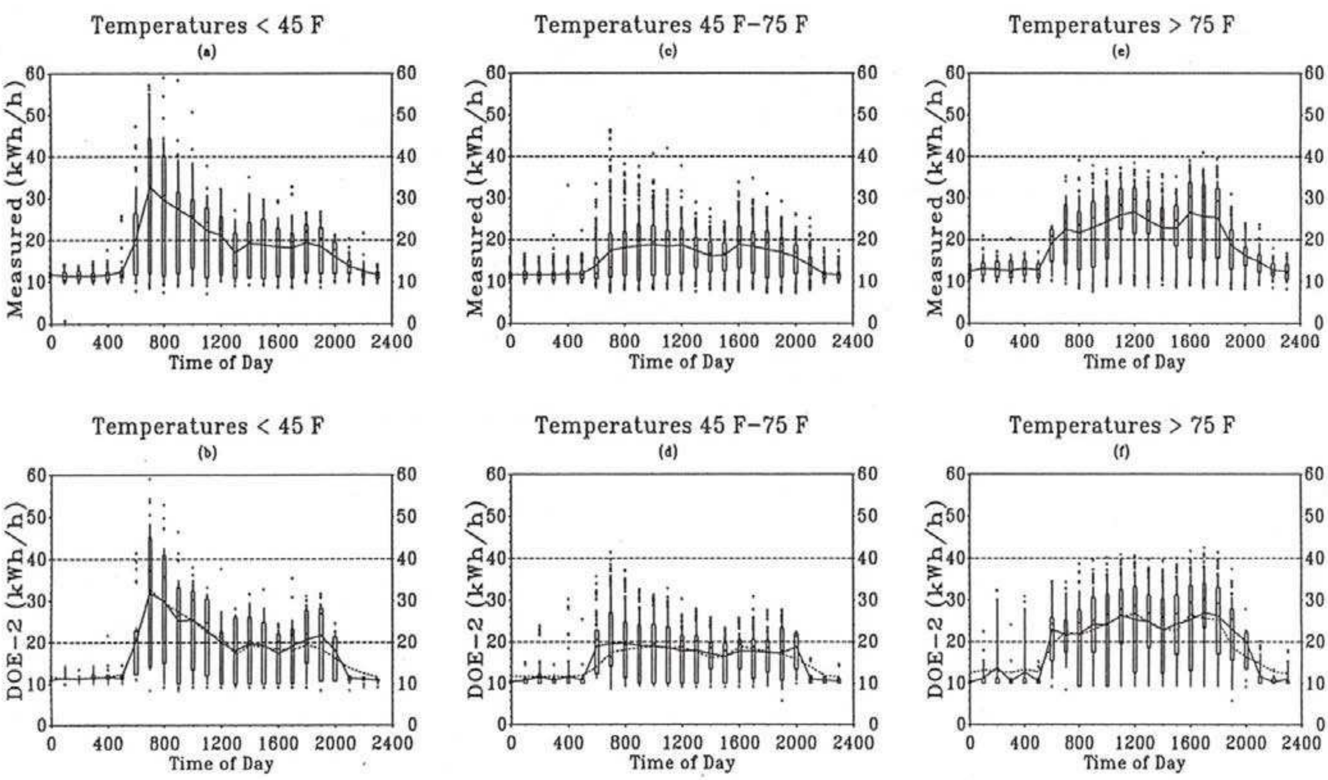

FIGURE C-2 Example weekday 24-hour weather-day-type box-whisker-mean plots for weekday temperatures. Graphs (a) and (b) represent measured and DOE-2 data for temperatures <45°F, (c) and (d) represent data for temperatures between 45°F and 75°F (7.2°C and 23.9°C), and (e) and (f) represent data for temperatures >75°F.

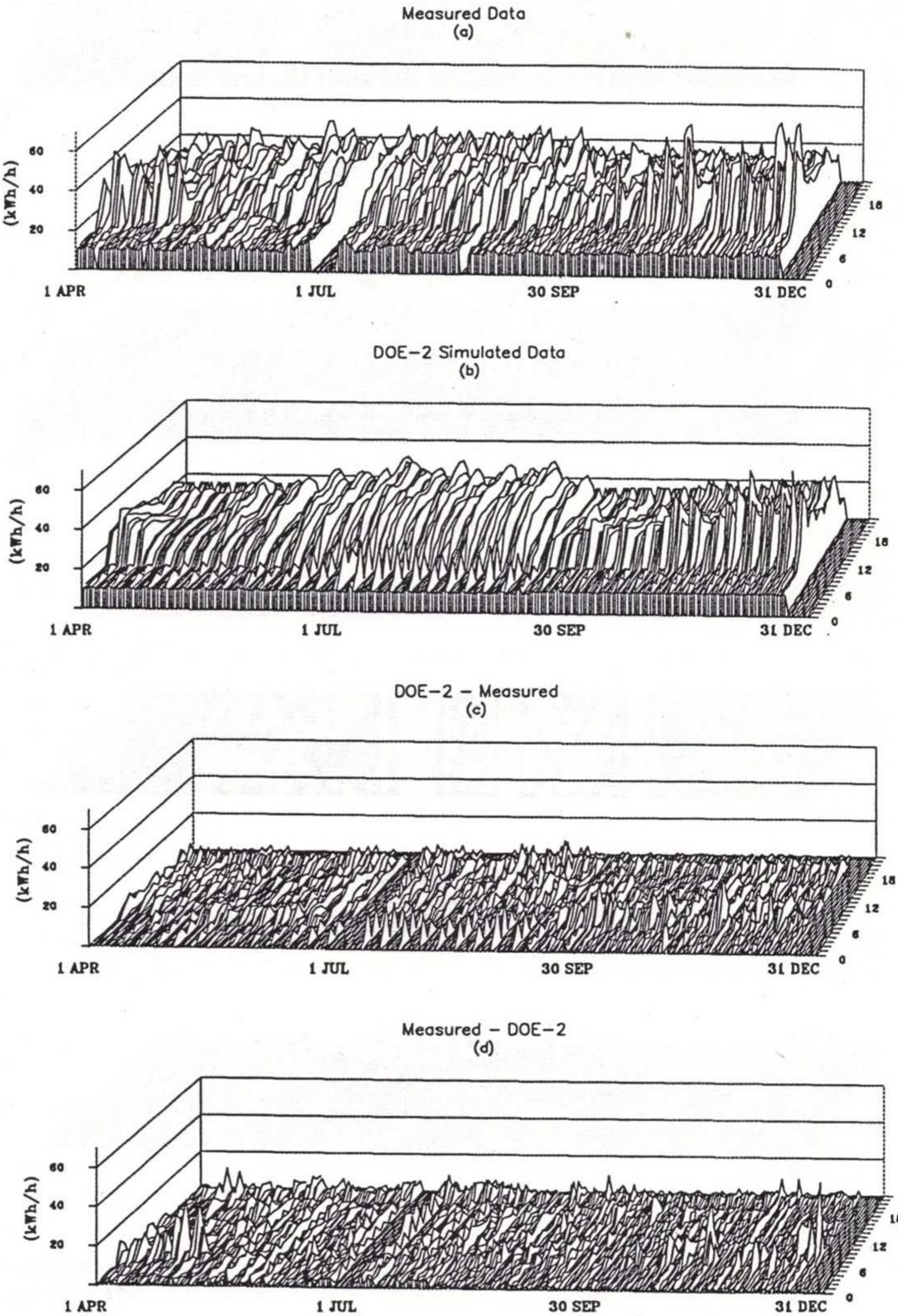

FIGURE C-3 Example comparative three-dimensional plots: (a) measured data, (b) simulated data, (c) simulated-measured data, and (d) measured-simulated data.

C2. STATISTICAL COMPARISON TECHNIQUES

Although graphical methods are useful for determining where simulated data differ from metered data, and some quantification can be applied, more definitive quantitative methods are required to determine compliance. Two statistical indexes are used for this purpose: hourly mean bias error (MBE) and coefficient of variation of the root-mean-square error [CV(RMSE)] (Kreider and Haberl 1994a, 1994b; Haberl and Thamilseran 1996).

MBE is calculated by first calculating the difference between measured energy use and simulated energy use for a given hour. Such differences are then calculated for all the hours over a given time period, usually a month or year. The differences are summed and then divided by the sum of the measured energy use over the same time period. MBE is expressed as a percent error.

The MBE measures how closely the energy use predicted by the model corresponds to the metered data on a monthly or annual basis. MBE, however, may be influenced by offsetting errors, so an additional index is often necessary.

The root-mean-square error (RMSE) is typically referred to as a measure of variability or how much spread exists in the data. For every hour, the error, or difference in paired data points is calculated and squared. The sum of the squared errors is then found for each month and for the total periods and divided by the respective number of points yielding the mean square error (MSE), whether for each month or the total period. A square root of the result is then reported as the RMSE.

The CV(RMSE) (%) (Draper and Smith 1981) is calculated by dividing the RMSE by the measured mean of the data.

$$\mathrm{CV(RMSE)} = 100 \times [(\sum(y_i - \hat{y}_i)^2)/(n-p)]^{1/2}/\bar{y}$$

CV(RMSE) allows one to determine how well a model fits the data; the lower the CV(RMSE), the better the calibration (the model in this case is the simulated data). Therefore, a CV(RMSE) is calculated using hourly data and to determine CV(RMSE) for both monthly and total data periods.

It’s much easier to achieve a lower MBE than a lower CV(RMSE). MBEs are frequently reported in a range of ±5% to ±10%, but the very best empirical models of building energy use performance (e.g., artificial neural networks used with a large commercial building) were only capable of producing CV(RMSE) in the 10% to 20% range for hourly comparisons. Typically, models are declared to be calibrated if they produce MBEs within ±10% and CV(RMSE)s within ±30% when using hourly data or 5% MBE and 15% CV(RMSE) with monthly data. (See Section 4.3.2.4 for further information on this topic.)

C2.1 Refine Model Until an Acceptable Calibration Is Achieved. If the statistical indexes calculated during the previous step indicate that the model is not sufficiently calibrated, revise the model and compare it again to measured data. Numerous iterations of this process may be needed to obtain acceptable calibration levels. In general, calibration levels should be less than expected savings.

C2.2 Produce Baseline and Postretrofit Models. This section describes the development of both of these models and how to proceed if it is not possible to calibrate simulation models to both the baseline and postretrofit buildings.

C2.2.1 Baseline Model. The baseline model represents the building as it would have been in the absence of the retrofit project. Typically, the baseline represents the state the building was in before the retrofit commenced. Occasionally, a building owner would have made some change to the building in the absence of the retrofit project. For example, consider the case when an owner already planned to replace a chiller and engages a contractor to provide a higher-efficiency chiller as part of a comprehensive retrofit to a building’s HVAC system. In such a case, calibrated simulation can be used to separate the impact of the two combined retrofits.

C2.2.2 Postretrofit Model. The postretrofit model represents the building as it is when the retrofit project is complete. Ideally, the postretrofit model would represent the building after start-up and commissioning procedures are completed. The postretrofit model, however, may represent whatever state the building is in when the owner and the contractor agree the project is substantially completed and the time period for measuring savings begins.

Often it is desirable to calibrate the postretrofit model to ensure that the newly installed measures are accurately represented. This step can serve to both check for proper measure operation and correct modeling techniques. When producing a postretrofit calibrated model after a baseline model has already been calibrated to the building, minimize the amount of duplicated work by limiting data collection activities to investigating changes between the baseline and postretrofit building. For example, confirm the installation and characteristics of installed measures, and verify measure operation. Also confirm whether changes to building operation (baseline shifts) occurred since the calibration of the baseline model. Modify the calibrated baseline model to develop the postretrofit model and calibrate that model to postretrofit data. Keep in mind that only two types of model changes are valid: (a) baseline changes applied equally to both the baseline and postretrofit models and (b) measure-related retrofit changes that are applied only to the postretrofit model.

C2.2.3 What to Do When It Is not Possible to Calibrate Simulation Models to Both the Baseline and Postretrofit Buildings. Ideally, both baseline and postretrofit models are calibrated to measured utility, indoor conditions, and weather data. In the event that insufficient information is available to calibrate both of these models, either model may be calibrated to measured data and the other developed by modifying the calibrated model.

In general, there are four reasons why it may not be possible to calibrate both baseline and postretrofit models to measured data: (a) collection of hourly utility data did not start until the measures were installed, (b) savings must be verified before sufficient time has elapsed to collect a minimum amount of postretrofit data, (c) measures are installed in a new building that does not have a preretrofit period, and (d) building configuration or operation has changed since installation of the measures. Following is a detailed description of each of these scenarios with instructions associated with each.

a. Collection of hourly utility data did not start until the measures were installed. Conduct a site visit before the measures are installed in accordance with the procedures described in Section 5.3.3.2. When the measures are installed, also install equipment to collect hourly utility data, perform spot measurements to verify operating characteristics, and continue to collect data for a year. During that time period, conduct an additional site survey to verify the installation of the measures. Finally, calibrate the postretrofit model to the measured data and modify that model to represent the baseline model.
b. Savings must be verified before sufficient time has elapsed to collect a minimum amount of postretrofit data. Although the most accurate results may be obtained by collecting a year's worth of preretrofit and postretrofit data, it is possible to verify savings before that much time has elapsed, provided the baseline model was adequately calibrated to hourly data. When such is the case, visit the site after the retrofit is complete and verify that the measures are installed and are functional (Section 5.3.3.3 of ASHRAE Guideline 14 provides guidance for verifying measure characteristics.). To produce the postretrofit model, modify the calibrated baseline model so that it reflects the characteristics and functions of the installed measures. The postretrofit model can also be compared to the spot measurements made during the postretrofit period.
c. Measures are installed in a new building that does not have a preretrofit period. When energy conservation measures are incorporated into a new construction project, the baseline building will not be a building that has ever existed. When this is the case, calibrate a simulation model to the postretrofit building and then modify that model to represent the baseline building. The process of arriving at the characteristics of the baseline building may require detailed certification of every input using values obtained from "average" sources, code books, or through negotiation.
d. Building configuration or operation has changed since installation of the measures. When the building configuration or operation changes after a baseline has been agreed upon by the buyer and seller (baseline shift), calibrated simulation may be applied to simulate the savings that would have been achieved had those changes never occurred. First, calibrate the simulation model to the building as it exists during the calibration period. Then, modify the calibrated model to produce baseline and postretrofit models that are consistent with the agreed-on baseline. When doing this, as possible, modify the calibrated model so that the changes in building configuration or operation are restored to the conditions contained in the agreed-on baseline. For example, if hours of operation change, modify the calibrated model so that hours of operation are those in the agreed-on baseline.

C2.3 Calculate Savings. Savings are equivalent to the energy use or demand of the baseline model minus the energy use or demand of the retrofit model. To simulate savings, first ensure that all inputs to the baseline model and the postretrofit model are consistent. Next, select the appropriate weather data set and run both models. Then compare the energy use projected by both models. Last, when there are multiple measures that interact and total savings need to be disaggregated by measure, a sequential modeling process is required to account for the interactive effects.

C2.3.1 Ensure All Inputs to the Baseline Model and the Postretrofit Model Are Consistent. When calculating savings, the only difference between the inputs to the baseline model and the postretrofit model are those directly related to the measures. Investigate any inconsistencies between the two models and correct them. For example, if building operation changes between the production of the baseline model and the postretrofit model, modify the postretrofit model schedule so that it is consistent with the baseline model.

C2.3.2 Select the Appropriate Weather Data Set and Run Both Models. Two different options are available for selecting weather data sets. If it is desired to simulate savings for a specific year, use weather data from that year. If it is desired to simulate savings for a typical year, use typical weather data. Once a weather data set is selected, run both the baseline model and the postretrofit model using the same weather data.

C2.3.3 Calculate Savings. To calculate savings, subtract energy use and or demand projected by the postretrofit model from energy use/demand projected by the baseline model. Note that the time of peak demand can shift, possibly affecting the relevant utility price to use in valuing savings.

C2.3.4 Account for Individual Savings of Multiple Interacting Measures. When multiple measures are combined in a single building, they often interact, with the result that savings achieved by the combined interacting measures are different than the sum of savings achieved had each measure been implemented individually (Wolpert et al. 1992). For example, consider the case when a high-efficiency motor retrofit is combined with a variable speed drive (VSD). The savings realized by the motor retrofit will be lower if it is controlled by the VSD. The VSD savings vary depending on whether it is controlling the old inefficient motor or the new high-efficiency motor.

To allocate interactive effects among measures, first rank measures in order. This order may be based on cost-effectiveness, the sequence in which measures would likely have been implemented had they been implemented individually, or any other basis agreed on by buyer and seller.

Next, sequentially simulate the measures as follows. The baseline model is modified so that it includes the highest ranked measure. The savings associated with this measure are then estimated by comparing the baseline model to the modified baseline model that includes the measure in question. This first modified model is then modified again so that it now includes both the first and the second measure. The savings associated with the second measure are then estimated by comparing the model with the first measure to the model with both the first and second ranked measures. Continue adding measures to the mix and estimating savings by comparing the current model (i.e., the one with the most recently added measure) to the previous model (i.e., the one with one fewer added measure). This process continues until a model is developed that includes all the measures. This final model should be identical to the postretrofit model.

C2.4 Report Observations and Savings. When the savings analysis is complete, prepare a report on the estimated savings. It is recommended that such a report include the following:

a. **Executive summary.** Provide an overview of the project and the estimated savings.
b. **Baseline building.** Describe the building before any measures were installed, including size, occupancy, and relevant mechanical, electrical, and other building systems.
c. **Measure descriptions.** For each measure, provide a description and explain why it reduces energy use/demand.
d. **Simulation plan.** Include a copy of the simulation plan that was used to guide the process.
e. **Methodology.** Describe the process by which savings were estimated. Follow the format provided in ASHRAE Guideline 14.
f. **Observations.** Describe the information either collected or produced for each methodology step, including a summary of collected data; model inputs; calibration indexes, including graphical and statistical data; and any other remarkable observations.
g. **Results.** Show the baseline value, the postretrofit value, and the difference for each measure and savings estimate.
h. **Appendices.** Provide information too detailed for the main body of the report. Ensure that sufficient model development and calibration documentation are provided to allow for accurate recreation of the baseline and postretrofit models by informed parties. Examples of such documentation include
    1. on site survey documentation,
    2. spot and short-term measurement documentation,
    3. calculations made to process observations into simulation inputs,
    4. utility data used for calibration,
    5. weather files if nonstandard data/modifications are used,
    6. simulation inputs and outputs,
    7. inputs used to simulate the baseline building,
    8. inputs changed from the baseline for each measure, and
    9. summary results and crosscheck worksheets.

Submit electronic copies of all simulation-input files with the report to allow for verification and to provide a permanent archive of the savings estimate.

(This informative annex is not part of this guideline. It is provided for informational purposes only.)

INFORMATIVE ANNEX D REGRESSION TECHNIQUES

D1. OVERVIEW

The whole-building approach, also called the "main meter approach," includes procedures that measure the performance of retrofits for those projects where whole-building preretrofit and postretrofit data are available to determine the savings and where the savings are expected to be significant enough that the difference between preretrofit and postretrofit use can be measured using a whole-building approach. whole-building methods can use monthly utility billing data (i.e., demand or use) or continuous measurements of the whole-building energy use after the retrofit on a more detailed measurement level (weekly, daily, or hourly). Submetering measurements can also be used to develop the whole-building models, provided the measurements are available for the preretrofit and postretrofit periods and the meters measure that portion of the building where the retrofit was applied. Each submetered measurement then requires a separate model. Whole-building measurements can also be used on stored-energy sources such as oil or coal inventories. In such cases, the energy used during a period needs to be calculated (i.e., any deliveries during the period minus measured reductions in stored fuel).

In most cases, the energy use and/or electric demand are dependent on one or more independent variables. The most common independent variable is outdoor temperature, which affects the building's heating and cooling energy use. Other independent variables can also affect a building's energy use and peak electric demand, including the building's occupancy (often expressed as weekday or weekend models), parking or exterior lighting loads, special events (e.g., Friday night football games), etc.

D2. WHOLE-BUILDING ENERGY USE MODELS

Whole-building models usually involve the use of a regression model that relates the energy use and peak demand to one or more independent variables. The most widely accepted technique uses linear regression or change-point linear regression to correlate energy use or peak demand (the dependent variable) with weather data and/or other independent variables. In most cases, the whole-building model has the form

$$E = C + B_1V_1 + B_2V_2 + B_3V_3 + \ldots + B_nV_n \qquad \text{(D-1)}$$

where

E = the energy use or demand estimated by the equation

C = a constant term in energy units/day or demand units/billing period

B_n = the regression coefficient of an independent variable V_n

V_n = the independent driving variable

In general, the procedure for using whole-building energy use models involves creating a whole-building model, creating a number of different regression models for the particular building, and comparing the results and selecting the best model using the coefficient of determination (R^2)[1] and the coefficient of variation of the root-mean-square error [CV(RMSE)]. Table D-1 and Figure D-1 illustrate models for the whole-building approach, including steady-state constant or mean models, models adjusted for the days in the billing period, two-parameter models, three-parameter models or variable-base degree-day (VBDD) models, four-parameter models, five-parameter models, and multivariate models. All of these models can be calculated with the ASHRAE Inverse Model Toolkit (IMT), which was developed from RP-1050 (Kissock et al. 2002).

The steady-state, linear, change-point linear, VBDD, and multivariate inverse models contained in ASHRAE's IMT have advantages over other types of models. First, because the models are simple and their use with a given data set requires no human intervention, the application of the models can be automated and applied to large numbers of buildings, such as those contained in utility databases. Such a procedure can help a utility or the owner of a large number of buildings identify which buildings have abnormally high energy use. Second, several studies have shown that linear and change-point linear model coefficients have physical significance to the operation of heating and cooling equipment that is controlled by a thermostat (Claridge et al. 1992; Fels 1986; Haberl and Cho 2004; Kissock et al. 1998; Kissock and Mulqueen 2008; Rabl 1988; Rabl and Rialhe 1992; Ruch et al. 1993; Ruch and Claridge 1993; Sever et al. 2011). Finally, numerous studies have reported the successful use of these models on a variety of different buildings (Beasley and Haberl 2002; Haberl et al. 1998, 2001; Hallinan et al. 2011; Raffio et al. 2007; Reddy et al. 1997a, 1997b; Schrock and Claridge 1989; Turner et al. 2000).

