computer programs used to generate these results have been subjected to a number of analytical verification, empirical validation, and comparative testing studies. However, there is no such thing as a completely validated building energy simulation computer program. All building models are simplifications of reality. The philosophy here is to generate a range of results from several programs that are generally accepted as representing the state-of-the-art in whole building energy simulation programs. To the extent possible, input errors or differences have been eliminated from the presented results. Thus, for a given case, the range of differences between comparative test results presented in Informative Annexes B8 and B16 represents legitimate algorithmic differences among these computer programs. For any given case, a tested program may fall outside this range without necessarily being incorrect. However, it is worthwhile to investigate the source of substantial differences, as the collective experience of the authors of this standard is that such differences often indicate problems with the software or its usage, including, but not limited to,

- *user input error, where the user misinterpreted or incorrectly entered one or more program inputs;*
- *a problem with a particular algorithm in the program;*
- *one or more program algorithms used outside their intended range.*

Also, for any given case, a program that yields values in the middle of the range established by the comparative test example results should not be perceived as better or worse than a program that yields values at the borders of the range.

Analytical verification test results for the HVAC equipment performance tests include both quasi-analytical solutions and simulation results in selected sections of Informative Annex B16. In general, it is difficult to develop worthwhile test cases that can be solved analytically or quasi-analytically, but such solutions are extremely useful when possible. Analytical or quasi-analytical solutions represent a "mathematical truth standard." That is, given the underlying physical assumptions in the case definitions, there is a mathematically correct solution for each case. In this context, the underlying physical assumptions regarding the mechanical equipment as defined in Sections 5.3 and 5.4 are representative of typical manufacturer data normally used by building design practitioners. Many "whole-building" simulation programs are designed to work with this type of data. It is important to understand the difference between a "mathematical truth standard" and an "absolute truth standard." In the former, we only test the solution process for a model, not the appropriateness of the model itself; that is, we accept the given underlying physical assumptions while recognizing that these assumptions represent a simplification of physical reality. An approximate truth standard from an experiment tests both the solution process and appropriateness of the model within experimental uncertainty. The ultimate or "absolute" validation truth standard would be comparison of simulation results with a perfectly performed empirical experiment, with all simulation inputs perfectly defined.

The quasi-analytical and analytical solution results presented in selected parts of Annex B16 represent a mathematical truth standard. This allows identification of bugs in the software that would not otherwise be apparent from comparing software only to other software and therefore improves the diagnostic capabilities of the test procedure. The primary purpose of also including simulation results for the cases where analytical or quasi-analytical solutions exist is to allow simulationists to compare their relative agreement (or disagreement) versus the analytical or quasi-analytical solution results to that for other simulation results. Perfect agreement among simulations and analytical or quasi-analytical solutions is not necessarily expected. The results give an indication of the degree of agreement that is possible between simulation results and the analytical or quasi-analytical solution results. Because the physical assumptions of a simulation may be different from those for analytical or quasi-analytical solutions, a tested program may disagree with such solutions without necessarily being incorrect. However, it is worthwhile to investigate the sources of differences as noted above.

1. PURPOSE

This standard specifies test procedures for evaluating the technical capabilities and ranges of applicability of computer programs that calculate the thermal performance of buildings and their HVAC systems.

2. SCOPE

These standard test procedures apply to building energy computer programs that calculate the thermal performance of a building and its mechanical systems. While these standard test procedures cannot test all algorithms within a building energy computer program, they can be used to indicate major flaws or limitations in capabilities.

3. DEFINITIONS, ABBREVIATIONS, AND ACRONYMS

3.1 Terms Defined for This Standard

adjusted net sensible capacity: the gross sensible capacity less the actual fan power. (Also see *gross sensible capacity*.)

adjusted net total capacity: the gross total capacity less the actual fan power. (Also see *gross total capacity*.)

altitude: vertical elevation above sea level.

analytical solution: mathematical solution of a model of reality that has a deterministic result for a given set of parameters and boundary conditions.

annual heating load: heating load for the entire one-year simulation period; e.g., for hourly simulation programs this is the sum of the hourly heating loads for the one-year simulation period.

annual hourly integrated maximum zone air temperature: the hourly zone temperature that represents the maximum for the one-year simulation period.

annual hourly integrated minimum zone air temperature: the hourly zone temperature that represents the minimum for the one-year simulation period.

annual hourly integrated peak heating load: the hourly heating load that represents the maximum for the one-year simulation period.

annual hourly integrated peak sensible cooling load: the hourly sensible cooling load that represents the maximum for the one-year simulation period.

annual hourly 1°C zone air temperature bin frequencies: number of hours that the zone air temperature has values within given bins (1°C bin width) for the one-year simulation period.

annual incident unshaded total solar radiation (diffuse and direct): sum of direct solar radiation and diffuse solar radiation that strikes a given surface for the entire one-year simulation period when no shading is present; e.g., for hourly simulation programs this is the sum of the hourly total incident solar radiation for the one-year simulation period.