Steady-state, daily single-variable models have disadvantages, including an insensitivity to dynamic effects (e.g., thermal mass), insensitivity to variables other than temperature (e.g., humidity and solar), and inappropriateness for other building types (e.g., buildings that have strong on/off schedule-dependent loads or that display multiple change points). If whole-building models are required in such applications, alternative models will need to be developed.

D2.1 Example Input File Description. To generate examples of the linear regression models listed in Section D2, two types of input files were created using uniform and nonuniform time scales. Uniform time-scale data files are composed of records in which all fields are measured over the same time scale. Nonuniform time-scale data files are composed of records in which the dependent variable and the independent variables are measured over different time scales. WINSAVE_UNIFORM.DAT, a sample data file using a uniform time scale for daily building

1. Coefficient of determination (R^2): a measure of the extent to which variations in the dependent variable from its mean value are explained by the regression model.

$$R^2 = 1 - \frac{\sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \bar{y}_i)^2}$$

where y_i, $\hat{y}_i$, $\bar{y}$ are the original data values, predicted values, and mean values, respectively.

TABLE D-1 Sample Models for the Whole-Building Energy Use Approach

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	$E = C + B_1(T)$	
Three-parameter model	Degree-days/temperature	$E = C + B_1(B_2 - T)^+$ $E = C + B_1(T - B_2)^+$	Seasonal weather-sensitive use (fuel in winter, electricity in summer for cooling); weather-sensitive use
Four-parameter change-point model	Temperature	$E = C + B_1(B_3 - T)^+ - B_2(T - B_3)^+$ $E = C - B_1(B_3 - T)^+ + B_2(T - B_3)^+$	
Five-parameter model	Degree-days/temperature	$E = C - B_1(\mathrm{DD}_{TH}) + B_2(\mathrm{DD}_{TC})$ $E = C + B_1(B_3 - T)^+ + B_2(T - B_4)^+$	Heating and cooling supplied by same meter
Multivariate model	Degree-days/temperature, other independent variables	Combination form	Energy use dependent on non-temperature-based variables (occupancy, production, etc.)
Variable-base degree-day model	Heating degree-days Cooling degree-days	$E = C + B_1\ (\mathrm{DD}_{BT})$	

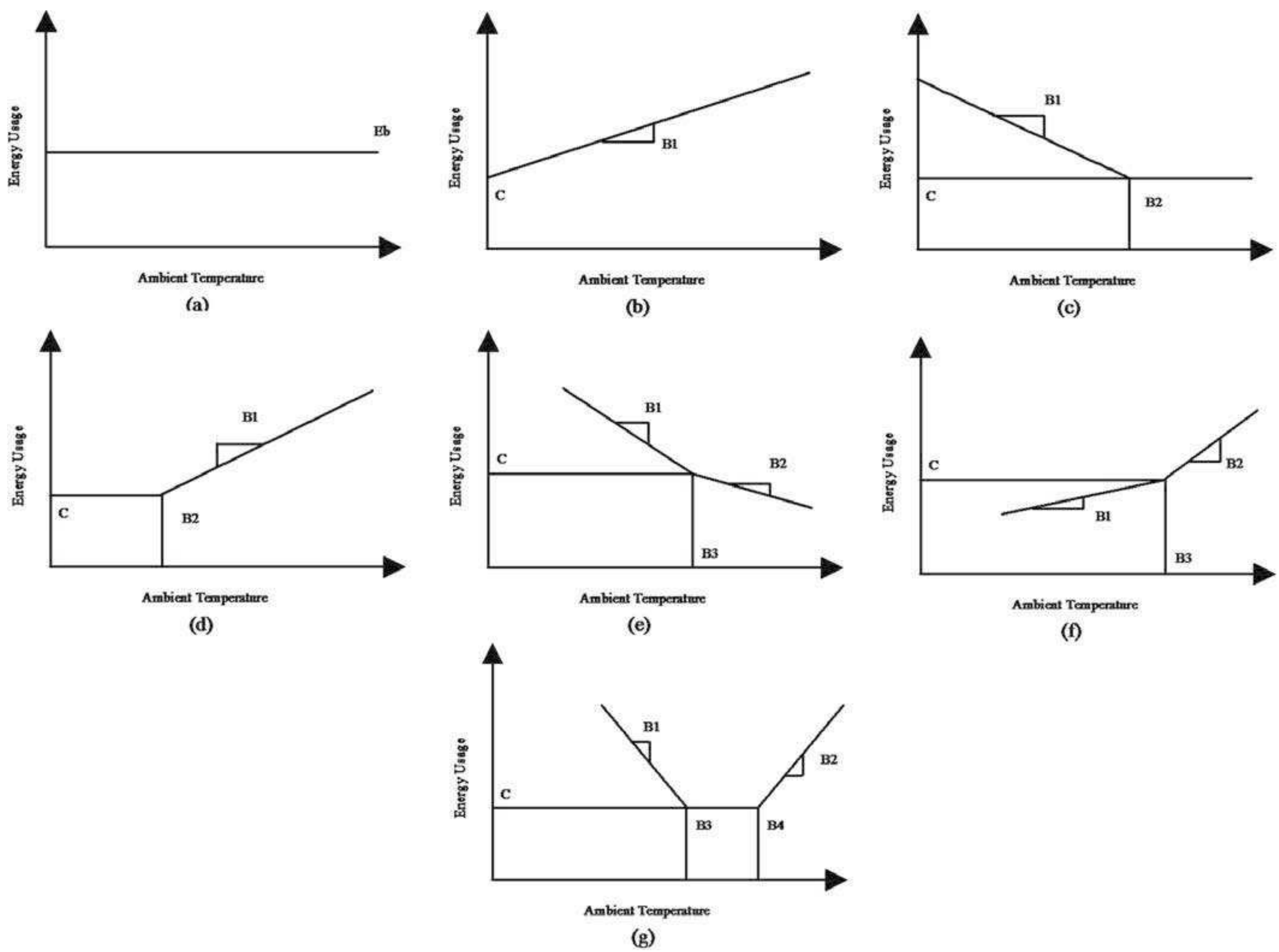

FIGURE D-1 Sample models for the whole-building approach: (a) mean, or one-parameter model; (b) two-parameter model; (c) three-parameter heating model (similar to a variable-base degree-day [VBDD] model for heating); (d) three-parameter cooling model (VBDD for cooling); (e) four-parameter heating model; (f) four-parameter cooling model; and (g) five-parameter model (ASHRAE 2009).

Building identification number	Month of the year	Day of the month	Year	Group	Chilled water consumption	Hot water consumption	Whole building electric	Chilled water and hot water consumption	Daily temperature
114	10	16	90	1	61.8	27.23	-99	89.03	76
114	10	17	90	1	65.2	25.68	-99	90.88	79
114	10	18	90	1	44.2	35.21	-99	79.41	64
114	10	19	90	1	42.6	38.66	-99	81.26	62
114	10	20	90	1	52	32.76	-99	84.76	70

FIGURE D-2 An example of the uniform data file.

Year	Month of the year	Day of the month	Monthly chilled water consumption	Monthly hot water consumption	Monthly whole building electric	Monthly average chilled water consumption	Monthly average hot water consumption	Monthly average whole building electric	Daily temperature
90	11	25	-99	-99	-99	-99	-99	-99	71
90	11	26	-99	-99	-99	-99	-99	-99	76
90	11	27	-99	-99	-99	-99	-99	-99	72
90	11	28	-99	-99	-99	-99	-99	-99	54
90	11	29	-99	-99	-99	-99	-99	-99	54
90	11	30	1409	1126.2	-99	46.97	37.54	-99	51

FIGURE D-3 An example of the nonuniform data file.

energy use, was used to generate examples of one-, two-, three-, four-, and five- parameter linear regression models. The file was modified to create a nonuniform input file, WINSAVE_NONUNIFORM.DAT, to generate examples for the day-adjusted model and the VBDD models.

The files contain energy consumption data from a three-story building that houses classrooms, offices, and a theatre. The building was built in 1962 and received an addition in 1976. Hence, the building operation period can be roughly divided into three parts: preretrofit, construction, and postretrofit. The following is a brief summary of the building information.

a. **Building envelope**
   1. 109,064 ft^2.
   2. Walls: concrete masonry unit with face brick and plaster exteriors.
   3. Windows: 10% of total wall area, single-pane clear operable.
   4. Roof: built-up on lightweight concrete deck.

b. **Building schedule**
   1. Classrooms 7:30 am to 6:30 pm (M through F).
   2. Offices 7:30 am to 5:30 pm (M through F).

c. **Building HVAC**
   1. 2 variable-volume dual-duct air-handling units (AHUs) (1 at 100 hp, AC-1, & 1 at 50 hp, AC-8).
   2. 5 constant-volume single-zone AHUs (1 at 20 hp, 2 at 5 hp, 2 at 3 hp).
   3. 1 constant-volume multizone AHU (25 hp).
   4. 1 variable-frequency-drive hot-deck fan (15 hp).
   5. 3 variable-volume chilled-water pumps (2 at 10 hp, 1 at 30 hp).
   6. 2 condensate pumps (each 3 hp).
   7. 2 constant-drive return air fans (each 10 hp).

d. **HVAC schedule**
   1. 20 hours a day.

The uniform time input file WINSAVE_UNIFORM.DAT has ten data channels of daily data, as seen in Figure D-2. The channels are listed as follows:

a. Building identification number.
b. Month of the year.
c. Day of the month.
d. Year.
e. Group.
f. Chilled-water consumption (MBtu/day [kJ/day]).
g. Hot-water consumption (MBtu/day [kJ/day]).
h. Whole-building electric (kWh/day [kJ/day]).
i. Chilled-water and hot-water consumption (MBtu/day, this channel was created for the purpose of demonstrating the five-parameter model).
j. Daily temperature (°F [°C]).

The nonuniform time input file WINSAVE_NONUNIFORM.DAT has ten data channels, as seen in Figure D-3. The channels are listed as follows:

a. Year.
b. Month of the year.
c. Day of the month.
d. Monthly chilled-water consumption (MBtu/month [kJ/month]).
e. Monthly hot-water consumption (MBtu/month [kJ/month]).
f. Monthly whole-building electric (kWh/month [kJ/month]).
g. Monthly average chilled-water consumption (MBtu/day [kJ/month]).
h. Monthly average hot-water consumption (MBtu/day [kJ/month]).

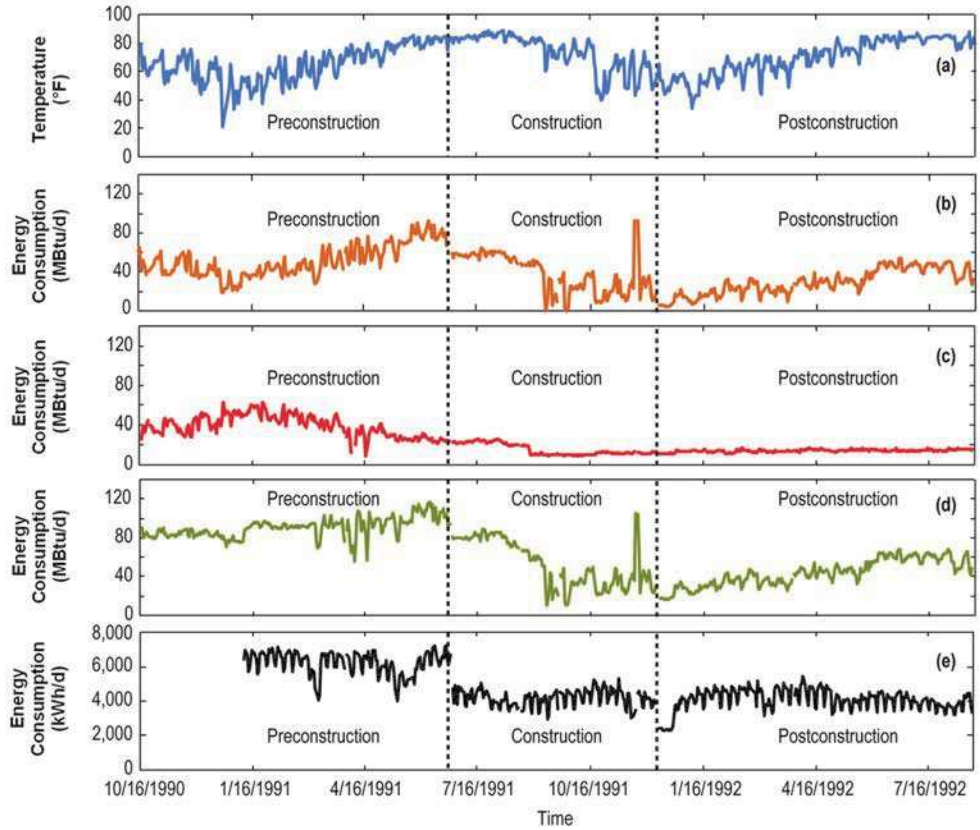

FIGURE D-4 Time-series plots of the daily energy consumption for the example building during the preconstruction, construction, and postconstruction periods: (a) outside dry-bulb temperature, (b) cooling energy consumption, (c) heating energy consumption, (d) heating and cooling energy consumption, and (e) plot of whole-building electric consumption.

TABLE D-2 Selection of Dependent and Independent Variables from WINSAVE_UNIFORM.DAT

Type of Regression Model	Selection of Dependent Variable	Channel Number	Selection of Independent Variable	Channel Number
One parameter	Whole-building electric	8	Hourly outdoor temperature	10
Two parameter	Chilled-water consumption	6	Hourly outdoor temperature	10
Three parameter	Chilled-water consumption	6	Hourly outdoor temperature	10
Four parameter	Chilled-water consumption	6	Hourly outdoor temperature	10
Five parameter	Chilled-water consumption plus hot-water consumption	9	Hourly outdoor temperature	10

TABLE D-3 Selection of Dependent and Independent Variables from WINSAVE_NONUNIFORM.DAT

Type of Regression Model	Selection of Dependent Variable	Channel Number	Selection of Independent Variable	Channel Number
One parameter	Whole-building electric	6/9	Hourly outdoor temperature	10
Two parameter	Chilled-water consumption	4/7	Hourly outdoor temperature	10
Three parameter (cooling)	Chilled-water consumption	4/7	Hourly outdoor temperature	10
Four parameter	Chilled-water consumption	4/7	Hourly outdoor temperature	10
Five parameter	Chilled-water consumption plus hot-water consumption	Not used	Hourly outdoor temperature	10
Variable-base degree-day model	Hot water consumption	8	Heating degree-days calculated from hourly outdoor temperature	10

Year	Month	Day	Monthly chilled water consumption	Monthly hot water consumption	Monthly electric consumption	Average temperature during the energy period	Monthly average chilled water consumption	Monthly average hot water consumption	Monthly average electric consumption	HDD during the energy use period	Predicted heating energy use	Residual
90.00	10.00	31.00	722.20	527.09	-99.00	23.30	17.00	-99.00	65.20	222.00	28.64	-11.64
90.00	11.00	30.00	1409.00	1126.20	-99.00	46.97	37.54	-99.00	63.80	486.00	37.62	-0.08
90.00	12.00	31.00	1093.20	1442.54	-99.00	35.26	46.53	-99.00	51.48	884.00	51.16	-4.63
91.00	1.00	31.00	1110.60	1653.65	157654.00	35.83	53.34	5085.61	49.87	934.00	52.86	0.48
91.00	2.00	28.00	1215.60	1343.92	183273.00	43.41	48.00	6545.46	59.25	581.00	40.85	7.15
91.00	3.00	31.00	1433.40	1285.38	181375.00	46.24	41.46	5850.81	63.74	504.00	38.23	3.23
91.00	4.00	30.00	1792.20	883.92	188741.00	59.74	29.46	6291.37	72.67	220.00	28.57	0.89
91.00	5.00	31.00	2203.00	846.59	171577.00	71.06	27.31	5534.74	79.39	61.00	23.16	4.15
91.00	6.00	25.00	1896.50	611.40	157656.00	75.86	24.46	6306.24	78.76	86.00	24.01	0.45

FIGURE D-5 Example residual file from the nonuniform timescale data input data file.

i. Monthly average whole-building electric (kWh/day [kJ/month]).
j. Daily temperature (°F [°C])

Monthly chilled-water, hot-water, and whole-building electric consumption were calculated by adding up the consumption for each entry over the period of each month (e.g., kWh/month). The monthly average chilled-water, hot-water, and whole-building electric consumption were calculated by dividing the monthly consumption of each entry by the number of days in that time period (e.g., kWh/days).

To get an approximate idea of the energy consumption data of the building, chilled-water consumption, hot-water consumption, whole-building electric consumption, chilled-water and hot-water consumption, and hourly temperature are plotted in time-series graphs. Figure D-4 shows this information graphically. Data will be selected accordingly and analyzed using the regression models mentioned in the previous section. The period between 16 October 1990 and 25 June 1991 has been taken as the preretrofit phase, the period between 26 June and 9 December 1991 has been taken as the construction phase, and the period from 10 December 1991 to 20 August 1992 is considered to be the postretrofit phase.

Tables D-2 and D-3 present the parameters selected from the WINSAVE_UNIFORM.DAT and WINSAVE_NON UNIFORM.DAT input files to generate examples for the options for regression models available for whole-building analysis

In the IMT, a residual file is provided for all types of models. This residual file can be used to evaluate the goodness-of-fit of the model. In the VBDD analysis, the residual file contains the average billing period temperature, which can then be used to calculate a monthly VBDD model that uses daily temperature data. The residual file from a nonuniform time-scale data input file includes the following:

a. All fields from records in the data input file that have valid[1] energy values, except the average daily temperature field. The average daily temperature field is replaced with the average temperature over energy time interval.
b. The number of degree-days in the energy time interval calculated to the best-fit reference temperature.
c. The difference between the predicted and observed values of energy use.

1. Any value except the value of the no-data flag.

An example residual file generated from a nonuniform time-scale data input file is shown in Figure D-5. The fields are listed below.

a. Year.
b. Month.
c. Day.
d. Monthly chilled-water consumption.
e. Monthly hot-water consumption.
f. Monthly electric consumption.
g. Average temperature during the energy period.
h. Monthly average chilled-water consumption.
i. Monthly average hot-water consumption.
j. Monthly average electric consumption.
k. Heating degree-days during the energy use period.
l. Predicted heating energy use.
m. The difference between observed and predicted energy use (residual).

D2.2 One-Parameter or Constant Models. One-parameter or constant models are models where the energy use is constant over a given period. Such models are appropriate for modeling buildings that consume electricity in a way that is independent of the outside weather conditions. For example, such models are appropriate for modeling electricity use in buildings which are on district heating and cooling systems, as the electricity use can be well represented by a constant weekday-weekend model. Constant models are often used to model submetered data on lighting use that is controlled by a predictable schedule.

D2.2.1 Example of a One-Parameter/Constant Model. In this example, the whole-building electric consumption is analyzed after grouping the data in preretrofit and postretrofit categories. As mentioned in the previous section, the period between 16 October 1990 and 25 June 1991 has been taken as the preretrofit phase and the period from 10 December 1991 to 20 August 1992 is considered to be the postretrofit phase. Regression analysis is performed using IMT. However, the data analyzed are obtained from the preconstruction and postconstruction periods only. Figure D-6 presents a regression analysis using a one-parameter model. Figure D-7 presents the regression specifications for the whole-building electric data analyzed with a one-parameter model.

D2.3 Day-Adjusted Models. Day-adjusted models are similar to any model type with the exception that the dependent variable is expressed as an energy use per day to adjust for variations in the number of days in a utility billing cycle. Such day-adjusted models are often used with one-, two-, three-, four-, and five-parameter linear or change-point linear monthly utility models, where the energy use per period is divided by the days in the billing period. A correction for the net bias error due to data length variations can also be applied before the linear or change-point linear regression is performed. An example of day-adjusted models is considered in conjunction with the two-parameter model in Figures D-8 through D-11.

D2.3.1 Example of a Day-Adjusted Model

D2.4 Two-Parameter Models. Two-parameter models are appropriate for modeling building heating or cooling energy use in climates where a building requires only heating, or only cooling, year around or for systems that provide only cooling or only heating. Examples include outdoor air preheating systems in arctic conditions and outdoor air precooling systems in near-tropical climates. Dual-duct, single-fan, constant-volume systems, without economizers, can also be modeled with two-parameter regression models. Constant-use domestic water-heating loads can also be modeled with two-parameter models, which are based on the water supply temperature.

IMT can find a simple linear regression model (two parameter) of type

$$\Upsilon = \beta_1 + \beta_2 X_1 \tag{D-2}$$

where β_1 and β_2 are regression coefficients, X_1 is the independent variable, and Υ is the dependent variable.

D2.4.1 Example of a Two-Parameter Model. In the next set of plots, the chilled-water consumption is analyzed after grouping the data in preretrofit and postretrofit categories as described previously. Regression analysis is performed using IMT. The data analyzed are obtained from the preconstruction and postconstruction periods only. Figure D-12 presents a regression analysis using a two-parameter model. Figure D-13 presents the regression specifics for the whole-building chilled-water consumption analyzed with the two-parameter model.

D2.5 Three-Parameter Models. Three-parameter models, which include change-point linear models or VBDD models, can be used on a wide range of building types, including residential heating and cooling loads, small commercial buildings, and models that describe the gas used by boiler thermal plants that serve one or more buildings (Kissock and Eger 2008). Three-parameter models have several formats, depending on whether or not the model is a VBDD model or three-parameter change-point linear model for heating or cooling. The VBDD model is defined as

$$E = C + B_1(\mathrm{DD}_{BT}) \tag{D-3}$$

where

E = energy use

C = constant energy use below (or above) the changepoint

B_1 = coefficient or slope that describes the linear dependency on degree-days

DD_{BT} = heating or cooling degree-days (or degree hours), which are based on the balance point temperature

The three-parameter change-point linear model for heating is described by[1]

$$E = C + B_1(B_2 - T)^+ \tag{D-4}$$

where

E = energy use

C = constant energy use above the change-point

B_1 = coefficient or slope that describes the linear dependency on temperature

B_2 = heating change-point temperature

T = ambient temperature for the period corresponding to the energy use

$+$ = positive values only inside the parenthesis

The three-parameter change-point linear model for cooling is described by

$$E = C + B_1(T - B_2)^+ \tag{D-5}$$

where

E = energy use

C = constant energy use below the change point

B_1 = coefficient or slope that describes the linear dependency on temperature

B_2 = cooling change-point temperature

T = ambient temperature for the period corresponding to the energy use

$+$ = positive values only for the parenthetical expression

D2.5.1 Example of a Three-Parameter Model. In the next set of plots, the chilled-water consumption is analyzed after grouping the data in preretrofit and postretrofit categories. Figure D-14 presents the scatter plot of the energy consumption from chilled-water use in relation to the outside temperature, with the associated three-parameter models. Figure D-15 presents the regression specifications for the data as analyzed with three-parameter models.

Note that there doesn't appear to be a close fit of the preretrofit data using a three-parameter model. The same data are modeled with a four-parameter model in the next section.

D2.6 Four-Parameter Models. The four-parameter change-point linear heating model is typically applicable to heating use in buildings with HVAC systems that have variable-air-volume (VAV) heating or whose output varies with the ambient temperature (Ruch and Claridge 1992). Four-parameter models have also been shown to be useful for modeling the whole-building electric consumption of grocery stores that have large refrigeration loads and significant cooling loads during the cooling season. Two types of four-parameter models include a heating model and a cooling model. The four-parameter change-point linear heating model is given by

$$E = C + B_1(B_3 - T)^+ - B_2(T - B_3)^+ \tag{D-6}$$

where

1. Temperatures below zero are calculated as positive increases away from the change-point temperature.

E = energy use

C = energy use at the change point

B_1 = coefficient or slope that describes the linear dependency on temperature below the change point

B_2 = coefficient or slope that describes the linear dependency on temperature above the change point

B_3 = change-point temperature

T = temperature for the period of interest

$+$ = positive values only for the parenthetical expression

The four-parameter change-point linear cooling model is given by

$$E = C - B_1(B_3 - T)^+ + B_2(T - B_3)^+ \tag{D-7}$$

where

E = energy use

C = energy use at the change point

B_1 = coefficient or slope that describes the linear dependency on temperature below the change point

B_2 = coefficient or slope that describes the linear dependency on temperature above the change point

B_3 = change-point temperature

T = temperature for the period of interest

$+$ = positive values only for the parenthetical expression

D2.6.1 Example of a Four-Parameter Model. Figures D-16 and D-17 present the scatter plot and output data for whole-building chilled-water consumption using a four-parameter model.

D2.7 Five-Parameter Models. Five-parameter change-point linear models are useful for modeling the whole-building energy use in buildings that contain air conditioning and electric heating. Such models are also useful for modeling the weather-dependent performance of the electricity consumption of VAV AHUs. The basic form for the weather dependency of either case is shown in Figure D-1, where there is an increase in electricity use below the change point associated with heating, an increase in the energy use above the change point associated with cooling, and constant energy use between the heating and cooling change points. Five-parameter change-point linear models can be described using VBDD models or a five-parameter model. The equation for describing the energy use with VBDDs is

$$E = C - B_1(\mathrm{DD}_{TH}) + B_2(\mathrm{DD}_{TC}) \tag{D-8}$$

where

E = energy use

C = constant energy use between the heating and cooling change points

B_1 = coefficient or slope that describes the linear dependency on heating degree-days

B_2 = coefficient or slope that describes the linear dependency on cooling degree-days

DD_{TH} = heating degree-days (or degree hours), which are based on the balance point temperature

DD_{TC} = cooling degree-days (or degree hours), which are based on the balance point temperature

The five-parameter change-point linear model that is based on temperature is

$$E = C + B_1(B_3 - T)^+ + B_2(T - B_4)^+ \tag{D-9}$$

where

E = energy use

C = energy use between the heating and cooling change points

B_1 = coefficient or slope that describes the linear dependency on temperature below the heating change point

B_2 = coefficient or slope that describes the linear dependency on temperature above the cooling change point

B_3 = heating change-point temperature

B_4 = cooling change-point temperature,

T = temperature for the period of interest

$+$ = positive values only for the parenthetical expression

D2.7.1 Example of a Five-Parameter Model. Figures D-18 and D-19 present the scatter plot and output data for combined hot-water and chilled-water consumption using a five-parameter model.

On comparing the five-parameter models, it was seen that the five-point model does not provide a good fit for the postretrofit period. Hence, another set of regression was conducted with the preretrofit model being fitted with a five-point model and the data obtained from the postretrofit period being fitted by a three-parameter model (Figures D-20 and D-21).

D2.7.2 Example of a Five-Parameter/Three-Parameter Model

D2.8 Multivariable Regression Models. The IMT can calculate a multiple-variable linear regression (MVR) model, with up to six independent variables, of the following type:

$$E = \beta_1 + \beta_2 X_1 + \beta_3 X_2 + \beta_4 X_3 + \beta_5 X_4 + \beta_6 X_5 + \beta_7 X_6 \tag{D-10}$$

where

E = energy use

β_1 through β_7 = regression coefficients

X_1 through X_6 = independent variables

D2.8.1 Example of a Variable-Base Degree-Day Model. During the 1980s, Fels (1986) and others adapted the VBDD method for use in measuring savings as the Princeton Scorekeeping Method (PRISM). The VBDD algorithm finds the base temperature that gives the best statistical fit between energy consumption and the number of VBDDs in each energy use period. The method was one of the first to include an estimate of the standard error for all regression parameters

(Goldberg 1982). The method found widespread use, especially in evaluation of residential energy conservation programs. Subsequently, PRISM was found to provide adequate fits with commercial building billing data (Eto 1988; Kissock and Fels 1995). However, the physical interpretation of VBDD parameters may not be applicable to commercial buildings with simultaneous heating and cooling (Rabl and Rialhe 1992; Kissock 1993). Several others have also adapted the VBDD method for baseline modeling. Sonderegger (1998) notes that, in his experience, the optimum is rather flat and that a fairly wide range of degree-day base temperatures produce similar results.

Nonuniform time-scale data files can be used with VBDD models. The VBDD model is defined as indicated in Equation D-3. Figures D-22 through D-25 present scatter plots and output data for hot-water consumption and chilled-water consumption using a VBDD model.

D3. WHOLE-BUILDING PEAK DEMAND MODELS

Whole-building peak electric demand models differ from whole-building energy use models in several respects. First, the models are not adjusted for the days in the billing period as the model is meant to represent the peak electric demand. Second, the models are usually analyzed against the maximum ambient temperature during the billing period. Models for whole-building peak electric demand can be classified according to weather-dependent and weather-independent models.

D3.1 Weather-Independent Whole-Building Peak Demand Models. Weather-independent whole-building peak demand models are used to measure the peak electric use in buildings or submetered data that do not show significant weather dependencies. ASHRAE has developed a diversity factor toolkit for calculating weather-independent whole-building peak demand models as part of RP-1093. This toolkit calculates the 24-hour diversity factors using a quartile analysis. An example of the application of this approach is given in Figures D-26 and D-27.

D3.2 Weather-Dependent Whole-Building Peak Demand Models. Weather-dependent whole-building peak demand models (Figures D-28, D-29, and D-30) can be used to model the peak electricity use of a facility. Such models can be calculated with linear and change-point linear models regressed against maximum temperatures for the billing period or calculated with an inverse bin model (Thamilseran and Haberl 1995; Thamilseran 1999).

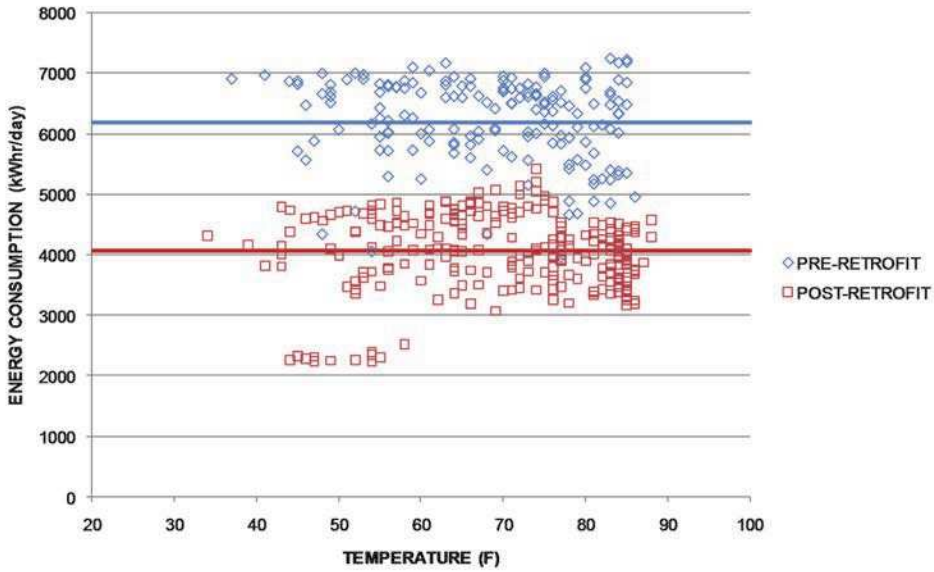

FIGURE D-6 XY scatter plot for whole-building electric data using data obtained from pre- and post-retrofit analysis analyzed with a one-parameter model. Preretrofit model: Ymean = 6192.065, StdDev = 834.293, and CV-StdDev = 13.474%; postretrofit model: Ymean = 4059.862, StdDev = 623.619, and CV-StdDev = 15.361%.

*********************************	*********************************
ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
*********************************	*********************************
Output file name = IMT.Out	Output file name = IMT.Out
*********************************	*********************************
Input data file name = 1PPRE.DAT	Input data file name = 1PPOST.DAT
Model type = Mean	Model type = Mean
Grouping column No = 0	Grouping column No = 0
Value for grouping = 0	Value for grouping = 0
Residual mode = 0	Residual mode = 0
# of X(Indep.) Var = 0	# of X(Indep.) Var = 0
Y1 column number = 1	Y1 column number = 1
X1 column number = 0 (unused)	X1 column number = 0 (unused)
X2 column number = 0 (unused)	X2 column number = 0 (unused)
X3 column number = 0 (unused)	X3 column number = 0 (unused)
X4 column number = 0 (unused)	X4 column number = 0 (unused)
X5 column number = 0 (unused)	X5 column number = 0 (unused)
X6 column number = 0 (unused)	X6 column number = 0 (unused)
*********************************	*********************************
Regression Results	Regression Results
N = 168	N = 253
Ymean = 6192.065	Ymean = 4059.862
StdDev = 834.293	StdDev = 623.619
CV–StdDev = 13.474 %	CV–StdDev = 15.361 %

FIGURE D-7 Inverse Model Toolkit (IMT) output for whole-building electric data using the one-parameter model.

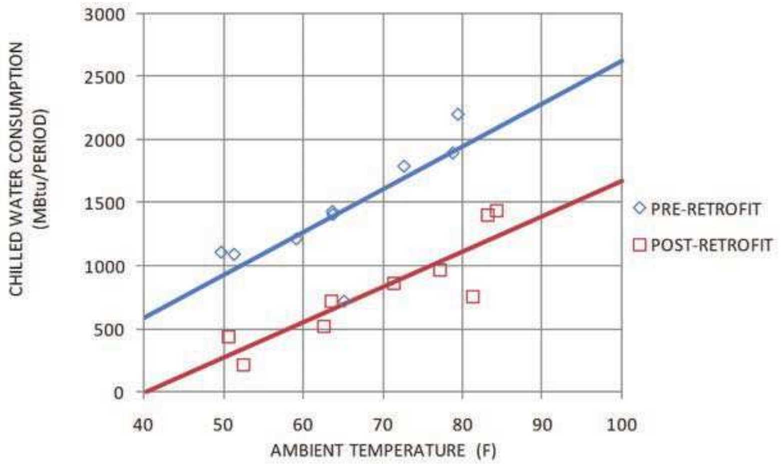

FIGURE D-8 Example adjusted monthly chilled-water consumption analysis (two-parameter model) on million-Btu-per-period basis. Preretrofit model: RMSE = 306.4365 and CV(RMSE) = 21.42%; postretrofit model: RMSE = 202.1776 and CV(RMSE) = 24.78%.

ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
Output file name = IMT.Out	Output file name = IMT.Out
Input data file name = PRE_2.DAT	Input data file name = POST_2.DAT
Model type = 2P	Model type = 2P
Grouping column No = 0	Grouping column No = 0
Value for grouping = 0	Value for grouping = 0
Residual mode = 0	Residual mode = 0
# of X(Indep.) Var = 1	# of X(Indep.) Var = 1
Y1 column number = 4	Y1 column number = 4
X1 column number = 10	X1 column number = 10
X2 column number = 0 (unused)	X2 column number = 0 (unused)
X3 column number = 0 (unused)	X3 column number = 0 (unused)
X4 column number = 0 (unused)	X4 column number = 0 (unused)
X5 column number = 0 (unused)	X5 column number = 0 (unused)
X6 column number = 0 (unused)	X6 column number = 0 (unused)
Regression Results	Regression Results
N = 9	N = 9
R2 = 0.615	R2 = 0.785
AdjR2 = 0.615	AdjR2 = 0.785
RMSE = 306.4365	RMSE = 202.1776
CV(RMSE) = 21.420%	CV(RMSE) = 24.778%
p = 0.266	p = -0.229
DW = 1.100 (p>0)	DW = 1.883 (p>0)
a = -784.6312 (669.7266)	a = -1136.6213 (392.4066)
X1 = 34.1300 (10.1976)	X1 = 28.0274 (5.5489)

FIGURE D-9 IMT output for two-parameter model for adjusted monthly chilled-water consumption analysis on million-Btu-per-period basis.

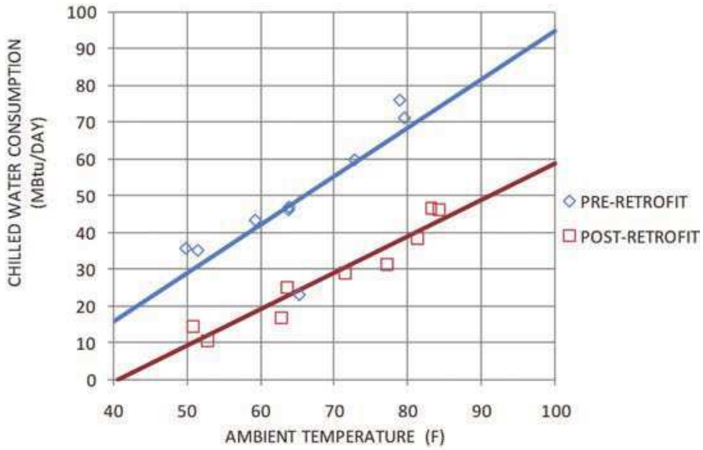

FIGURE D-10 Example adjusted monthly chilled-water consumption analysis (two-parameter model) on million-Btu-per-day basis. Preretrofit model: RMSE = 10.8726 and CV(RMSE) = 22.36%; postretrofit model: RMSE = 3.9673 and CV(RMSE) = 13.847%.

ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
Output file name = IMT.Out	Output file name = IMT.Out
Input data file name = PRE_2.DAT	Input data file name = POST_2.DAT
Model type = 2P	Model type = 2P
Grouping column No = 0	Grouping column No = 0
Value for grouping = 0	Value for grouping = 0
Residual mode = 0	Residual mode = 0
# of X(Indep.) Var = 1	# of X(Indep.) Var = 1
Y1 column number = 7	Y1 column number = 7
X1 column number = 10	X1 column number = 10
X2 column number = 0 (unused)	X2 column number = 0 (unused)
X3 column number = 0 (unused)	X3 column number = 0 (unused)
X4 column number = 0 (unused)	X4 column number = 0 (unused)
X5 column number = 0 (unused)	X5 column number = 0 (unused)
X6 column number = 0 (unused)	X6 column number = 0 (unused)
Regression Results	Regression Results
N = 9	N = 9
R2 = 0.653	R2 = 0.922
AdjR2 = 0.653	AdjR2 = 0.922
RMSE = 10.8726	RMSE = 3.9673
CV(RMSE) = 22.358%	CV(RMSE) = 13.847%
p = 0.485	p = -0.048
DW = 0.908 (p>0)	DW = 2.041 (p>0)
a = -36.6937 (23.7623)	a = -40.1793 (7.7002)
X1 = 1.3146 (0.3618)	X1 = 0.9880 (0.1089)

FIGURE D-11 IMT output for two-parameter model for adjusted monthly chilled-water consumption analysis on million-Btu-per-day basis.

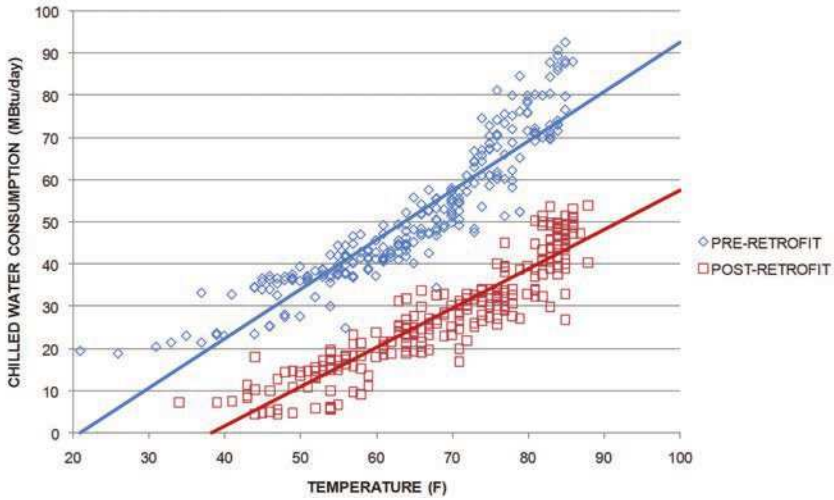

FIGURE D-12 XY scatter plot for chilled-water consumption using data obtained from pre- and postretrofit analysis, analyzed with a two-parameter model. Preretrofit model: RMSE = 6.5982 and CV(RMSE) = 12.8%; postretrofit model: RMSE = 5.0185 and CV(RMSE) = 17.1%.

ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
Output file name = IMT.Out	Output file name = IMT.Out
Input data file name = PRERETRO.dat Model type = 2P Grouping column No = 0 Value for grouping = 0 Residual mode = 0 # of X(Indep.) Var = 1 Y1 column number = 6 X1 column number = 10 X2 column number = 0 (unused) X3 column number = 0 (unused) X4 column number = 0 (unused) X5 column number = 0 (unused) X6 column number = 0 (unused)	Input data file name = POSTRETRO.dat Model type = 2P Grouping column No = 0 Value for grouping = 0 Residual mode = 0 # of X(Indep.) Var = 1 Y1 column number = 6 X1 column number = 10 X2 column number = 0 (unused) X3 column number = 0 (unused) X4 column number = 0 (unused) X5 column number = 0 (unused) X6 column number = 0 (unused)
Regression Results	Regression Results
N = 250	N = 253
R2 = 0.842	R2 = 0.853
AdjR2 = 0.842	AdjR2 = 0.853
RMSE = 6.5982	RMSE = 5.0185
CV(RMSE) = 12.811%	CV(RMSE) = 17.060%
p = 0.680	p = 0.633
DW = 0.639 (p>0)	DW = 0.729 (p>0)
a = -24.6745 (2.1349)	a = -35.6330 (1.7325)
X1 = 1.1743 (0.0323)	X1 = 0.9314 (0.0244)

FIGURE D-13 IMT output for two-parameter model.

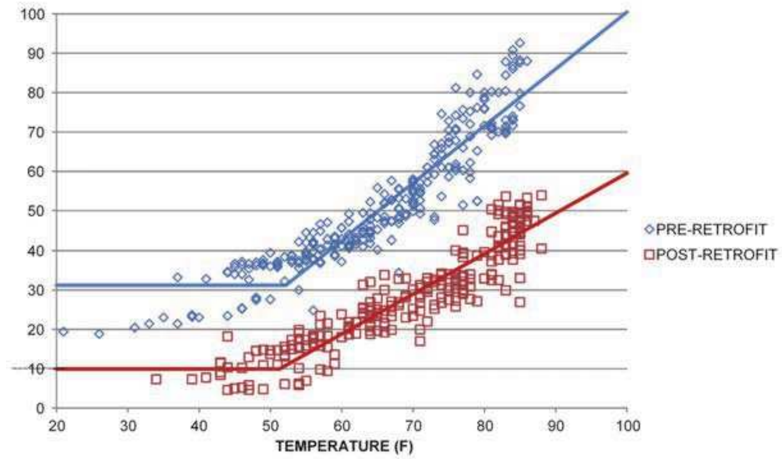

FIGURE D-14 Three-parameter model analysis for chilled-water vs. temperature grouped by pre- and postretrofit data. Preretrofit model: RMSE = 6.0779 and CV(RMSE) = 11.801%; postretrofit model: RMSE = 4.7937 and CV(RMSE) = 16.295%.

ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
Output file name = IMT.Out	Output file name = IMT.Out
Input data file name = PRERETRO.dat	Input data file name = POSTRETRO.dat
Model type = 3P Cooling	Model type = 3P Cooling
Grouping column No = 0	Grouping column No = 0
Value for grouping = 0	Value for grouping = 0
Residual mode = 0	Residual mode = 0
# of X(Indep.) Var = 1	# of X(Indep.) Var = 1
Y1 column number = 6	Y1 column number = 6
X1 column number = 10	X1 column number = 10
X2 column number = 0 (unused)	X2 column number = 0 (unused)
X3 column number = 0 (unused)	X3 column number = 0 (unused)
X4 column number = 0 (unused)	X4 column number = 0 (unused)
X5 column number = 0 (unused)	X5 column number = 0 (unused)
X6 column number = 0 (unused)	X6 column number = 0 (unused)
Regression Results	Regression Results
N = 250	N = 253
R2 = 0.866	R2 = 0.866
AdjR2 = 0.866	AdjR2 = 0.866
RMSE = 6.0779	RMSE = 4.7937
CV(RMSE) = 11.801%	CV(RMSE) = 16.295%
p = 0.639	p = 0.624
DW = 0.718 (p>0)	DW = 0.744 (p>0)
N1 = 43	N1 = 24
N2 = 207	N2 = 229
Ycp = 31.2180 (0.6358)	Ycp = 9.9693 (0.5692)
LS = 0.0000 (0.0000)	LS = 0.0000 (0.0000)
RS = 1.4483 (0.0362)	RS = 1.0179 (0.0253)
Xcp = 52.2000 (1.3000)	Xcp = 51.2800 (1.0800)

FIGURE D-15 IMT regression specifications for a three-parameter model analysis for chilled-water vs. temperature grouped by pre- and postretrofit data.