annual mean zone air temperature: the average zone air temperature for the one-year simulation period; e.g., for hourly simulation programs this is the average of the hourly zone air temperatures for the one-year simulation period.

annual sensible cooling load: sensible cooling load for the entire one-year simulation period; e.g., for hourly simulation programs this is the sum of the hourly sensible cooling loads for the one-year simulation period.

annual transmitted solar radiation (diffuse and direct): sum of direct solar radiation and diffuse solar radiation that passes through a given window for the entire one-year simulation period. This quantity does not include radiation that is absorbed in the glass and conducted inward as heat. This quantity may be taken as the optically transmitted solar radiation through a window that is backed by a perfectly absorbing black cavity.

apparatus dew point (ADP): the effective coil surface temperature when there is dehumidification; this is the temperature to which all the supply air would be cooled if 100% of the supply air contacted the coil. On the psychrometric chart, this is the intersection of the condition line and the saturation curve, where the condition line is the line going through entering air conditions with slope defined by the sensible heat ratio ([gross sensible capacity]/[gross total capacity]). (Also see *gross sensible capacity* and *gross total capacity*.)

building thermal envelope and fabric: includes the building thermal envelope as defined in *ASHRAE Terminology*,[1] as well as internal thermal capacitance and heat and mass transfer between internal zones.

bypass factor (BF): can be thought of as the percentage of the distribution air that does not come into contact with the cooling coil; the remaining air is assumed to exit the coil at the average coil temperature (apparatus dew point). (See also *apparatus dew point*.)

coefficient of performance (COP): for a cooling (refrigeration) system, the ratio, using the same units in the numerator as in the denominator, of the net refrigeration effect to the corresponding energy input. For the purpose of calculating COP, corresponding energy input is the related cooling energy consumption, except for cases CE300–CE440 (see Sections 5.3.3, 5.3.4.1, and 5.3.4.2) where the indoor air distribution fan energy is included only during times when heat is being extracted by the evaporator coil. (Also see *net refrigeration effect* and *cooling energy consumption*.)

combined radiative and convective surface coefficient: constant of proportionality relating the rate of combined convective and radiative heat transfer at a surface to the temperature difference across the air film on that surface.

combined surface coefficient: see *combined radiative and convective surface coefficient*.

conductance: thermal conductance.

cooling energy consumption: the site electric energy consumption of the mechanical cooling equipment including the compressor, air distribution fan (regardless of whether the compressor is on or off), condenser fan, and related auxiliaries.

COP2: the ratio, using the same units, of the gross total evaporator coil load to the sum of the compressor and outdoor condenser fan energy consumptions. (Also see *gross total evaporator coil load*.)

COP_{SEER}: the seasonal energy efficiency ratio (dimensionless).

COP degradation factor (CDF): a multiplier (≤1) applied to the full-load system COP or COP2. CDF is a function of part-load ratio. (Also see *part-load ratio*.)

deep ground temperature: ground temperature at or below a soil depth of two meters.

degradation coefficient: measure of efficiency loss due to cycling of equipment.

dew-point temperature: the temperature of saturated air at a given humidity ratio and pressure. As moist air is cooled at constant pressure, the dew point is the temperature at which condensation begins. (Also see *humidity ratio*.)

direct solar radiation: the solar radiation received from the sun without having been scattered by the atmosphere or other objects such as the ground; this is also called beam or direct-beam radiation.

diffuse solar radiation: the solar radiation received from the sun after its direction has been changed by scattering by the atmosphere or other objects such as the ground.

economizer: a control system that conserves energy, usually by using outside air and control logic to maintain a fixed minimum of outside air when increased outside-air flow rates are not called for.

energy efficiency ratio (EER): the ratio of net refrigeration effect (in Btu per hour) to cooling energy consumption (in watts) so that EER is stated in units of (Btu/h)/W. (Also see *net refrigeration effect* and *cooling energy consumption*.)

entering dry-bulb temperature (EDB): the temperature that a thermometer would measure for air entering the evaporator coil. For a draw-through fan configuration with no heat gains or losses in the ductwork and no outside air mixed with return air, EDB equals the indoor dry-bulb temperature. For a similar configuration but when outside air is mixed with return air, EDB equals the mixed-air dry-bulb temperature.

entering wet-bulb temperature (EWB): the temperature that the wet-bulb portion of a psychrometer would measure if exposed to air entering the evaporator coil. For a draw-through fan with no heat gains or losses in the ductwork and no outside air mixed with return air, this would also be the zone air wet-bulb temperature. For a similar configuration but when outside air is mixed with return air, EWB equals the mixed-air wet-bulb temperature. For mixtures of water vapor and dry air at atmospheric temperatures and pressures, the wet-bulb temperature is approximately equal to the adiabatic saturation temperature (temperature of the air after undergoing a theoretical adiabatic saturation process). The wet-bulb temperature given in psychrometric charts is really the adiabatic saturation temperature.