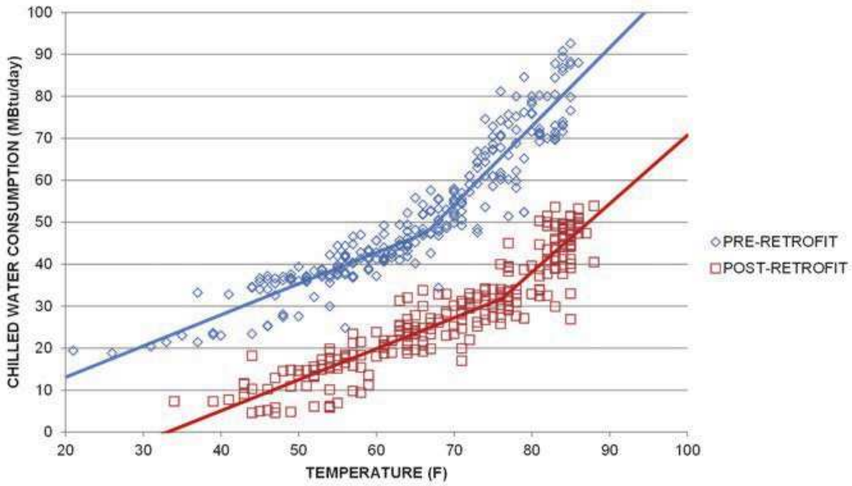

FIGURE D-16 XY scatter plot for chilled-water consumption using data obtained from postretrofit analysis, analyzed with a four-parameter model. Preretrofit model: RMSE = 5.3303 and CV(RMSE) = 10.35%; postretrofit model: RMSE = 4.5372 and CV(RMSE) = 15.423%.

ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
Output file name = IMT.Out	Output file name = IMT.Out
Input data file name = PRERETRO.dat	Input data file name = POSTRETRO.dat Model type = 4P
Grouping column No = 0 Value for grouping = 0 Residual mode = 0 # of X(Indep.) Var = 1 Y1 column number = 6 X1 column number = 10 X2 column number = 0 (unused) X3 column number = 0 (unused) X4 column number = 0 (unused) X5 column number = 0 (unused) X6 column number = 0 (unused)	Grouping column No = 0 Value for grouping = 0 Residual mode = 0 # of X(Indep.) Var = 1 Y1 column number = 6 X1 column number = 10 X2 column number = 0 (unused) X3 column number = 0 (unused) X4 column number = 0 (unused) X5 column number = 0 (unused) X6 column number = 0 (unused)
Regression Results	Regression Results
N = 250	N = 253
R2 = 0.897	R2 = 0.880
AdjR2 = 0.897	AdjR2 = 0.880
RMSE = 5.3303	RMSE = 4.5372
CV(RMSE) = 10.350%	CV(RMSE) = 15.423%
p = 0.608	p = 0.550
DW = 0.773 (p>0)	DW = 0.892 (p>0)
N1 = 129	N1 = 156
N2 = 121	N2 = 97
Ycp = 47.6395 (4.1293)	Ycp = 31.7898 (3.4417)
LS = 0.7428 (0.0456)	LS = 0.7391 (0.0337)
RS = 1.8695 (0.1078)	RS = 1.6295 (0.1226)
Xcp = 66.5000 (1.3000)	Xcp = 76.1200 (1.0800)

FIGURE D-17 IMT output for the four-parameter model.

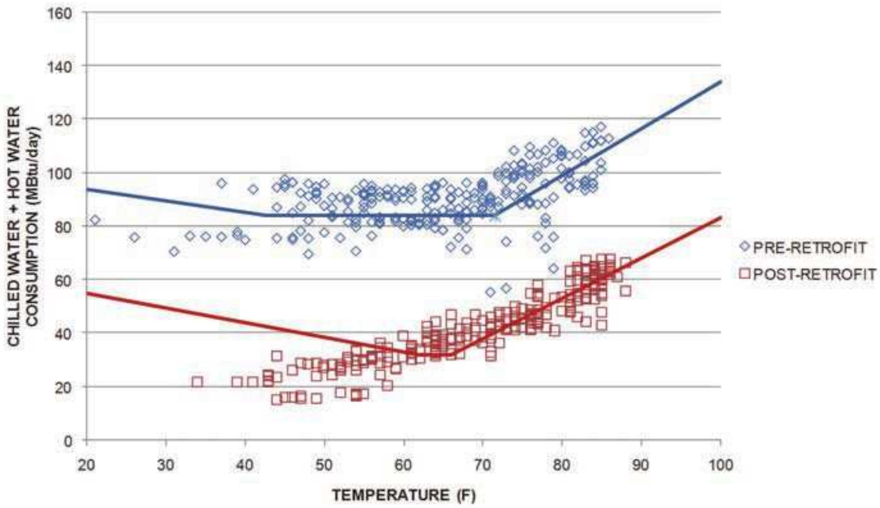

FIGURE D-18 XY scatter plot for combined hot-water and chilled-water consumption using data obtained from pre- and postretrofit periods, analyzed with a five-parameter model. Preretrofit model: RMSE = 26.7108 and CV(RMSE) = 30.32%; postretrofit model: RMSE = 15.3932 and CV(RMSE) = 36.319%.

**********************************	**********************************
***********************	***********************
ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
**********************************	**********************************
***********************	***********************
Output file name = IMT.Out	Output file name = IMT.Out
**********************************	**********************************
***********************	***********************
Input data file name = PRERETRO.dat	Input data file name = POSTRETRO.dat
Model type = 5P	Model type = 5P
Grouping column No = 0	Grouping column No = 0
Value for grouping = 0	Value for grouping = 0
Residual mode = 0	Residual mode = 0
# of X(Indep.) Var = 1	# of X(Indep.) Var = 1
Y1 column number = 9	Y1 column number = 9
X1 column number = 10	X1 column number = 10
X2 column number = 0 (unused)	X2 column number = 0 (unused)
X3 column number = 0 (unused)	X3 column number = 0 (unused)
X4 column number = 0 (unused)	X4 column number = 0 (unused)
X5 column number = 0 (unused)	X5 column number = 0 (unused)
X6 column number = 0 (unused)	X6 column number = 0 (unused)
**********************************	**********************************
***********************	***********************
Regression Results	Regression Results
N = 252	N = 254
R2 = 0.070	R2 = 0.431
AdjR2 = 0.070	AdjR2 = 0.431
RMSE = 26.7108	RMSE = 15.3932
CV(RMSE) = 30.320%	CV(RMSE) = 36.319%
p = 0.110	p = 0.034
DW = 1.780 (p>0)	DW = 1.930 (p>0)
Xcp1 = 42.6667 (2.4050)	Xcp1 = 61.9960 (1.9980)
Xcp2 = 71.5556 (2.4050)	Xcp2 = 65.9980 (1.9980)
Ycp = 84.0721 (1.9882)	Ycp = 32.2360 (1.7409)
LS = 0.4340 (0.8079)	LS = 0.5468 (0.2091)
RS = 1.7550 (0.4157)	RS = 1.4943 (0.1421)

FIGURE D-19 IMT output for the five-parameter model.

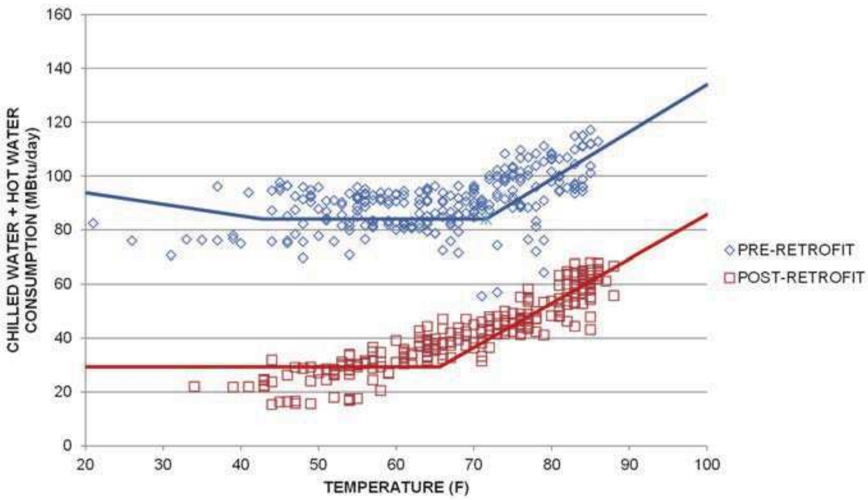

FIGURE D-20 XY scatter plot for combined hot-water and chilled-water consumption using data obtained from pre- and postretrofit periods, analyzed with a five-parameter model for preretrofit period and a three-parameter model for postretrofit period. Preretrofit model: RMSE = 26.7108 and CV(RMSE) = 30.32%; postretrofit model: RMSE = 15.6154 and CV(RMSE) = 36.843%.

ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
Output file name = IMT.Out	Output file name = IMT.Out
Input data file name = VDD_PRE.DAT	Input data file name = VDD_POST.DAT
Model type = HDD	Model type = HDD
Grouping column No = 0	Grouping column No = 0
Value for grouping = 0	Value for grouping = 0
Residual mode = 1	Residual mode = 1
# of X(Indep.) Var = 1	# of X(Indep.) Var = 1
Y1 column number = 8	Y1 column number = 8
X1 column number = 10	X1 column number = 10
X2 column number = 0 (unused)	X2 column number = 0 (unused)
X3 column number = 0 (unused)	X3 column number = 0 (unused)
X4 column number = 0 (unused)	X4 column number = 0 (unused)
X5 column number = 0 (unused)	X5 column number = 0 (unused)
X6 column number = 0 (unused)	X6 column number = 0 (unused)
Regression Results	Regression Results
N = 9	N = 9
R2 = 0.803	R2 = 0.339
AdjR2 = 0.803	AdjR2 = 0.339
RMSE = 5.8168	RMSE = 1.4828
CV(RMSE) = 16.103%	CV(RMSE) = 10.980%
p = 0.335	p = -0.286
DW = 1.140 (p>0)	DW = 2.444 (p>0)
DD Base = 80	DD Base = 80
a = 21.0841 (3.4210)	a = 14.5019 (0.7225)
X1 = 0.0340 (0.0064)	X1 = -0.0031 (0.0017)

FIGURE D-21 IMT output for the five-parameter model.

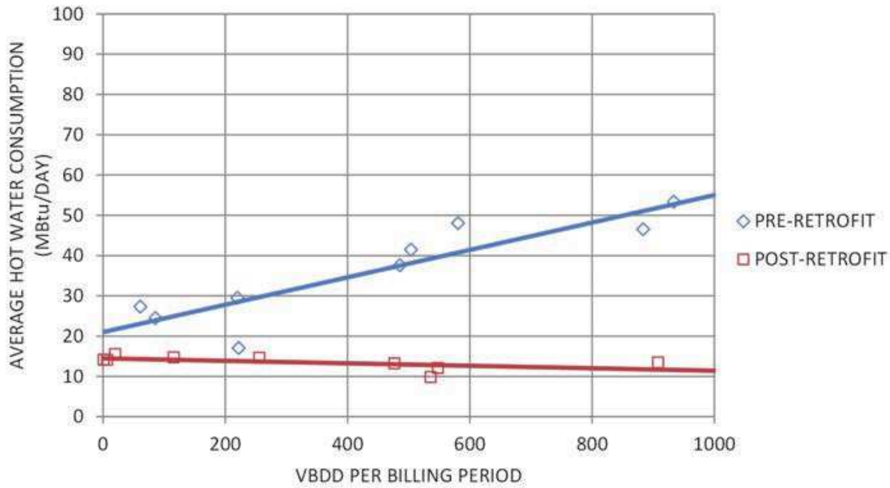

FIGURE D-22 XY scatter plot for hot-water consumption using data obtained from pre- and postretrofit analysis and analyzed with a variable-base degree-day model. Preretrofit model: RMSE = 5.8168 and CV(RMSE) = 26.203%; postretrofit model: RMSE = 1.4828 and CV(RMSE) = 10.98%.

ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
Output file name = IMT.Out	Output file name = IMT.Out
Input data file name = VDD_PRE.DAT	Input data file name = VDD_POST.DAT
Model type = HDD	Model type = HDD
Grouping column No = 0	Grouping column No = 0
Value for grouping = 0	Value for grouping = 0
Residual mode = 1	Residual mode = 1
# of X(Indep.) Var = 1	# of X(Indep.) Var = 1
Y1 column number = 8	Y1 column number = 8
X1 column number = 10	X1 column number = 10
X2 column number = 0 (unused)	X2 column number = 0 (unused)
X3 column number = 0 (unused)	X3 column number = 0 (unused)
X4 column number = 0 (unused)	X4 column number = 0 (unused)
X5 column number = 0 (unused)	X5 column number = 0 (unused)
X6 column number = 0 (unused)	X6 column number = 0 (unused)
Regression Results	Regression Results
N = 9	N = 9
R2 = 0.803	R2 = 0.339
AdjR2 = 0.803	AdjR2 = 0.339
RMSE = 5.8168	RMSE = 1.4828
CV(RMSE) = 16.103%	CV(RMSE) = 10.980%
p = 0.335	p = -0.286
DW = 1.140 (p>0)	DW = 2.444 (p>0)
DD Base = 80	DD Base = 80
a = 21.0841 (3.4210)	a = 14.5019 (0.7225)
X1 = 0.0340 (0.0064)	X1 = -0.0031 (0.0017)

FIGURE D-23 IMT output for a variable-base degree-day heating degree-day (HDD) model.

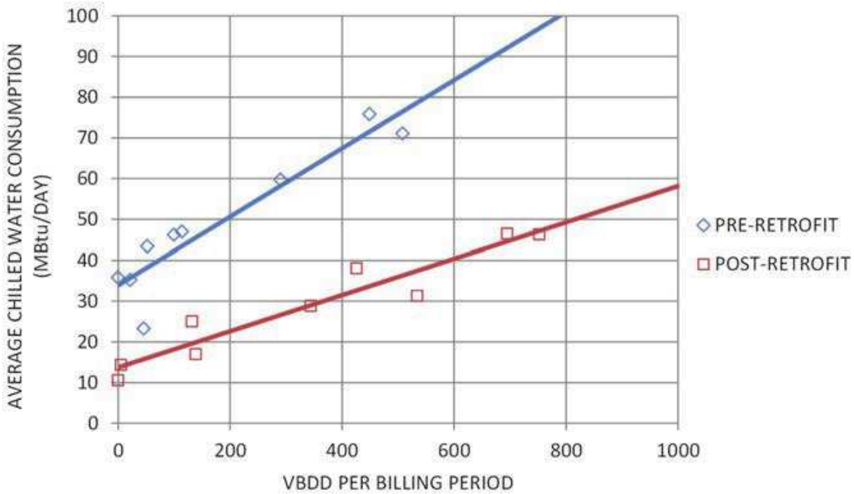

FIGURE D-24 XY scatter plot for chilled-water consumption using data obtained from pre- and postretrofit analysis, analyzed with a variable-base degree-day model. Preretrofit model: RMSE = 5.8168 and CV(RMSE) = 26.203%; postretrofit model: RMSE = 1.4828 and CV(RMSE) = 10.98%.

**********************************	**********************************
**********************	**********************
ASHRAE INVERSE MODELING TOOLKIT (1.9)	ASHRAE INVERSE MODELING TOOLKIT (1.9)
**********************************	**********************************
**********************	**********************
Output file name = IMT.Out	Output file name = IMT.Out
**********************************	**********************************
**********************	**********************
Input data file name = VDD_PRE.DAT	Input data file name = VDD_POST.DAT
Model type = CDD	Model type = CDD
Grouping column No = 0	Grouping column No = 0
Value for grouping = 0	Value for grouping = 0
Residual mode = 1	Residual mode = 1
# of X(Indep.) Var = 1	# of X(Indep.) Var = 1
Y1 column number = 7	Y1 column number = 7
X1 column number = 10	X1 column number = 10
X2 column number = 0 (unused)	X2 column number = 0 (unused)
X3 column number = 0 (unused)	X3 column number = 0 (unused)
X4 column number = 0 (unused)	X4 column number = 0 (unused)
X5 column number = 0 (unused)	X5 column number = 0 (unused)
X6 column number = 0 (unused)	X6 column number = 0
**********************************	**********************************
**********************	**********************
Regression Results	Regression Results
N = 9	N = 9
R2 = 0.867	R2 = 0.915
AdjR2 = 0.867	AdjR2 = 0.915
RMSE = 6.7392	RMSE = 4.1383
CV(RMSE) = 13.858%	CV(RMSE) = 14.444%
p = -0.448	p = -0.289
DW = 1.591 (p>0)	DW = 2.196 (p>0)
DD Base = 63	DD Base = 60
A = 33.8982 (3.1317)	A = 13.7152 (2.2075)
X1 = 0.0839 (0.0124)	X1 = 0.0444 (0.0051)

FIGURE D-25 IMT output for a variable-base degree-day cooling degree-day (CDD) model.

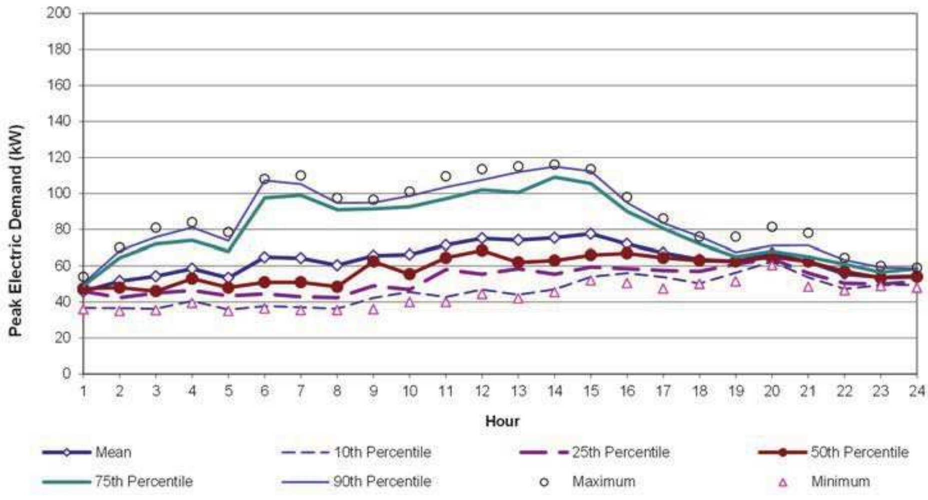

FIGURE D-26 Example of weekend hourly whole-building electric demand (RP-1093 model), June 2007.

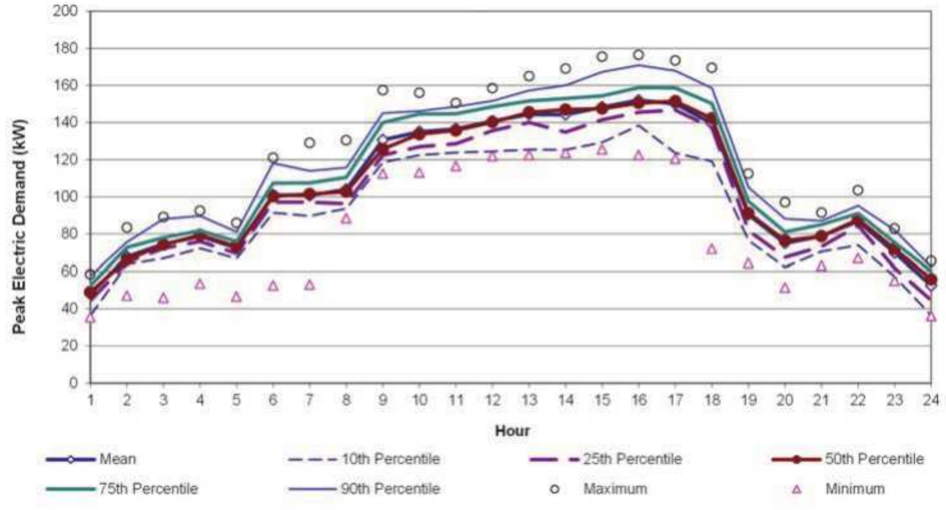

FIGURE D-27 Example of weekday hourly whole-building electric demand (RP-1093 model), June 2007.

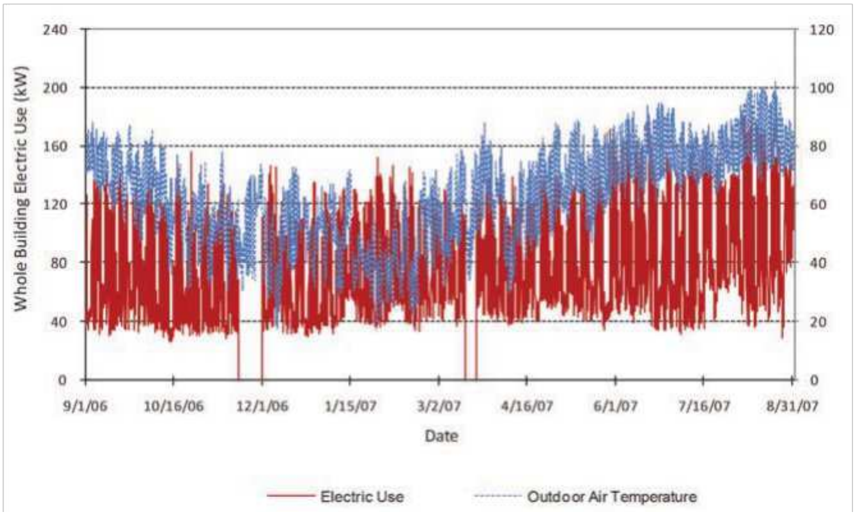

FIGURE D-28 Example of electricity data for hourly whole-building electric use and corresponding outdoor temperature (ASHRAE headquarters building).

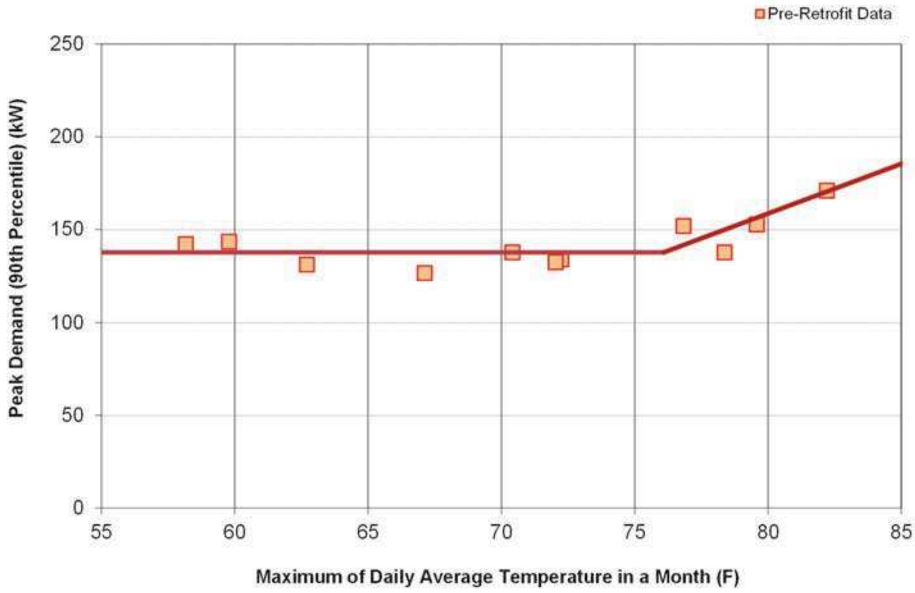

FIGURE D-29 Example of a weather-dependent whole-building peak monthly demand model.

```
*******************************************************
ASHRAE INVERSE MODELING TOOLKIT (1.9)
*******************************************************
Output file name = IMT.Out
*******************************************************
Input data file name = PRE_RETROFIT.DAT
Model type = 3P Cooling
Grouping column No = 5
Value for grouping = 2
Residual mode = 0
# of X(Indep.) Var = 1
Y1 column number = 9
X1 column number = 10
X2 column number = 0 (unused)
X3 column number = 0 (unused)
X4 column number = 0 (unused)
X5 column number = 0 (unused)
X6 column number = 0 (unused)
*******************************************************
Regression Results
------------------------------
N = 11
------------------------------
R2 = 0.573
------------------------------
AdjR2 = 0.573
------------------------------
RMSE = 8.8099
------------------------------
CV(RMSE) = 6.212%
------------------------------
p = -0.043
------------------------------
DW = 1.594 (p>0)
------------------------------
N1 = 8
------------------------------
N2 = 3
------------------------------
Ycp = 137.5487 (2.9267)
------------------------------
LS = 0.0000 (0.0000)
------------------------------
RS = 5.3612 (1.5429)
------------------------------
Xcp = 76.0800 (1.4800)
------------------------------
```

FIGURE D-30 Example of a weather-dependent whole-building peak demand model.

(This normative annex is part of this guideline and is required for its use.)

NORMATIVE ANNEX E
RETROFIT ISOLATION APPROACH TECHNIQUES

E1. RETROFIT ISOLATION APPROACH FOR PUMPS

Pumping systems in building heating, ventilation, and air-conditioning (HVAC) applications use different types and numbers of pumps, various control strategies, and several types of piping layouts. Pump electric power demand variation with heating or cooling loads depends on the system design and control method used. Building hydronic systems and their control typically fall into the following three categories.

a. **Constant speed, constant volume.** Constant-volume pumping systems use three-way valves and bypass loops at the end use or at the pump. As the load varies in the system, pump pressure and flow are held relatively constant, and the pump input power remains nearly constant. Pump motor speed is constant.
b. **Constant speed, variable volume.** Variable pumping systems use two-way control valves to modulate flow to the end use as required. In constant-speed variable-volume pumping systems, the flow varies along the pump curve as the system pressure drop changes in response to the load. In some cases, a bypass valve may be modulated if system differential pressure becomes too large.
c. **Variable speed, variable volume.** Like the constant-speed, variable-volume system, flow to the zone loads is typically modulated using two-way control valves. However, in variable-speed variable-volume pumping systems, a static pressure controller is used to adjust pump speed to match the flow load requirements.

To ensure applicability to a wide variety of pumping systems, the in situ testing guidelines contain six different methods. The preferred method is determined by the user based on the system type and control and the desired level of uncertainty, cost, and degree of intrusion. The first two methods involve testing at a single operating point. The third and fourth procedures involve testing at multiple operating points under imposed system loading. The fifth method also involves multiple operating points, in this case, obtained through short-term monitoring of the system without imposed loading. The final procedure operates the pump with the fluid flow path completely blocked. While this procedure is not useful for generating a power versus load relationship, it can be used to confirm manufacturer's data or to identify pump impeller diameter.

Test methods have been developed to apply to the typical pumping systems described above (Table E-1). Different methods can be used for each type of pumping system, depending on the available resources and possible degree of intrusion on operation. The following paragraphs describe each of the test methods in the context of a particular pumping system application.

Constant-volume pumping systems have a single possible operating point. Knowledge of the power use at the operating point and the total operating hours are enough to determine annual energy use. The first test method, which evaluates the power use at this single operating point, is naturally suited to this application.

Variable-volume pumping systems with constant-speed pumps have a single possible operating point for any given flow, as determined by the pump curve at that flow rate. The second and third testing methods were specifically designed for this application. In the second procedure, the power use is measured at one flow rate, and manufacturer's data on the pump, motor, and drive system are used to create a part-load power use curve. The single measured test point is used to calibrate or confirm pump curve reliability. The third testing method does not use pump curve estimations but imposes loads on the system using existing control, discharge, or balancing valves. Because the pump operates at constant speed, it does not matter how the load is imposed. The power use is measured at a range of flow rates to determine the part-load power use curve. In both methods, the part-load power use curve and flow load frequency distribution are used to determine annual energy use.

In variable-speed variable-volume pumping applications, the operating point cannot be determined solely from the pump curve and flow load because a given flow could be provided at various pressures or speeds. The system design and control strategy place constraints on either the pressure or flow. A typical variable-speed-controlled system will have a range of system curves that call for the same flow rate,

TABLE E-1 Applicability of Test Methods to Common Pumping Systems

Test Method	Pumping System		
	Constant Speed, Constant Volume	Constant Speed, Variable Volume	Variable Speed, Variable Volume
Single point	✓✓		
Single point with manufacturer's pump curve		✓✓	
Multiple point with imposed loads at pump		✓✓	
Multiple point with imposed loads at zone		✓✓	✓✓
Multiple point through short-term monitoring		✓✓	✓✓
No-flow test for pump characteristics	✓✓	✓✓	✓✓

TABLE E-2 Nomenclature for Calculations and Uncertainty Analysis

Value	Symbol	Units/Variable
Bin energy use	E	kWh
Power level	P	kW
Pump capacity/flow rate	Q	gpm, L/s
Total pump pressure	H	ft, psi, kPa
Pump discharge pressure	H_d	ft, psi, kPa
Pump suction pressure	H_s	ft, psi, kPa
Pump rotational speed	S	rpm
Number of hours	T	number
Uncertainty	w	kWh
Total annual uncertainty	U	kWh
Predictor variable	x	varies
Response variable	y	varies
Expected value	$E[\ ]$	x, y
Variance	Var	x^2, y^2
Intercept	β_0	y
First- and second-order coefficients	β_1, β_2	y/x, y/x^2
Standard error of regression	σ^2	y^2
Error	e	x, y
Mean value	m	x, y
Predicted value symbol	^	NA

depending on the occupancy, season, and load. There are two options for accurately determining the part-load power use curve. In both cases, the boundaries of an in situ test include the pump and system (piping, valves, and controllers) so that the control strategy is included within the data set. In the fourth method, the power use is measured at a range of loads, which are imposed on the pumping system. The artificial imposition of loads on the system must be done at the zone level to account for the control strategy and system design. If loads are imposed directly on the pump, by manipulating control valve position for example, the measurement of power use will not necessarily reflect the building pump and system operating conditions.

For the fifth method, the pump system is monitored as the building experiences a range of thermal loads, with no artificial imposition of loads. An accurate part-load power curve can be developed if the load variation during the monitoring period reflects the full range of annual load characteristics. A representative full-day or half-day monitoring period with natural variations in load may be sufficient. For both methods, the measured part-load power use curves and flow load frequency distribution are used to determine annual energy use. Methods 4 and 5 can also be applied to constant-speed variable-flow systems.

The different testing methods have different minimum measurement requirements. In methods where manufacturer's data or curves are to be used, the minimum measurements include volumetric flow rate, coincident root-mean-square (RMS) power, differential pressure, and rotational speed. For methods developing a part-load power use curve through direct measurements, only volumetric flow rate and coincident RMS power use are required. Additional measurements may be desired by the user if the data are to be used for more complete analysis and evaluation of the pumping system.

Centrifugal pump performance should be expressed in the following terms:

a. Pump head or pressure difference; ft, psi, kPa
b. Pump capacity, volumetric flow rate; gpm, L/s
c. Pump speed; rpm
d. Pump power; hp, kW

Centrifugal pump energy characteristics should be calculated in the following terms:

a. Annual energy use, kWh/yr
b. peak energy demand, kW

Table E-2 summarizes the symbols used in the testing guidelines for both pump performance calculations and uncertainty analysis.

a. **Pump data.** Before testing, record manufacturer, type, size, and serial number of the pumps, and obtain pump performance curves from the manufacturer. If pump performance curves cannot be obtained, Method 2 may not be used.
b. **Pump and system.** Record dimensions and physical condition of the pumps. Record dimensions and physical condition of the suction and discharge piping, locations of existing pressure taps, and locations and descriptions of piping and/or fittings adjacent to the pump.
c. **Motor data.** Before testing, record manufacturer, type, size, and serial number of the motor. Record motor nameplate voltage, amperes, and horsepower or kilowatts.
d. **Motor and drive**. Record dimensions and physical condition of the motor. Record type, dimensions, and physical condition of the drive assembly.
e. **Calibration.** Before testing, calibrate all measurement instruments, or provide evidence of current calibration, in accordance with the standards.
f. **Instrumentation.** Choose and connect measurement instruments in accordance with the standards.
g. **Operation.** Before testing, establish and verify prescribed operating conditions and proper operation of pump and test equipment.
h. **Precision.** Allowable fluctuations in instrumentation must be within the stated limits before recording at required test points.

E1.1 Pump Testing Methods. The test methods detail the measurement requirements for volumetric flow rate, coincident RMS power, differential pressure, and rotational speed at defined operating conditions. Temperature measurements are included to check the consistency of fluid characteristics during testing. Recording of pump and motor nameplate ratings and data are common to all methods. A separate test at the shutoff head is required to determine the impeller size if the size cannot be verified through existing documentation.

E1.1.1 Method 1—Single-Point Test

E1.1.1.1 Description. Measure (a) volumetric flow rate, (b) coincident RMS power, (c) differential pressure, and (d) rotational speed while the pump is at typical operating conditions. Used to confirm design operating conditions and pump and system curves.

E1.1.1.2 Applications. Constant-speed constant-volume pumping systems. Steps include the following:

a. Operate pump at typical existing operating conditions for the system.
b. Measure pump suction and discharge pressure or differential pressure.
c. Measure pump capacity.
d. Measure motor RMS power input.
e. Measure speed.
f. Calculate pump and energy characteristics.

E1.1.2 Method 2—Single-Point Test with Manufacturer's Pump Curve

E1.1.2.1 Description. Measure (a) volumetric flow rate, (b) coincident RMS power, (c) differential pressure, and (d) rotational speed while the pump is at typical operating conditions. Used with manufacturer's data on the pump, motor, and drive system and engineering principles to determine power at other operating points. Pump operation at other operating conditions is assumed to follow pump curve. If single-point test does not confirm operation within 5% of manufacturer's pump curve, Method 3 or Method 4 must be used.

E1.1.2.2 Applications. Constant-speed variable-volume pumping systems. Steps include the following:

a. Obtain manufacturer's pump performance curves. If the performance curves for the pump are not available, Method 3 must be used.
b. Operate pump at typical existing operating conditions.
c. Measure pump suction and discharge pressure or differential pressure.
d. Measure pump capacity.
e. Measure motor RMS power input.
f. Measure speed.
g. Calculate pump and energy characteristics.

E1.1.3 Method 3—Multiple-Point Test with Imposed Loads at Pump

E1.1.3.1 Description. Measure (a) volumetric flow rate and (b) coincident RMS power while the pump is operated at a range of flow load conditions as prescribed in the test procedures. The loads are imposed downstream of the pump with existing control valves. Pump operation follows the pump curve. Pump differential pressure and rotational speed may also be measured for more complete pump system evaluation.

E1.1.3.2 Applications. Constant-speed variable-volume pumping systems. Steps include the following:

a. Operate pump with system configuration set for maximum flow.
b. Measure pump capacity.
c. Measure motor RMS power input.
d. Change system configuration to reduce flow and repeat measurement steps 2 and 3.
e. Calculate pump and energy characteristics.

E1.1.4 Method 4—Multiple-Point Test with Imposed Loads at Zone

E1.1.4.1 Description. Monitor (a) volumetric flow rate and (b) coincident RMS power for a range of building or zone thermal loads as prescribed in the test procedures. The loads are imposed on the building or zones such that the system will experience a broad range of flow rates. The existing pump variable-speed-control strategy is allowed to operate. Pump differential pressure and rotational speed may also be measured for more complete pump system evaluation.

E1.1.4.2 Applications. Variable-volume systems. Steps include the following:

a. Operate pump with system configured for maximum flow rate.
b. Measure pump capacity.
c. Measure motor RMS power input.
d. Change system configuration and repeat measurement steps 2 and 3.
e. Calculate pump and energy characteristics.

E1.1.5 Method 5—Multiple-Point Test through Short-Term Monitoring

E1.1.5.1 Description. Monitor (a) volumetric flow rate and (b) coincident RMS power for a range of building or zone thermal loads as prescribed in the test procedures. A monitoring period must be selected such that the system will experience a broad range of loads and pump flow rates. Pump differential pressure and rotational speed may also be measured for more complete pump system evaluation.

E1.1.5.2 Applications. Variable-speed variable-volume systems. Steps include the following:

a. Choose appropriate time period for test.
b. Monitor pump operation and record data values for pump capacity and motor RMS power input.
c. Calculate pump and energy characteristics.

E1.1.6 Method 6—No-Flow Test for Pump Characteristics

E1.1.6.1 Description. Measure differential pressure at zero flow conditions (shutoff head) and compare to manufacturer's pump curves to determine impeller size.

E1.1.6.2 Applications. All types of centrifugal pumps (not recommended for use on positive displacement pumps). Steps include the following:

a. Run pump at design operating conditions and close discharge valve completely.
b. Measure pump suction and discharge pressure or differential pressure.
c. Measure speed.
d. Calculate shutoff head.
e. Compare shutoff head with manufacturer's pump performance curve to determine and/or verify impeller diameter.

E1.2 Calculations

E1.2.1 Flow Load Frequency Distribution. A flow load frequency distribution must be provided by the user of ASHRAE Guideline 14. The distribution must provide the number of operating hours of the system for a set of bins covering the entire range of flow capacity of the system with a maximum normalized range of 10% per bin.

E1.2.2 Peak Power Demand. The peak power demand is the maximum instantaneous power use. It is recommended that the recorded peak be measured at an actual operating condition of the pump and system. If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the alternating current (AC) circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

E1.2.3 Part-Load Power Curve Calculation. The part-load power use curve is defined as the relationship between pump power and flow rate and can be of several functional forms. The choice of the regression model depends on the system type and control strategy (see Sections E2.2.4 through E2.2.8). Constant-speed constant-volume pumping systems do not require regression analysis because they have a single operating point.

E1.2.4 Method 1—Single-Point Test

E1.2.4.1 Description. Measure (a) volumetric flow rate, (b) coincident RMS power, (c) differential pressure, and (d) rotational speed while the pump is at typical operating conditions. Used to confirm design operating conditions and pump and system curves.

E1.2.4.2 Applications. Constant-volume constant-speed pumping systems. Steps include the following:

a. Operate pump at typical existing operating conditions for the system.
b. Measure pump suction and discharge pressure or differential pressure.
c. Measure pump capacity.
d. Measure motor RMS power input.
e. Measure speed.
f. Calculate pump and energy characteristics.

E1.2.5 Method 2—Single-Point Test with Manufacturer's Pump Curve. The measurement procedure for Method 2 determines the pump capacity, differential pressure, rotational speed, and power use at a single point. The part-load power curve is determined directly from manufacturer's data. To continue with Method 2, the experimentally measured operating point must correspond to the manufacturer's pump curve within 5% of both capacity and differential pressure. Equations for the calculation of pump water horsepower and pump brake horsepower are referenced in ASHRAE Standard 111 (ASHRAE 1988). The pump affinity laws can be used to make necessary corrections for variations in pump rotational speed. The result of these calculations should be a nearly linear relationship of pump kilowatts as a function of volumetric flow rate.

E1.2.6 Methods 3, 4, and 5—Multiple-Point Tests. Constant-speed variable-volume pumping systems will generally require the use of a linear regression model with a nonzero intercept. Variable-speed variable-volume pumping systems will generally require the use of a second order polynomial regression of power on volumetric flow rate with a nonzero intercept, based on measured power and flow. However, the best model depends on the installation and control strategy. In many cases, the best regression model must be selected from inspection of the experimental data. The uncertainty analysis suggested in Section 5.2.4 has been explicitly solved for a quadratic regression model.

E1.2.7 Annual Energy Use Normalization. The user may normalize the load and power measurements in order to have the units of part-load ratio and fraction of full-load power. However, the uncertainty analysis is designed for the use of absolute values of measured values and errors. Therefore, the normalization should only be done after all the calculations and uncertainty analyses are complete. The measurements can be normalized to either the maximum measured value or the rated capacity of the equipment.

E1.2.8 Annual Energy Use—Constant-Speed Constant-Volume Pumping Systems. For a constant-volume pumping system, the flow load at the pump is virtually constant. Therefore, the power demand of the pump and motor is nearly constant, and the frequency of the load is simply the operating hours of the pump. The total annual energy use is given by Equation E-1:

$$E_{annual} = T \times P \qquad \text{(E-1)}$$

where

E_{annual} = total annual energy use
T = annual operating hours
P = equipment power use

E1.2.9 Annual Energy Use—Variable-Volume Pumping Systems. For both constant-speed variable-volume systems and variable-speed variable-volume systems, the power demand of the pump and motor varies as a function of the flow requirements of the system. The frequency distribution of the load provides the operating hours of the pump at each bin level, while the in situ testing determines the part-load power use at each bin level. The total annual energy use is given by Equation E-2:

$$E_{annual} = \sum (T_i \times P_i) \qquad \text{(E-2)}$$

where

E_{annual} = total annual energy use
$\sum$ = summation over i
i = bin index, as defined by the load frequency distribution
T = number of hours in bin i
P_i = equipment power input at load bin i

E2. RETROFIT ISOLATION APPROACH FOR FANS

The test methods detail the measurement requirements for volumetric flow rate, coincident RMS power use, fan differential pressure, and fan rotational speed at defined operating conditions. Temperature and barometer measurements are included to check the consistency of fluid characteristics during the test and to make density corrections as required. Recording of fan and motor nameplate ratings and data are common to all methods.

a. **Fan data.** Before testing, record the manufacturer, type, size, and serial number of the fans, and obtain fan performance curves from the manufacturer. If fan performance curves cannot be obtained, Method 2 may not be used.
b. **Fan and system.** Record dimensions and physical condition of the fan and enclosure. Record dimensions and physical condition of the inlet and discharge ductwork; locations of existing pressure taps; and locations and descriptions of coils, filters, or other equipment adjacent to the fan.
c. **Motor data.** Before testing, record the manufacturer, type, size, and serial number of the motor. Record motor nameplate voltage, amperes, and horsepower or kilowatts.
d. **Motor and drive.** Record dimensions and physical condition of the motor. Record the type, dimensions, and physical condition of the drive assembly.
e. **Calibration.** Before testing, calibrate all measurement instruments, or provide evidence of current calibration, in accordance with the standards.
f. **Instrumentation.** Choose and connect measurement instruments in accordance with the standards.
g. **Operation.** Before testing, establish and verify prescribed operating conditions and proper operation of fan and test equipment.
h. **Precision.** Allowable fluctuations in instrumentation must be within limits before recording at required test points.

E2.1 Fan Test Methods

E2.1.1 Method 1—Single-Point Test

E2.1.1.1 Description. Measure (a) volumetric flow rate, (b) coincident RMS power use, (c) fan differential pressure, and (d) fan rotational speed while the fan is at typical operating conditions. Data are used to confirm design operating conditions and fan and system curves.

E2.1.1.2 Applications. Constant-volume fan systems. Steps include the following:

a. Operate fan at typical existing operating conditions for the system.
b. Measure fan inlet and discharge pressure or (preferably) differential pressure.
c. Measure fan flow capacity.
d. Measure motor RMS power input.
e. Measure fan speed.
f. Calculate fan and energy characteristics.

E2.1.2 Method 2—Single-Point Test with Manufacturer's Data

E2.1.2.1 Description. Measure (a) volumetric flow rate, (b) coincident RMS power use, (c) fan differential pressure, and (d) fan rotational speed while the fan is at typical operating conditions. Data are used with manufacturer's data on the fan, motor, and drive system and engineering principles to determine power at other operating points. Fan operation at other operating conditions is assumed to follow the fan curve. If a single-point test does not confirm operation within 5% of manufacturer's fan curve, Method 3 or Method 4 must be used.

E2.1.2.2 Applications. Variable-volume systems without fan control. Steps include the following:

a. Obtain manufacturer's fan performance curves.
b. Operate fan at typical existing operating conditions.
c. Measure fan inlet and discharge pressure or preferably differential pressure.
d. Measure fan flow capacity.
e. Measure motor RMS power input.
f. Measure fan speed.
g. Calculate fan and energy characteristics.

E2.1.3 Method 3—Multiple-Point Test with Imposed Loads at Fan

E2.1.3.1 Description. Measure (a) volumetric flow rate and (b) coincident RMS power while the fan is operated at a range of flow rate conditions as prescribed in the test procedures. The loads are imposed downstream of the fan with existing dampers. Fan operation follows the fan curve. Fan differential pressure and rotational speed may also be measured for more complete fan system evaluation.

E2.1.3.2 Applications. Variable-volume systems without fan control. Steps include the following:

a. Operate fan with system configuration set for maximum flow.
b. Measure fan flow capacity.
c. Measure motor RMS power input.
d. Change system configuration to reduce flow and repeat measurement steps 2 and 3.
e. Calculate fan and energy characteristics.

E2.1.4 Method 4—Multiple-Point Test with Imposed Loads at Zone

E2.1.4.1 Description. Measure (a) volumetric flow rate and (b) coincident RMS power use while the fan is operated at a range of flow rate conditions as prescribed in the test procedures. Thermal loads are imposed at the building or zone level such that the system will experience a broad range of flow rates. The existing fan variable-speed-control strategy is allowed to operate. Fan differential pressure and rotational speed may also be measured for more complete fan system evaluation.

E2.1.4.2 Applications. Variable-volume systems. Steps include the following:

a. Operate fan with system configured for maximum flow rate.
b. Measure fan capacity.
c. Measure motor RMS power input.

d. Change system configuration and repeat measurement steps 2 and 3.
e. Calculate fan and energy characteristics.

E2.1.5 Method 5—Multiple-Point Test through Short-Term Monitoring

E2.1.5.1 Description. Monitor (a) volumetric flow rate and (b) coincident RMS power while the fan operates at a range of flow rates. The range of flow rates will depend on the building or zones experiencing a wide range of thermal loads. A time period must be selected such that the system will experience a broad range of loads and fan flow rates. The existing fan variable-speed-control strategy is allowed to operate. Fan differential pressure and rotational speed may also be measured for more complete fan system evaluation.

E2.1.5.2 Applications. Variable-volume systems. Steps include the following:

a. Choose appropriate time period for test.
b. Monitor fan operation and record data values for fan capacity and motor RMS power input.
c. Calculate fan and energy characteristics.

E2.2 Calculations

E2.2.1 Flow Load Frequency Distribution. A flow load frequency distribution must be provided by the user of ASHRAE Guideline 14. The distribution must provide the number of operating hours of the system for a set of bins covering the entire range of flow capacity of the system with a maximum normalized range of 10% per bin.

E2.2.2 Peak Power Demand. The peak power demand is the maximum instantaneous power input. It is recommended that the recorded peak be measured at an actual operating condition of the fan and system. If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the AC circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

E2.2.3 Part-Load Power Curve Calculation. The part-load power use curve is defined as the relationship between fan power and volumetric flow rate and can be of several functional forms. The choice of the regression model depends on the system type and control strategy (see Sections E2.2.4 through E2.2.8). Constant-speed constant-volume fan systems do not require regression analysis because they have a single operating point.

E2.2.4 Method 2—Single-Point Test with Manufacturer's Fan Curve. The measurement procedure for Method 2 determines the fan capacity, differential pressure, rotational speed, and power use at a single point. The part-load power curve is determined directly from manufacturer's data. The experimentally measured operating point must correspond to the manufacturer's fan curve within 5% of both capacity and differential pressure in order to continue with Method 2. The fan affinity laws, referenced in ASHRAE Standard 111 (ASHRAE 1988), can be used to make necessary corrections for variations in fan rotational speed, flow rate, or differential pressure. The result of these calculations for constant-speed systems should be a nearly linear relationship of fan kilowatts as a function of volumetric flow rate.

E2.2.5 Methods 3, 4, and 5—Multiple-Point Tests. Variable-volume fan systems without fan control will generally require the use of a linear regression model with a nonzero intercept. Variable-volume fan systems with fan control will generally require the use of a second-order polynomial regression of power on volumetric flow rate with a nonzero intercept, based on measured power and flow. However, the best model depends on the installation and control strategy. In many cases, the best regression model must be selected from inspection of the experimental data. The uncertainty analysis suggested in Section 5.2.4 has been explicitly solved for a quadratic regression model.

E2.2.6 Annual Energy Use Normalization. The user may normalize the load and power measurements in order to have the units of part-load ratio and fraction of full-load power. However, the uncertainty analysis is designed for the use of absolute values of measured values and errors. Therefore, the normalization should only be done after all the calculations and uncertainty analyses are complete. The measurements can be normalized to either the maximum measured value or the rated capacity of the equipment.

E2.2.7 Annual Energy Use—Constant-Volume Fan Systems. For a constant-volume system, the flow load at the fan is virtually constant. Therefore, the power demand of the fan and motor is nearly constant, and the frequency of the load is simply the operating hours of the fan. The total annual energy use is given by Equation E-3:

$$E_{annual} = T \times P \tag{E-3}$$

where

E_{annual}	=	total annual energy use
T	=	annual operating hours
P	=	equipment power input

E2.2.8 Annual Energy Use—Variable-Volume Systems. For variable-volume systems with and without fan control, the power demand of the fan and motor varies as a function of the flow requirements of the system. The frequency distribution of the load provides the operating hours of the fan at each bin level while the in situ testing determines the part-load power use at each bin level. The total annual energy use is given by Equation E-4:

$$E_{annual} = \sum_i (T_i \times P_i) \tag{E-4}$$

where

E_{annual}	=	total annual energy use
Σ	=	summation over i
i	=	bin index, as defined by the load frequency distribution
T_i	=	number of hours in bin i
P_i	=	equipment power use at load bin i

E3. RETROFIT ISOLATION APPROACH FOR CHILLERS

The chiller testing guidelines provide testing methods to evaluate annual energy use and peak demand characteristics for installed water-cooled chillers. An in situ testing methodology requires short-term testing procedures to determine the part-load performance of installed chiller systems at a full range of building thermal loads and coincident ambient conditions. The test methods determine chiller power demand at various thermal loads using a thermodynamic model with inputs from direct measurements, statistical regression analysis, manufacturer's data, and engineering principles. The determined part-load power use curve is then used with a load frequency distribution to calculate annual energy use. The user of ASHRAE Guideline 14 has to provide a thermal load frequency distribution, and in some cases, coincident chilled-water supply and condenser water return temperatures, to calculate annual energy use.

A complete performance mapping of chiller operating characteristics would allow for the power use of the chiller to be determined for all operating conditions. However, a complete performance map of chillers is impractical to expect from short-term field measurements. A simpler testing methodology considers the building and the chiller together. If the chiller system is monitored as the building experiences a broad range of thermal loads, the control strategy will be included within the data set. Because of the wide range of chiller systems, control strategies, and climate zones, no single testing procedure can apply to all system types. The preferred method will be determined by the user based on the system type and control and the desired level of uncertainty and degree of intrusion.

Chiller systems have two main components, the "load" side, which includes the evaporator characteristics and building load, and the "heat rejection" side, which includes the condenser and the ambient conditions under which it is operating. The load side can be controlled to a limited degree in a short-term test by careful timing and manipulation of the building control. The heat-rejection side can also be controlled to a limited degree by manipulation of cooling tower return water temperature. However, the range of both the load and heat-rejection sides of the chiller system will be limited by a bounding set of ambient conditions. Adjustments are required for variable ambient conditions at a range of building thermal loads.

Chiller power use will be a function of the following:

a. Building thermal load
b. Evaporator and condenser flow rates
c. Entering and leaving chilled water temperatures
d. Entering and leaving condenser water temperatures
e. Internal chiller controls

Therefore, a large number of independent variables must be considered. Some of these are commonly held constants (e.g., evaporator flow rate) and could be removed from the analysis. Because in situ performance testing of chillers requires a short-term measurement or monitoring strategy and power use needs to be evaluated at a wide range of ambient conditions, a model is used to characterize chiller performance from relatively few measurements. A thermodynamically based chiller model that has a limited number of parameters and two levels of complexity make it attractive for practical and effective field testing (Gordon and Ng 1994; Gordon et al. 1995). Gordon and Ng (1994) validated such a chiller model with field data for centrifugal chillers and with manufacturer's data for reciprocating chillers.

One of the testing methods is designed to use manufacturer's data after a single-point performance measurement. Although the thermodynamic model has been validated using manufacturer's data (Gordon and Ng 1994), it is not always possible to do so. Manufacturer's data are based on their own internal models of chiller performance. As such, the accuracy of the data varies with the time of production of the chiller and the degree of complexity of the model used to produce the data. More recently, manufacturers have not published tables of performance but used computer models designed to size chillers to predict chiller performance at a given set of conditions. Finally, the assumptions of what chiller parameters remain fixed as others change varies among manufacturers. Therefore, the use of chiller performance data for Method 1 may be limited by the chiller's date of production and assumptions of the manufacturer's data.

Chiller performance should be expressed in the following terms:

a. Evaporator load; tons, kBtu/h, kW
b. Chilled-water supply temperature; °F, °C
c. Condenser water return temperature; °F, °C

Chiller energy characteristics should be calculated in the following terms:

a. Annual energy use, kWh/yr
b. peak energy demand, kW

The following sections describe the chiller models and the testing methods based on the models.

Table E-3 summarizes the symbols used in the testing guidelines for the chiller models, chiller performance calculations, and the uncertainty analyses.

E3.1 Conversion Factors. The following conversion factors can be used to make unit conversions between the various commonly used values for expressing chiller efficiency.

a. Coefficient of performance (COP)

$$\text{COP} = \frac{\text{Kilowatt refrigeration effect}}{\text{Kilowatt input}}$$

b. Energy efficiency ratio (EER)

$$\text{EER} = \frac{\text{British thermal units per hour refrigeration effect}}{\text{Kilowatt input}}$$

c. Power per ton

$$\text{Kilowatts per ton (kW/ton)} = \frac{\text{Kilowatt input}}{\text{Tons refrigeration}}$$

TABLE E-3 Nomenclature for Calculations and Uncertainty Analysis

Value	Symbol	Units/Variable
Bin energy use	E	kWh
Power level	P	kW
Chiller load	Q_{evap}	kBtu, tons, kW
Chilled water supply temperature	T_{chwST}	°F, °C
Condenser water return temperature	T_{chwST}	°F, °C
Number of hours	T	number
Uncertainty	w	kWh
Total annual uncertainty	U	kWh
Predictor variable	x	varies
Response variable	y	varies
Expected value	$E[\ ]$	x, y
Variance	Var	x^2, y^2
Intercept	β_0	y
1st and 2nd order coefficients	β_1, β_2	y/x, y/x^2
Standard error of regression	σ^2	y^2
Error	e	x, y
Mean value	m	x, y
Predicted value symbol	^	NA

These alternative measures of efficiency are related as follows:

$$\text{COP} = 0.293 \times \text{EER} \qquad \text{EER} = 3.413 \times \text{COP}$$
$$\text{kW/ton} = 12/\text{EER} \qquad \text{EER} = 12/(\text{kW/ton})$$
$$\text{kW/ton} = 3.516 \times \text{COP} \qquad \text{COP} = 3.516/(\text{kW/ton})$$

a. **Chiller data.** Before testing, record the manufacturer, type, size, and serial number of the chiller, and obtain chiller performance data from the manufacturer. The use of chiller performance data for Method 1 may be limited by the chiller's date of production.
b. **Chiller and system.** Evaluate and record the physical condition of the chiller. Record dimensions and physical condition of the evaporator and condenser piping, location of existing instrumentation, and locations and descriptions of pumps or other equipment adjacent to the chiller.
c. **Calibration.** Before testing, calibrate all measurement instruments, or provide evidence of current calibration, in accordance with Annex A2.
d. **Instrumentation.** Choose and connect measurement instruments in accordance with Sections 5 and 6 and Annexes A and B and all requirements of the instrumentation manufacturers.
e. **Operation.** Before testing, establish and verify prescribed operating conditions and proper operation of chiller and test equipment.

E3.2 Thermodynamic Chiller Model Description. The chiller model expresses chiller efficiency as 1/COP because it has a linear relationship with 1/(evaporator load). The final result of the model can then be inverted to the conventional efficiency measures of COP or kW/ton.

E3.3 Simple Model. The simpler version of the chiller model developed by Gordon and Ng (1994) predicts a linear relationship between 1/COP and $1/Q_{evap}$, with a scatter about the line due to variations in evaporator and condenser water temperatures. Coefficients found by using the performance data in linear regressions characterize the irreversibilities of the particular chiller in question. Once the coefficients have been determined, the simple model will predict chiller COP as a function of evaporator load. Equation E-5 shows all the terms of the simpler form of the model. In the resulting prediction, Equation E-6, the coefficient c_1 characterizes the internal chiller losses while the coefficient c_0 combines the other terms of the simple model.

$$\frac{1}{\text{COP}} = -1 + \left(\frac{T_{cwRT}}{T_{chwST}}\right) + \left(\frac{1}{Q_{evap}}\right)\left(\frac{q_{evap}T_{cwRT}}{T_{chwST}} - q_{cond}\right) + f_{HX} \tag{E-5}$$

where

COP = coefficient of performance
T_{cwRT} = entering (return) condenser water temperature, K
T_{chwST} = leaving (supply) evaporator water temperature, K
Q_{evap} = evaporator load
q_{evap} = rate of internal losses in evaporator
q_{cond} = rate of internal losses in condenser
f_{HX} = dimensionless term (normally negligible, see Gordon et al. [1995])

$$\frac{1}{\text{COP}} = c_1\left(\frac{1}{Q_{evap}}\right) + c_0 \tag{E-6}$$

where

COP = coefficient of performance
Q_{evap} = evaporator load
c_1 and c_0 = linear regression coefficients

The simple model requires measurement of the chiller load (evaporator flow rate and entering and leaving chilled-water temperatures) and coincident RMS power use only. Variations in chilled-water supply and condenser water return temperatures are not considered. The simple model is applicable to chiller systems with constant temperature control of evaporator and condenser temperatures, chiller systems whose control and climate limit the variation of evaporator and condenser temperatures, and chiller systems where evaporator and condenser temperatures are a function of chiller load.

E3.4 Temperature-Dependent Model. The temperature-dependent model carries the thermodynamic analysis one step further by defining the losses in the heat exchangers of the evaporator and condenser as a function of the chilled-water supply and condenser water return temperatures. The resulting expression has three coefficients (A_0, A_1, A_2), which replace the terms for the internal losses (q_{evap}, q_{cond}) in the simple chiller model. The simple model is a special limiting case of the temperature-dependent model. The result is an expression for chiller 1/COP as a function of the evaporator load, chilled-water supply temperature, and condenser water return temperature. These parameters are commonly reported in manufacturer's performance data and are also commonly controlled chiller-plant variables. The coefficients (A_0, A_1, A_2) found by using the performance data in linear regressions characterize the characteristics of the particular chiller in question. Once the coefficients have been determined, the temperature-dependent model predicts chiller COP under a wide range of operating conditions. Equation E-7 shows the form of the temperature-dependent model:

$$\frac{1}{\mathrm{COP}} = -1 + \left(\frac{T_{cwRT}}{T_{chwST}}\right) + \frac{-A_0 + A_1(T_{cwRT}) - A_2\left(\frac{T_{cwRT}}{T_{chwST}}\right)}{Q_{evap}} \tag{E-7}$$

where

COP = coefficient of performance

T_{cwRT} = entering (return) condenser water temperature, K

T_{chwST} = leaving (supply) evaporator water temperature, K

A_0 = linear regression coefficient

A_1 = linear regression coefficient

A_2 = linear regression coefficient

Q_{evap} = evaporator load

The temperature-dependent model requires measurement of the chiller load (evaporator flow rate and entering and leaving chilled water temperatures), coincident RMS power use, chilled-water supply temperature, and condenser water return temperature. Variations in chilled-water supply and condenser water return temperatures are considered in the model. The temperature-dependent model is applicable to all chiller systems.

E3.4.1 Temperature-Dependent Model Implementation Procedure. To implement the temperature-dependent model, measured data of chiller load, coincident RMS power use, chilled-water supply temperature, and condenser water return temperature are used to calculate the three coefficients (A_0, A_1, A_2). A plot of α (Equation E-8) versus the temperature ratio (T_{cwRT}/T_{chwST}; K) should result in a set of parallel straight lines, one for each value of condenser water return temperature. The slope of the regression lines determines the value of coefficient A_2:

$$\alpha = \left(\frac{1}{\mathrm{COP}} + 1 - \left(\frac{T_{cwRT}}{T_{chwST}}\right)\right)Q_{evap} \tag{E-8}$$

where

α = functional dependence against (T_{cwRT}/T_{chwST})

COP = coefficient of performance

T_{cwRT} = entering (return) condenser water temperature, K

T_{chwST} = leaving (supply) evaporator water temperature, K

Q_{evap} = evaporator load

A plot of β (Equation E-9), using the value of A_2 already calculated, versus the condenser water return temperature (T_{cwRT}; K) should result in a single straight line. The slope of the regression line determines the value of coefficient A_1, while the intercept determines the value of coefficient A_0.

$$\beta = \left(\frac{1}{\mathrm{COP}} + 1 - \left(\frac{T_{cwRT}}{T_{chwST}}\right)\right)Q_{evap} + A_2\left(\frac{T_{cwRT}}{T_{chwST}}\right) \tag{E-9}$$

where

β = functional dependence against T_{cwRT}

COP = coefficient of performance

T_{cwRT} = entering (return) condenser water temperature, K

T_{chwST} = leaving (supply) evaporator water temperature, K

Q_{evap} = evaporator load

A_2 = regression coefficient

After calculation of the model coefficients, Equation E-7 is used to predict the COP for a wide range of measured input parameters of chiller load, chilled-water supply temperature, and condenser water return temperature.

E3.5 Chiller Testing Methods. Five testing methods have been developed. In all cases, the data are used to implement either the simple or temperature-dependent models described in the previous sections. For those methods using the simple model, the load profile will be limited to an evaporator load frequency distribution. For those methods using the temperature-dependent model, the load profile will include coincident chilled-water supply and condenser water return temperatures in addition to the evaporator load frequency distribution.

E3.5.1 Method 1—Single-Point Test with Manufacturer's Data

E3.5.1.1 Description. A single operating point test requiring measurement of (a) RMS power input, (b) evaporator flow rate, (c) entering and leaving chilled-water temperatures, and (d) return condenser water temperature while the chiller system operates at existing typical conditions. Used to confirm design operating conditions and manufacturer's data at a single point and determine the validity of model predictions based on manufacturer's data.

E3.5.1.2 Applications. All chiller systems with available data. Steps include the following:

a. Obtain manufacturer's chiller performance data. If the performance curves for the chiller are not available, Method 1 is not applicable. The data must be analyzed to determine whether it is applicable to the thermodynamic model.
b. Operate chiller at typical existing operating conditions.
c. Measure evaporator load.
d. Measure coincident chilled-water supply temperature.
e. Measure coincident condenser water return temperature.

f. Measure coincident chiller RMS power input.
g. Calculate chiller and energy characteristics.

E3.5.2 Method 2—Imposed Load Test for Simple Model

E3.5.2.1 Description. A multiple operating point test requiring measurement of (a) RMS power input, (b) evaporator flow rate, and (c) entering and leaving chilled-water temperatures while the chiller system operates at a range of thermal load conditions. The load variations are imposed on the building through manipulation of cooling setpoints or internal gains to obtain a range of loads typical of annual operation for the system. The simple thermodynamic model is then used to develop a linear regression fit of COP as a function of load. Variations in chilled-water supply and condenser water return temperatures are not considered.

E3.5.2.2 Applications. (a) Chiller systems with constant temperature control of evaporator and condenser temperatures, (b) chiller systems whose control and climate limit the variation of evaporator and condenser temperatures, and (c) chiller systems where evaporator and condenser temperatures are a function of chiller load. Steps include the following:

a. Operate chiller at typical existing operating conditions.
b. Measure evaporator load.
c. Measure coincident chiller RMS power input.
d. Change building cooling setpoints to increase or decrease evaporator load and repeat measurement steps 2 and 3.
e. Calculate chiller and energy characteristics.

E3.5.3 Method 3—Imposed Load Test for Temperature-Dependent Model

E3.5.3.1 Description. A multiple operating point test requiring measurement of (a) RMS power input, (b) evaporator flow rate, (c) entering and leaving chilled-water temperatures, and (d) return condenser water temperature while the chiller system operates at a range of thermal load conditions. The load variations are imposed on the building through manipulation of cooling setpoints or internal gains, while coincident variations in chilled-water and condenser water temperatures are also imposed to obtain a range of operating conditions typical of annual operation for the system. The temperature-dependent thermodynamic model is then used to determine the coefficients of the model to calculate COP as a function of load, chilled-water supply temperature, and condenser water return temperature.

E3.5.3.2 Applications. All chiller systems. Steps include the following:

a. Operate chiller at typical existing operating conditions.
b. Measure evaporator load.
c. Measure coincident chilled-water supply temperature.
d. Measure coincident condenser water return temperature.
e. Measure coincident chiller RMS power input.
f. Change building cooling setpoints or internal gains to increase or decrease evaporator load and repeat measurement steps 2, 3, 4, and 5.
g. Calculate chiller and energy characteristics.

E3.5.4 Method 4—Short-Term Monitoring Test for Simple Model

E3.5.4.1 Description. A short-term monitoring test requiring measurement of (a) RMS power input, (b) evaporator flow rate, and (c) entering and leaving chilled-water temperatures while the chiller system operates at a range of thermal load conditions. A time period for the test is selected such that the load variations are representative of annual operation for the system. The simple thermodynamic model is then used to develop a linear regression fit of COP as a function of load. Variations in chilled-water supply and condenser water return temperatures are not considered.

E3.5.4.2 Applications. (a) Chiller systems with constant temperature control of evaporator and condenser temperatures, (b) chiller systems whose control and climate limit the variation of evaporator and condenser temperatures, and (c) chiller systems where evaporator and condenser temperatures are a function of chiller load. Steps include the following:

a. Choose appropriate time period for test.
b. Monitor chiller operation and record data values for evaporator load and coincident chiller RMS power input.
c. Calculate chiller and energy characteristics.

E3.5.5 Method 5—Short-Term Monitoring Test for Temperature-Dependent Model

E3.5.5.1 Description. A short-term monitoring-point test requiring measurement of (a) RMS power input, (b) evaporator flow rate, (c) entering and leaving chilled-water temperatures, and (d) return condenser water temperature while the chiller system operates at a range of thermal load conditions. A time period for the test is selected such that the load and water temperature variations are representative of annual operation for the system. The temperature-dependent thermodynamic model is then used to determine the coefficients of the model to calculate COP as a function of load, chilled-water supply temperature, and condenser water return temperature.

E3.5.5.2 Applications. All chiller systems. Steps include the following:

a. Choose appropriate time period for test.
b. Monitor chiller operation and record data values for evaporator load, coincident chilled-water supply temperature, coincident condenser water return temperature, and coincident chiller RMS power input.
c. Calculate chiller and energy characteristics.

E3.6 Calculations

E3.6.1 Load Frequency Distribution. A load frequency distribution must be provided by the user of ASHRAE Guideline 14. The simple model requires a chiller load distribution only. The distribution must provide the number of operating hours of the system for a set of bins covering the entire range of chiller loads with a maximum normalized range of 10% per bin. The temperature-dependent model requires a chiller load distribution with coincident chilled water supply temperature and condenser water return temperature. The size of the coincident temperature bins can greatly affect the total number of bins. It is recommended that 1°F or 2°F (0.56°C or 1.1°C) temperature bins be used with the temperature-dependent model calculations.

E3.6.2 Peak Power Demand. The peak power demand is the maximum instantaneous power use. It is recommended that the recorded peak be measured at an actual operating condition of the chiller and system. If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the AC circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

E3.6.3 Part-Load Power Curve Calculation. The part-load power use curve will be determined by the choice of chiller model. See Sections E3.2 and E3.3 for the implementation procedures for the simple and temperature-dependent chiller models. For the temperature dependent chiller model, the chilled-water supply temperature and condenser water return temperature must be in degrees Kelvin for the regression calculations.

E3.6.4 Method 1—Single-Point Test with Manufacturer's Data. The chiller manufacturer's data should be used to develop the simple or temperature-dependent model coefficients before testing. If the data are consistent with the model, the measurement procedure for Method 1 determines the chiller capacity, power input, chilled-water supply temperature, and condenser water return temperature at a single point. The part-load power curve is determined directly from manufacturer's data. The experimentally measured operating point must correspond to the manufacturer's chiller data within 5% of both capacity and power use in order to continue with Method 1. The model coefficients from the chiller manufacturer's data can then be used to determine the power use of the chiller at a range of loads and water temperatures.

E3.6.5 Annual Energy Use. For calculation of annual energy use, the simple or temperature-dependent models determine the power demand of the chiller at each bin of the load distribution. The load frequency distribution and the two water temperatures provide the operating hours of the chiller at each bin level. The energy use for each bin is given by Equation E-10, the power level for each bin is given by Equation E-11, and the total annual energy use is given by Equation E-12.

$$E_i = T_i \times P_i \qquad \text{(E-10)}$$

where

E_i = energy use for each bin (i)

i = bin index, as defined by load frequency distribution

T_i = number of hours in bin i

P_i = equipment power use at load bin i

$$P_i = \left(\frac{1}{\text{Eff}_i}\right) \times (Q_{evap,\,i}) \qquad \text{(E-11)}$$

where

i = bin index, as defined by load frequency distribution

P_i = equipment power use at load bin i

Eff_i = chiller 1/COP in bin i

$Q_{evap,i}$ = chiller load in bin i

$$E_{annual} = \sum_i (T_i \times P_i) \qquad \text{(E-12)}$$

where

E_{annual} = annual energy use

i = bin index, as defined by load frequency distribution

Σ = summation over frequency distribution

T_i = number of hours in bin i

P_i = equipment power use at load bin i

E3.6.6 Annual Energy Use Normalization. The user may normalize the load and power measurements in order to have the units of part-load ratio and fraction of full-load power. However, the uncertainty analysis is designed for the use of absolute values of measured values and errors. Therefore, the normalization should only be done after all the calculations and uncertainty analyses are complete. The measurements can be normalized to either the maximum measured value or the rated capacity of the equipment.

E4. RETROFIT ISOLATION APPROACH FOR BOILERS AND FURNACES

E4.1 Boiler/Furnace Testing Methods. Twelve testing methods have been developed and are described below.

E4.1.1 Method 1a—Single-Point Test (Direct Method)

E4.1.1.1 Description. Measure (a) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.), (b) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), and (c) heat inputs.

E4.1.1.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Operate boiler at typical existing operating conditions for the system.
b. Measure mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.).
c. Measure mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.).
d. Measure heat inputs.
e. Calculate efficiency using the direct efficiency method.
f. Calculate boiler and efficiency characteristics.

E4.1.2 Method 1b—Single-Point Test (Direct Heat Loss Method)

E4.1.2.1 Description. Measure (a) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses) and (b) heat inputs.

E4.1.2.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Operate boiler at typical existing operating conditions for the system.
b. Measure all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses).
c. Measure heat inputs.
d. Calculate efficiency using direct heat loss method.
e. Calculate boiler and efficiency characteristics.

E4.1.3 Method 1c—Single-Point Test (Indirect Combustion Method)

E4.1.3.1 Description. Measure (a) enthalpy of all combustion products, (b) enthalpy of fuel, (c) enthalpy of combustion air, and (d) heat inputs.

E4.1.3.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Operate boiler at typical existing operating conditions for system.
b. Measure enthalpy of all combustion products, enthalpy of the fuel, and enthalpy of combustion air.
c. Measure heat inputs.
d. Calculate efficiency using the indirect combustion method.
e. Calculate boiler and efficiency characteristics.

E4.1.4 Method 2a—Single-Point Test with Manufacturer's Data (Direct Method)

E4.1.4.1 Description. Measure (a) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.), (b) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), and (c) heat inputs. Data are used with manufacturer's published boiler efficiency curves and engineering principles to determine efficiency at other operating points. Boiler efficiency at other operating points is assumed to follow the manufacturer's curve. If a single-point test does not confirm manufacturer's curve within 5%, another boiler efficiency method must be used.

E4.1.4.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Operate boiler at typical existing operating conditions for the system.
b. Obtain manufacturer's boiler efficiency curve.
c. Measure mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.).
d. Measure mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.).
e. Measure heat inputs.
f. Calculate efficiency using the direct efficiency method for the single point and compare to manufacturer's curve.
g. Calculate boiler and efficiency characteristics.

E4.1.5 Method 2b—Single-Point Test with Manufacturer's Data (Direct Heat Loss Method)

E4.1.5.1 Description. Measure (a) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses) and (b) heat inputs. Data are used with manufacturer's published boiler efficiency curves and engineering principles to determine efficiency at other operating points. Boiler efficiency at other operating points is assumed to follow the manufacturer's curve. If single-point test does not confirm manufacturer's curve within 5%, another boiler efficiency method must be used.

E4.1.5.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Operate boiler at typical existing operating conditions for the system.
b. Obtain manufacturer's boiler efficiency curve.
c. Measure all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses).
d. Measure heat inputs.
e. Calculate efficiency using direct heat loss method for a single point and compare to manufacturer's curve.
f. Calculate boiler and efficiency characteristics.

E4.1.6 Method 2c—Single-Point Test with Manufacturer's Data (Indirect Combustion Method)

E4.1.6.1 Description. Measure (a) enthalpy of all combustion products, (b) enthalpy of fuel, (c) enthalpy of combustion air, and (d) heat inputs. Data are used with manufacturer's published boiler efficiency curves and engineering principles to determine efficiency at other operating points. Boiler efficiency at other operating points is assumed to follow the manufacturer's curve. If single-point test does not confirm manufacturer's curve within 5%, another boiler efficiency method must be used.

E4.1.6.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Operate boiler at typical existing operating conditions for system.
b. Obtain manufacturer's boiler efficiency curve.
c. Measure enthalpy of all combustion products, enthalpy of the fuel, and enthalpy of combustion air.
d. Measure heat inputs.
e. Calculate efficiency using the indirect combustion method and compare to manufacturer's curve.
f. Calculate boiler and efficiency characteristics.

E4.1.7 Method 3a—Multiple-Point Test with Imposed Loads (Direct Efficiency Method)

E4.1.7.1 Description. Measure over a range of operating conditions (a) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.), (b) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), and (c) heat inputs. Different loads are imposed on the boiler and measurements are repeated. Boiler operation is assumed to follow manufacturer's efficiency curve.

E4.1.7.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Obtain manufacturer's efficiency curves.
b. Operate boiler at a given load.
c. Measure mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.).
d. Measure mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.).
e. Measure heat inputs.
f. Calculate efficiency using the direct efficiency method.
g. Change load on boiler and repeat steps 2 through 6.
h. Calculate boiler and efficiency characteristics.

E4.1.8 Method 3b—Multiple-Point Test with Imposed Loads (Direct Heat Loss Method)

E4.1.8.1 Description. Measure over a range of operating conditions (a) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses) and (b) heat inputs. Different loads are imposed on the boiler and measurements are repeated. Boiler operation is assumed to follow manufacturer's efficiency curve.

E4.1.8.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Obtain manufacturer's boiler efficiency curve.
b. Operate boiler at a given load.
c. Measure all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses).
d. Measure heat inputs.
e. Calculate efficiency using direct heat loss method for a single point and compare to manufacturer's curve.
f. Change load on boiler and repeat steps 2 through 5.
g. Calculate boiler and efficiency characteristics.

E4.1.9 Method 3c—Multiple-Point Test with Imposed Loads (Indirect Combustion Method)

E4.1.9.1 Description. Measure over a range of operating conditions (a) enthalpy of all combustion products, (b) enthalpy of fuel, (c) enthalpy of combustion air, and (d) heat inputs. Different loads are imposed on the boiler and measurements are repeated. Boiler operation is assumed to follow the manufacturer's efficiency curve.

E4.1.9.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Obtain manufacturer's boiler efficiency curve.
b. Operate boiler at a given load.
c. Measure enthalpy of all combustion products, enthalpy of the fuel, and enthalpy of combustion air.
d. Measure heat inputs.
e. Calculate efficiency using the indirect combustion method and compare to manufacturer's curve.
f. Change load on boiler and repeat steps 2 through 5.
g. Calculate boiler and efficiency characteristics.

E4.1.10 Method 4a—Multiple-Point Test through Short-Term Monitoring (Direct Method)

E4.1.10.1 Description. Monitor over a range of operating conditions (a) mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.), (b) mass flow and enthalpy of fluid streams entering the boiler (feedwater, desuperheating sprays, etc.), and (c) heat inputs. The range of boiler loads should cover those that the boiler would normally be expected to experience (low and high).

E4.1.10.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Choose appropriate time period for test.
b. Monitor boiler operation and record data values for mass flow and enthalpy of fluid streams leaving the boiler (main steam, blowdown, etc.) and entering the boiler (feedwater, desuperheating sprays, etc.),
c. Monitor and record data values for heat inputs.
d. Calculate efficiency using the direct efficiency method.
e. Calculate boiler and efficiency characteristics.

E4.1.11 Method 4b—Multiple-Point Test through Short-Term Monitoring (Direct Heat Loss Method)

E4.1.11.1 Description. Monitor over a range of operating conditions (a) all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses) and (b) heat inputs. The range of boiler loads should cover those that the boiler would normally be expected to experience (low and high).

E4.1.11.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Choose appropriate period for the test.
b. Monitor all boiler losses (dry flue gas loss, fuel hydrogen heat loss, combustion air moisture heat loss, radiation heat loss, convection heat loss, uncombusted fuel loss, blowdown loss, and unaccounted for losses).
c. Monitor heat inputs.
d. Calculate efficiency using direct heat loss method for a single point and compare to manufacturer's curve.
e. Calculate boiler and efficiency characteristics.

E4.1.12 Method 4c—Multiple-Point Test through Short-Term Monitoring (Indirect Combustion Efficiency Method)

E4.1.12.1 Description. Monitor over a range of operating conditions (a) enthalpy of all combustion products, (b) enthalpy of fuel, (c) enthalpy of combustion air, and (d) heat inputs. The range of boiler loads should cover the loads that the boiler would normally be expected to experience (low and high).

E4.1.12.2 Applications. Nonreheat boilers and furnaces. Steps include the following:

a. Choose appropriate time period for test.
b. Monitor enthalpy of all combustion products, enthalpy of the fuel, and enthalpy of combustion air.
c. Monitor heat inputs.
d. Calculate efficiency using the indirect combustion efficiency method and compare to manufacturer's curve.
e. Calculate boiler and efficiency characteristics.

E4.2 Calculations

E4.2.1 Flow Load Frequency Distribution. A boiler load frequency distribution must be provided by the user of ASHRAE Guideline 14. The distribution must provide the number of operating hours of the system for a set of bins covering the entire range of flow capacity of the system with a maximum normalized range of 10% per bin.

E4.2.2 Peak Power Demand (Electric Boilers). The peak power demand is the maximum instantaneous power use. It is recommended that the recorded peak be measured at an actual operating condition of the boiler. If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the AC circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

E4.2.3 Part-Load Boiler Curve Calculation. The part load boiler use curve is boiler efficiency (y-axis) plotted against the boiler capacity (x-axis), with the maximum value on the x-axis representing the maximum boiler capacity. The choice of the regression model depends on the system type and control strategy.

E4.2.4 Method 2—Single-Point Test with Manufacturer's Fan Curve. The measurement procedure for Method 2 determines the boiler efficiency at a given capacity. The part load power curve is determined directly from manufacturer's data. The experimentally measured operating point must correspond to the manufacturer's curve within 5% of both capacity and efficiency in order to continue with Method 2.

E4.2.5 Methods 3 and 4—Multiple-Point Tests. Boilers with variable fire rates will generally require the use of a linear regression model with a nonzero intercept. The best model depends on the installation and control strategy. In many cases, the best regression model must be selected from inspection of the experimental data.

E4.2.6 Annual Energy Use—Constant-Fire Boilers. For constant-fire boilers, the boiler load is virtually constant. Therefore, the fuel input is nearly constant, and the frequency of the load is simply the operating hours of the boiler. The total annual energy use is given by

$$E_{annual} = T \times P \tag{E-13}$$

where

E_{annual} = total annual energy use

T = annual operating hours

P = equipment fuel input

E4.2.7 Annual Energy Use—Variable-Fire Boilers. For variable-fire boilers, the output of the boiler varies, as does the fuel input. The frequency distribution of the load provides the operating hours of the boiler at each bin level, while the in situ testing determines the part-load fuel input and boiler efficiency at each bin level. The total annual energy use is given by

$$E_{annual} = \sum_i (T_i \times P_i) \tag{E-14}$$

where

E_{annual} = total annual energy use

i = bin index, as defined by load variable frequency distribution

$\sum$ = summation

T_i = number of hours in bin i

P_i = equipment fuel input at load bin i

E5. RETROFIT ISOLATION APPROACH FOR LIGHTING

E5.1 Thermal Interaction and Lighting Use Profiles

E5.1.1 Thermal Interactions. Lighting retrofits can decrease cooling loads and increase heating loads by an amount equal to the thermal load of the wattage reduction caused by the lighting retrofit. The amount of the cooling reduction or heating increase will vary depending upon the type of HVAC system, chiller and boiler efficiency, and cost of cooling or heating fuel. Previously published studies show the cooling interaction can increase savings by 10% to 20%. The increased heating requirements can reduce savings by 5% to 20% (Bou-Saada et al. 1996).

E5.1.2 Lighting Use Profiles. The calculation of savings from lighting retrofits involves ascertaining the wattage reduction associated with the new fixtures and an estimate or measurement of the hours per day that the lights are used. Lighting use profiles can be sampled with lighting loggers or measured at the electrical distribution panel. Lighting use profiles can be predictable (e.g., weekday and weekend vary by less than 10%) or variable.

E5.1.3 Predictable Lighting Use Profile. Typical of office buildings where the lighting profile is predictable for weekday and weekend diversity profiles. Sampling of profiles will probably predict diversity profiles (e.g., ±10%).

E5.1.4 Variable Lighting Use Profile. Typical of buildings with variable occupancy, such as conference centers and/or hotels/motels. Sampling of profiles will not predict diversity profiles (e.g., ≥10%).

E5.1.5 Lighting Levels. Lighting levels should be sampled before/after the retrofit. All lighting retrofits should use Illuminating Engineering Society (IES) recommended lighting levels (or better). Any preretrofit condition that is not maintaining IES lighting levels should be documented and brought to the attention of the building owner or administrator. Adjustments may need to be made if postretrofit lighting levels are greater that preretrofit lighting levels.

E5.1.6 Daylighting. Lighting retrofits can involve the installation of daylighting sensors to dim fixtures near the perimeter of the building or below skylights when IES-recommended lighting levels can be maintained with daylighting and/or supplemental lighting. Measuring the savings from such retrofits usually involves before and after measurements of electrical power and lighting use profiles.

TABLE E-4 Lighting Methods

Type of Measurement	Lighting Power Levels	Lighting Diversity Factors	Thermal Interaction
Before/after measured lighting power levels and stipulated diversity profiles	Sampled before and after	Stipulated	No thermal interaction
Before/after measured lighting power levels and sampled before/after diversity profiles	Sampled before and after	Sampled before and after	No thermal interaction
Baseline measured lighting power levels with sampled diversity profiles and postretrofit power levels with continuous diversity profile measurements	Sampled before and after	Sampled before and continuously measured after	No thermal interaction
Baseline measured lighting power levels with baseline sampled diversity profiles and postretrofit continuous submetered lighting	Sampled before and continuously measured after	Sampled before; continuous submetering used after	No thermal interaction
Method 1, 2, or 3 with measured thermal effect	Uses 1, 2, or 3	Uses 1, 2, or 3	Calculated thermal interaction
Before/after submetered lighting and thermal measurements	Measured before and after	Measured before and after	Measured thermal interactions

E5.2 Methods for Calculating Savings from Lighting Measurements (Table E-4)

a. Baseline and postretrofit measured lighting power levels and stipulated diversity profiles.
b. Baseline and postretrofit measured lighting power levels and sampled baseline and postretrofit diversity profiles.
c. Baseline measured lighting power levels with baseline sampled diversity profiles and postretrofit power levels with postretrofit continuous diversity profile measurements.
d. Baseline measured lighting power levels with baseline sampled diversity profiles and postretrofit continuous submetered lighting.
e. Method 1, 2, or 3 with measured thermal effect (heating and cooling).
f. Baseline and postretrofit submetered lighting and thermal measurements.

E5.2.1 Method 1—Before/After Measured Lighting Power Levels and Stipulated Diversity Profiles

E5.2.1.1 Description. (a) Obtain before/after lighting power levels using RMS watt/fixture measurements for the preretrofit fixtures and the postretrofit fixtures and (b) stipulate the lighting use profiles using the best available information that represents lighting use profiles for the facility.

E5.2.1.2 Applications. (a) Exterior lighting on a timer or photocell and (b) interior hallway lighting or any interior lighting used continuously or on a timer. Steps include the following:

a. Obtain measured RMS watt/fixture data for preretrofit and postretrofit fixtures.
b. Count the fixtures associated with each functional area in the building (e.g., areas that have different use profiles).
c. Define the lighting use profiles for each functional area using the appropriate information that represents lighting use profiles (e.g., continuously on, on during evening hours, etc.).
d. Calculate lighting energy use characteristics.

E5.2.2 Method 2—Before/After Measured Lighting Power Levels and Sampled Before/After Diversity Profiles

E5.2.2.1 Description. Measure (a) lighting power levels using RMS watt meter for a sample of the preretrofit fixtures and the postretrofit fixtures and (b) lighting use profiles using light loggers or portable metering attached to the lighting circuits.

E5.2.2.2 Application. Any exterior lighting or interior lighting with predictable use profiles. Steps include the following:

a. Measure watt/fixture using RMS wattmeter for preretrofit and postretrofit fixtures.
b. Count the fixtures associated with each functional area in the building (i.e., areas that have different use profiles).
c. Sample lighting use profiles for each functional area using lighting loggers and/or portable submetered RMS watt meters on lighting circuits.
d. Calculate lighting energy use characteristics.

E5.2.3 Method 3—Baseline Measured Lighting Power Levels with Baseline Sampled Diversity Profiles and Postretrofit Measured Power Levels with Postretrofit Continuous Diversity Profile Measurements

E5.2.3.1 Description. (a) Obtain lighting power levels using RMS watt/fixture measurements for the preretrofit fixtures and the postretrofit fixtures, (b) sample the baseline lighting use profiles using light loggers or RMS watt measurements on submetered lighting circuits, and (c) continuously measure the postretrofit lighting use profiles using light loggers or RMS watt measurements on submetered lighting circuits.

E5.2.3.2 Application. Any exterior lighting or interior lighting. Steps include the following:

a. Obtain lighting power levels using RMS watt/fixture measurements for the preretrofit fixtures and the postretrofit fixtures.
b. Sample the baseline lighting use profiles using light loggers or RMS watt measurements on submetered lighting circuits.
c. Continuously measure the postretrofit lighting use profiles using light loggers or RMS watt measurements on submetered lighting circuits.
d. Calculate lighting energy use characteristics.

E5.2.4 Method 4—Baseline Measured Lighting Power Levels with Baseline Sampled Diversity Profiles and Postretrofit Continuous Submetered Lighting

E5.2.4.1 Description. (a) Obtain lighting power levels using RMS watt/fixture measurements for the preretrofit fixtures, (b) sample the baseline lighting use profiles using light loggers or RMS watt measurements on submetered lighting circuits, and (c) continuously measure the postretrofit lighting power use using RMS watt measurements on submetered lighting circuits.

E5.2.4.2 Application. Any exterior lighting or interior lighting. Steps include the following:

a. Obtain lighting power levels using RMS watt/fixture measurements for the preretrofit fixtures.
b. Sample the baseline lighting use profiles using light loggers or RMS watt measurements on submetered lighting circuits.
c. Continuously measure the postretrofit lighting use using RMS watt measurements on submetered lighting circuits.
d. Calculate lighting energy use characteristics.

E5.2.5 Method 5—Method 1, 2, or 3 Used with Measured Thermal Effect (Heating and Cooling)

E5.2.5.1 Description. (a) Obtain lighting power profiles and use using Method 1, 2, or 3; (b) calculate the heating- or cooling-system efficiency using HVAC component isolation methods described in this document; and (c) calculate decrease in cooling load and increase in heating load.

E5.2.5.2 Application. Any interior lighting. Steps include the following:

a. Obtain lighting power profiles and use using Method 1, 2, or 3.
b. Calculate the heating- or cooling-system efficiency using HVAC component isolation methods described in this document.
c. Calculate decrease in cooling load and increase in heating load.
d. Calculate lighting energy use characteristics.

E5.2.6 Method 6—Before/After Submetered Lighting and Thermal Measurements

E5.2.6.1 Description. (a) Obtain lighting energy use by measuring RMS lighting use continuously at the submetered level for preretrofit and postretrofit conditions, (b) obtain thermal energy use data by measuring submetered cooling or heating energy use for preretrofit and postretrofit conditions, and (c) develop representative lighting use profiles from the submetered lighting data.

E5.2.6.2 Applications. (a) Any interior lighting projects and (2) any exterior lighting projects (no thermal interaction). Steps include the following:

a. Obtain measured submetered lighting data for preretrofit and postretrofit periods.
b. Develop representative lighting use profiles from the submetered lighting data.
c. Calculate decrease in cooling load and increase in heating load.
d. Calculate lighting energy use characteristics.

E5.3 Calculations

E5.3.1 Annual Energy Use. Annual energy use is calculated according to the methods described in Table E-5. The savings are then determined by comparing the annual lighting energy use during the baseline period to the annual lighting energy use during the postretrofit period.

The thermal energy effect can either be calculated using the component efficiency methods or it can be measured using whole-building before/after cooling and heating measurements.

E5.3.2 Peak Power Demand. The peak power demand is the maximum instantaneous power use determined by an evaluation of the 24-hour profiles for the baseline and postretrofit period.

Reductions in peak power demand can then be calculated by comparing peak electricity use for similar days (e.g., same month, same day of the week) according to demand billing period.

If the peak demand is not measured during the test and must be calculated from a part-load power curve, it is recommended that the extrapolation from the highest measured power value be no more than 20%. The electric power measurements must be true RMS power, where the instruments measure the active power of the ac circuit, equaling the voltage multiplied by that part of the current in phase with the voltage.

If peak reductions from the chiller are being considered, then it is recommended that component efficiency tests of the chiller be performed to correspond to the increased/decreased load on the chiller.

E6. RETROFIT ISOLATION APPROACH FOR UNITARY AND SPLIT CONDENSING EQUIPMENT

E6.1 Statement of the Problem. The need for a retrofit isolation measurement and verification (M&V) plan and test procedure for unitary and split condensing equipment is driven by the extraordinary prevalence of such equipment in the residential, commercial, and industrial building population. As Section 4.4 states, a good savings measurement plan should "address the balance between the level of uncertainty and the costs of the process." This properly recognizes that if a monitoring protocol costs more to implement than the energy saved by the new piece of equipment, it is of little value. When dealing with unitary and split condensing equipment, the levels of uncertainty are higher and costs of the equipment are lower than virtually all other pieces of HVAC equipment for which other measurement of energy and demand savings protocols have been developed elsewhere in

TABLE E-5 Calculations

Type of Measurement	Preretrofit Electricity Use Calculations	Postretrofit Electricity Use Calculations	Thermal Energy Use Calculations
Before/after measured lighting power levels and stipulated diversity profiles	For each lighting circuit: Annual energy use = (Power levels) × (24 h *stipulated* profiles) × (Number of days assigned to each profile)	For each lighting circuit: Annual energy use = (Power levels) × (24 h *stipulated* profiles) × (Number of days assigned to each profile)	None
Before/after measured lighting power levels and sampled before/after diversity profiles	For each lighting circuit: Annual energy use = (Power levels) × (24 h *sampled* profiles) × (Number of days assigned to each profile)	For each lighting circuit: Annual energy use = (Power levels) × (24 h *sampled* profiles) × (Number of days assigned to each profile)	None
Baseline measured lighting power levels with sampled diversity profiles and postretrofit power levels with continuous diversity profile measurements	For each lighting circuit: Annual energy use = (Power levels) × (24 h *sampled* profiles) × (Number of days assigned to each profile)	For each lighting circuit: Annual energy use = (Power levels) × (Continuous diversity profile measurements)	None
Baseline measured lighting power levels with baseline sampled diversity profiles and postretrofit continuous submetered lighting	For each lighting circuit: Annual energy use = (Power levels) × (24 h *sampled* profiles) × (Number of days assigned to each profile)	For each lighting circuit: Annual energy use = submetered lighting energy use	None
Method 1, 2, 3, or 4 with measured thermal effect	Annual energy use = Method 1, 2, 3, or 4, as appropriate	Annual energy use = Method 1, 2, 3, or 4, as appropriate	Pre- and postretrofit thermal loads from the lighting are calculated using the component efficiency measurement methods for HVAC systems.
Before/after submetered lighting and thermal measurements	For each lighting circuit: Annual energy use = submetered lighting energy use		Pre- and postretrofit thermal loads are calculated using before/after whole-building cooling and heating submetered measurements.

this guideline. Indeed, many pieces of smaller unitary and split condensing equipment may either cost as little as $1000 or use as little as $500 or less in annual energy costs, which is the installed cost of a few monitoring points. Thus, a unitary and split condensing equipment protocol is going to have to use a minimum number of monitoring points, include more simplifying assumptions, and have more uncertainty than the protocols for other bigger, more complicated pieces of HVAC equipment found elsewhere in this guideline to maintain this necessary balance between uncertainty and cost.

Furthermore, these simplifying assumptions will almost always tend to understate the actual energy and demand savings delivered by the new equipment. The benefits of an energy and demand savings measurement protocol for unitary and split condensing equipment outweigh their shortcomings, providing the owner with quantified savings and in many instances, utility rebates.

While the measurement of baseline data for the equipment to be replaced would tend to result in higher quality data, this involves monitoring the equipment for a fairly significant period of time before the old equipment can be replaced. Thus, such methods impose a significant cost to the building owner in the form of lost energy savings for the period of time when the equipment could have been replaced and was not because historical submetering data were being collected. It is assumed in the development of this protocol that the building owner will want to maximize the energy and demand savings by replacing the equipment as soon as possible. The cost issue also exerts a disproportionately larger effect in a preconstruction measurement/postconstruction measurement protocol as compared to other larger pieces of HVAC equipment where this lost energy savings penalty is proportionately smaller.

It should be kept in mind that most unitary and split condensing equipment tend to operate by cycling compressors, condenser fans, and/or burners on and off in response to variations in load. This is in contrast to larger, more expensive and more complicated pieces of HVAC equipment, such as centrifugal chillers, which respond to load variations by nonlinear methods such as variable-speed drives, hot-gas bypass, and inlet guide vanes. The on/off control of most unitary and split condensing equipment provides a convenient starting point for the simplifying assumption of linearity in comparing the operation of the old vs. the new equipment. Of course, the performance of unitary and split-system air-cooled compressors does vary slightly in response to the condensing temperatures of the equipment, but much less so than say a water-cooled centrifugal chiller. Lower condensing temperatures do result in an increase in compressor efficiency.

E6.2 Factors Affecting Unitary and Split Condenser Equipment Performance. The actual performance of old and new unitary and split condenser equipment in buildings can vary widely due to a number of factors, including the following:

a. Adequacy of duct sealing.
b. Proper refrigerant charge and airflow.
c. Corrosion and fouling of heat transfer surfaces (old equipment).
d. Adequacy of fan static pressure.
e. Adequacy or presence (or lack thereof) of economizer cycle operation.
f. Adequacy of condenser fan control and operation.
g. Proper matching of compressor and thermostat stages.
h. Proper matching of condensing unit and evaporator in split systems.
i. Adequacy of thermostat location.
j. Proper or improper system balancing.
k. Adequacy of refrigerant piping seals and valves.
l. Adequacy of compressor motor and refrigerant seals.
m. Adequacy of system capacity to system requirements.
n. Type of HVAC system being used (e.g., constant volume, variable air volume [VAV], multizone, reheat).

Because of the difficulty quantifying these and other factors, a simplified M&V plan for unitary and split condensing equipment could have significant uncertainty.

E6.3 Method for Split Condensing Equipment (Cooling Only). A split condensing (cooling only) unit can be considered and modeled as a combination of the following elements:

a. Constant-speed air-conditioning compressors that cycle on/off in response to load variations.
b. Constant-speed air-conditioning condenser fans that cycle on/off in response to load variations.

E6.3.1 Measurement Approach. The proposed measurement approach relies on making the simplifying assumption of constant efficiency about each of the following two elements. A relatively small subset of available unitary equipment may have two-speed compressors that may complicate the use of this method.

a. **Measurement approach for constant-speed compressors.** The new compressor will be continuously monitored for power consumption over each month by a power meter wired to a current transformer (CT) connected to the power input for the entire compressor motor circuit.
b. **Measurement approach for constant-speed condenser fans.** The new condenser section will be continuously monitored for power consumption over each month by a power meter wired to a CT connected to the power input for the entire condenser fan motor circuit.

E6.3.2 Baseline Period Data. If baseline period data are available for the above equipment, the data can be used to calibrate the performance of the old unit that is to be removed and demonstrate how much less efficient than nameplate efficiency it operates at to determine the actual seasonal energy efficiency ratio (SEER).

E6.3.3 Algorithm for Savings Determination. Energy and demand savings for the newly installed unitary equipment is the sum of the following two elements:

a. Compressor demand and energy savings.
b. Condenser fan demand and energy savings.
    1. Energy savings for constant-speed compressors: **Energy savings per period** = (new compressor measured kWh/period) × [1 − (old equipment nameplate SEER)/(new equipment nameplate SEER)] × [products of applicable adjustment factors in Section 6]
    2. Energy savings for constant-speed condenser fans: **Energy savings per period** = (new condenser fan measured kWh/period) × [1 − (old equipment nameplate condenser fan watts/(new equipment nameplate condenser fan watts)] × [products of applicable adjustment factors in Section 6]

E6.3.4 Measurement Procedure. The energy use of the new compressors and condensers will be monitored and summed over the period of time of interest (usually monthly) by an electronic data logger or energy management system.

E6.3.5 Quality Control Procedures. The primary equipment types used for this method are electric power meters wired to CTs. The polarity of the CTs should be verified to be correct upon their installation. Shunt resistors and CT output should be verified upon installation.

E6.3.6 Savings Reporting Frequency and Format. The usual reporting frequency for the energy savings is monthly or as required by the owner or terms of the performance contract. The report should consist of the following information in columnar format:

a. Equipment inner diameter (ID)
b. Compressor/condenser size and model
c. Kilowatt-hours/period
d. Old nameplate SEER
e. New nameplate SEER
f. Adjustment factors
g. Energy savings

Numerical data in all columns should be totaled.

E6.4 Method for Split Heat-Pump Condensing Equipment. A split heat-pump condensing unit can be considered and modeled as a combination of the following elements:

a. Constant-speed air-conditioning compressors that cycle on/off in response to load variations.
b. Constant-speed air-conditioning condenser fans that cycle on/off in response to load variations.
c. Constant-speed heat-pump compressors that cycle on/off in response to load variations.
d. Electric resistance heaters below certain outdoor air temperatures (e.g., 30°F (–1.1°C).

E6.4.1 Measurement Approach. The proposed measurement approach relies on making the simplifying assumption of constant efficiency about each of the following elements.

a. **Measurement approach for constant-speed compressors.** The new compressor will be continuously monitored for power consumption over each month by a power meter wired to a CT connected to the power input for the entire compressor motor circuit. A sensor will indicate whether or not the compressor is acting in cooling or heating mode. Energy use by the compressor will be totaled separately to indicate the total energy use in cooling mode and in heating mode during each monitoring period.
b. **Measurement approach for constant-speed condenser fans.** The new condenser section will be continuously monitored for power consumption over each month by a power meter wired to a CT connected to the power input for the entire condenser fan motor circuit.
c. **Measurement approach for supplemental electric resistance heat.** Unless it can be shown otherwise, it will be assumed that any electric resistance heat use at very low outdoor ambient conditions is the same between the old equipment and the new equipment.

E6.4.2 Baseline Period Data. If baseline period data are available from the above-mentioned equipment, the data can be used to calibrate the performance of the old unit that is to be removed and demonstrate how much less efficiently it operates than nameplate efficiency to determine the actual SEER.

E6.4.3 Algorithm for Savings Determination. Energy and demand savings for the newly installed unitary equipment is the sum of the following elements:

a. Compressor cooling demand and energy savings.
b. Compressor heating energy savings.
c. Condenser fan demand and energy savings.

1. Cooling energy savings for constant-speed compressors: **Energy savings per period** = (new compressor measured kWh/period) × [1 – (old equipment nameplate SEER)/(new equipment nameplate SEER)] × [products of applicable adjustment factors in Section 6]
2. Heating energy savings for constant speed compressors: **Energy savings per period** = (new compressor measured kWh/period) × [1 – (old equipment nameplate heat pump HPSF)/(new equipment nameplate heat pump HPSF)] × [products of applicable adjustment factors in Section 6]
3. Energy savings for constant speed condenser fans are included in the SEER and HPSF ratings.

E6.4.4 Measurement Procedure. The energy use of the new compressors and condensers will be monitored and summed over the period of time of interest (usually monthly) by an electronic data logger or energy management system.

E6.4.5 Quality Control Procedures. The primary equipment types used for this method are electric power meters wired to CTs. The polarity of the CTs should be verified to be correct upon their installation. Shunt resistors and CT output should be verified upon installation.

E6.4.6 Savings Reporting Frequency and Format. The usual reporting frequency for the energy savings is monthly or as required by the owner or terms of the performance contract. The report should consist of the following information in columnar format:

a. Equipment ID
b. Compressor/condenser size and model
c. kWh/period cooling
d. kWh/period heating
e. Old nameplate SEER
f. New nameplate SEER
g. Old nameplate horsepower (kWh) heating efficiency
h. New nameplate horsepower (kWh) heating efficiency
i. Adjustment factors
j. Energy savings

Numerical data in all columns should be totaled.

E6.5 Method for Unitary Equipment. A piece of unitary HVAC equipment can be considered and modeled as a combination of the following elements:

a. Constant-speed compressors that cycle on/off in response to load variations.
b. Constant-speed condenser fans that cycle on/off in response to load variations.
c. A constant-speed ventilation fan.
d. A heater section that cycles on/off in response to load variations.

E6.5.1 Selected Measurement Approach and Compliance Path. The proposed measurement approach relies on measuring or making assumptions about each of the four unitary HVAC equipment elements. A relatively small subset of available unitary equipment may have variable or two-speed compressors or ventilation fans that may complicate the use of this method.

a. **Measurement approach for constant-speed compressors.** The new compressor will be continuously monitored for power consumption over each month by a power meter connected to a CT connected to the power input for the entire compressor motor circuit.
b. **Measurement approach for constant-speed condenser fans.** The new condenser section will be continuously monitored for power consumption over each month by a power meter connected to a CT connected to the power input for the entire condenser fan motor circuit.
c. **Measurement approach for a constant-speed ventilation fan.** The new ventilator fan will be continuously monitored for power consumption over each month by a power meter connected to a CT connected to the power input for ventilator fan motor circuit.
d. **Measurement approach for heater section.** If the new heater section is natural-gas fired, a gas meter will be inserted in the natural-gas pipe leading to the furnace section to measure monthly natural-gas consumption. If the new heater section is supplied with hot-water or steam, then a British thermal unit meter will be inserted to measure the thermal input to the unit. If the old and new heater sections are electric resistance, measurement is unnecessary, as there will be no significant energy savings.

E6.5.2 Baseline Period Data. If baseline period data that include performance at AHRI conditions are available for the above equipment, the data can be used to calibrate the performance of the old unit that is to be removed and demonstrate how much less efficient it is than nameplate efficiency.

E6.5.3 Algorithm for Savings Determination. Energy and demand savings for the newly installed unitary equipment is the sum of the following four elements:

a. Compressor demand and energy savings.
b. Heater section energy savings.
   1. Energy savings for constant-speed compressors: **Energy savings per period (kWh)** = (new compressor measured kWh/period) × [1 – (old equipment nameplate SEER)/(new equipment nameplate SEER)] × [products of applicable adjustment factors in Section 6]
   2. Electric savings for natural-gas heating section: **Electric savings per period (kWh)** = [natural gas (in cubic feet) used per period] × (Btu/ft^3) × (combustion efficiency of unit) × (1 kWh/3413 Btu)
   3. Electric demand savings: **Demand savings per period (kW)** = {[old equipment nameplate capacity (tons)/(old equipment nameplate SEER)]} – [(new equipment nameplate SEER)/(new equipment nameplate SEER)]

E6.5.4 Measurement Procedure. The energy use of the new compressors and condensers will be monitored and summed over the period of time of interest (usually monthly) by an electronic data logger or energy management system.

E6.5.5 Quality Control Procedures. The primary equipment types used for this method are electric power meters wired to CTs. The polarity of the CTs should be verified to be correct upon their installation. Shunt resistors and CT output should be verified upon installation.

E6.5.6 Savings Reporting Frequency and Format. The usual reporting frequency for the energy savings is monthly or as required by the owner or terms of the performance contract. The report should consist of the following information in columnar format:

a. Equipment ID
b. Compressor/condenser/ventilator fan
c. Cooling kilowatt-hours/period
d. Ventilation fan kilowatt-hours/period
e. Old nameplate SEER
f. New nameplate SEER
g. Natural gas or thermal heat/period
h. Avoided electric heat energy in kilowatt-hours/period
i. Adjustment factors
j. Energy savings

Numerical data in all columns should be totaled.

E6.6 Ancillary System Improvement Adjustment Factors. Frequently, the newly installed equipment will either have features not found in the old, removed equipment (e.g., air-side economizer cycle) or will be accompanied by other ancillary measures whose energy savings may not be realized by the previous protocols. The following system improvement factors are intended to address that gap.

E6.6.1 Installation of Air-Side Economizer in New Equipment when Old Equipment Did not Have It. Many older rooftop unitary HVAC units may not have air-side economizer free cooling cycle capability or controls, or if they do, the controls may have failed. The following prescriptive methods can allow for an adjustment factor to make up for the extra energy savings from the new air-side economizer cycles that are not picked up by the basic energy savings protocol.

a. **Computer simulation.** The additional cooling savings from the installation of the air-side economizer cycle may be calculated prescriptively by a computer energy simulation program comparing the old equipment operation without the economizer to the new equipment operation with the economizer cycle.
b. **Bin or modified bin method.** The additional cooling savings from the installation of the air-side economizer cycle may be calculated prescriptively by using a bin method or modified bin method to determine the fraction of annual cooling energy saved by the installation of an economizer cycle.
c. **Default value method.** In the "E-Cube study" (Wolpert and Houghton 1998), the savings from an air-side economizer were computer simulated for a 10-ton (2032-kg) rooftop unit located in Boston, MA. The result was a 32% cooling energy savings. Based on this, a default value of 30% is recommended if site-specific computer simulations or bin method analysis is possible.

(This informative annex is not part of this guideline. It is provided for informational purposes only.)

INFORMATIVE ANNEX F
INFORMATIVE REFERENCES AND BIBLIOGRAPHY

References that appear in the informative annexes of this guideline are listed alphabetically, followed by an informative bibliography organized by annex. References that appear in normative annexes can be found in Section 10 of this guideline.

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POLICY STATEMENT DEFINING ASHRAE'S CONCERN FOR THE ENVIRONMENTAL IMPACT OF ITS ACTIVITIES

ASHRAE is concerned with the impact of its members' activities on both the indoor and outdoor environment. ASHRAE's members will strive to minimize any possible deleterious effect on the indoor and outdoor environment of the systems and components in their responsibility while maximizing the beneficial effects these systems provide, consistent with accepted Standards and the practical state of the art.

ASHRAE's short-range goal is to ensure that the systems and components within its scope do not impact the indoor and outdoor environment to a greater extent than specified by the Standards and Guidelines as established by itself and other responsible bodies.

As an ongoing goal, ASHRAE will, through its Standards Committee and extensive technical committee structure, continue to generate up-to-date Standards and Guidelines where appropriate and adopt, recommend, and promote those new and revised Standards developed by other responsible organizations.

Through its *Handbook*, appropriate chapters will contain up-to-date Standards and design considerations as the material is systematically revised.

ASHRAE will take the lead with respect to dissemination of environmental information of its primary interest and will seek out and disseminate information from other responsible organizations that is pertinent, as guides to updating Standards and Guidelines.

The effects of the design and selection of equipment and systems will be considered within the scope of the system's intended use and expected misuse. The disposal of hazardous materials, if any, will also be considered.

ASHRAE's primary concern for environmental impact will be at the site where equipment within ASHRAE's scope operates. However, energy source selection and the possible environmental impact due to the energy source and energy transportation will be considered where possible. Recommendations concerning energy source selection should be made by its members.

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About ASHRAE

ASHRAE, founded in 1894, is a global society advancing human well-being through sustainable technology for the built environment. The Society and its members focus on building systems, energy efficiency, indoor air quality, refrigeration, and sustainability. Through research, Standards writing, publishing, certification and continuing education, ASHRAE shapes tomorrow's built environment today.

For more information or to become a member of ASHRAE, visit www.ashrae.org.

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ASHRAE offers its Standards and Guidelines in print, as immediately downloadable PDFs, on CD-ROM, and via ASHRAE Digital Collections, which provides online access with automatic updates as well as historical versions of publications. Selected Standards and Guidelines are also offered in redline versions that indicate the changes made between the active Standard or Guideline and its previous edition. For more information, visit the Standards and Guidelines section of the ASHRAE Bookstore at www.ashrae.org/bookstore.

IMPORTANT NOTICES ABOUT THIS GUIDELINE

To ensure that you have all of the approved addenda, errata, and interpretations for this Guideline, visit www.ashrae.org/standards to download them free of charge.

Addenda, errata, and interpretations for ASHRAE Standards and Guidelines are no longer distributed with copies of the Standards and Guidelines. ASHRAE provides these addenda, errata, and interpretations only in electronic form to promote more sustainable use of resources.

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