evaporator coil loads: the actual sensible heat and latent heat removed from the distribution air by the evaporator coil. These loads include indoor air distribution fan heat for times when the compressor is operating, and they are limited by the system capacity (where system capacity is a function of operating conditions). Sensible evaporator coil load applies only to sensible heat removal. Latent evaporator coil load applies only to latent heat removal. (Also see *sensible heat* and *latent heat*.)

extinction coefficient: the proportionality constant K in Bouguer's Law ($(dI) = (I \text{ K } dx)$) where I is the local intensity of solar radiation within a medium and x is the distance the radiation travels through the medium.

free float: refers to a situation where mechanical heating and cooling equipment is off so that the space or zone temperature varies without constraint.

gross sensible capacity: the rate of sensible heat removal by the cooling coil for a given set of operating conditions. This value varies as a function of performance parameters such as EWB, ODB, EDB, and airflow rate. (Also see *sensible heat*.)

gross total capacity: the total rate of both sensible heat and latent heat removal by the cooling coil for a given set of operating conditions. This value varies as a function of performance parameters such as EWB, ODB, EDB, and airflow rate. (Also see *sensible heat* and *latent heat*.)

gross total coil load (or gross total evaporator coil load): the sum of the sensible heat and latent heat removed from the distribution air by the evaporator coil.

heat input ratio (HIR): a ratio that is the inverse of the efficiency.

hourly free-floating zone air temperature: zone air temperature for a given hour, when heating and cooling equipment is off or for an unconditioned zone.

hourly heating load: heating load for a given hour.

hourly incident unshaded solar radiation (direct and diffuse): sum of direct solar radiation and diffuse solar radiation that strikes a given surface for a given hour.

hourly sensible cooling load: sensible cooling load for a given hour.

humidity ratio: the ratio of the mass of water vapor to the mass of dry air in a moist air sample.

incidence angle: angle defined by the intersection of a line normal to a surface and a ray that strikes that surface.

index of refraction: relates the angle of refraction (x_2) to the angle of incidence (x_1) at the surface interface of two media according to Snell's law ($n_1 \sin(x_1) = n_2 \sin(x_2)$) where n_1 and n_2 are indices of refraction for each medium.

indoor dry-bulb temperature (IDB): the temperature that a thermometer would measure if exposed to indoor air.

infiltration: the leakage of air through any building element (e.g., walls, windows, and doors).

infrared emittance: the ratio of the infrared spectrum radiant flux emitted by a body to that emitted by a blackbody at the same temperature and under the same conditions.

internal gains: heat gains generated inside the space or zone.

latent heat: the change in enthalpy associated with a change in humidity ratio, caused by the addition or removal of moisture. (Also see *humidity ratio*.)

net refrigeration effect: the rate of heat removal (sensible + latent) by the evaporator coil, as regulated by the thermostat (i.e., not necessarily the full load capacity), after deducting internal and external heat transfers to air passing over the evaporator coil. For the tests of Section 5.3, the net refrigeration effect is the evaporator coil load less the actual air distribution fan heat for the time when the compressor is operating; at full load, this is also the adjusted net total capacity. (Also see *adjusted net total capacity*, *evaporator coil load*, *sensible heat*, and *latent heat*.)

net sensible capacity: the gross sensible capacity less the default rate of fan heat assumed by the manufacturer; this rate of fan heat is not necessarily the same as for the actual installed fan (see *adjusted net sensible capacity*). (Also see *gross sensible capacity.*)

net total capacity: the gross total capacity less the default rate of fan heat assumed by the manufacturer; this rate of fan heat is not necessarily the same as for the actual installed fan (see *adjusted net total capacity*). (Also see *gross total capacity.*)

nonproportional-type thermostat: a thermostat that provides two position (ON/OFF) control.

outdoor dry-bulb temperature (ODB): the temperature that a thermometer would measure if exposed to outdoor air. This is the temperature of air entering the condenser coil.

part-load factor (PLF): the ratio of the efficiency at part load to the steady-state efficiency; it represents the degradation in efficiency due to part-load operation.

part-load ratio for cooling (PLR): the ratio of the net refrigeration effect to the adjusted net total capacity for the cooling coil. As shown in Annex B13, for the purpose of calculating the COP degradation factor (CDF), defining PLR as the ratio of gross total evaporator coil load to the gross total capacity produces an equivalent CDF. (Also see *net refrigeration effect*, *adjusted net total capacity*, *COP degradation factor*, *gross total evaporator coil load*, and *gross total capacity*.)

part-load ratio for furnace (PLR_f): the ratio of the net heating effect to the adjusted net total capacity for the furnace.

quasi-analytical solution: the mathematical solution of a model of reality for a given set of parameters and boundary conditions; such a result may be computed by generally accepted numerical method calculations, provided that such calculations occur outside the environment of a whole-building energy simulation program and can be scrutinized.

relative humidity: the ratio of the mole fraction of water vapor in a given moist air sample to the mole fraction in an air sample that is saturated and at the same temperature and pressure. This is equivalent to the ratio of partial pressure of the water vapor in a sample to the saturation pressure at the same temperature.

seasonal energy efficiency ratio (SEER): the ratio of net refrigeration effect in Btu to the cooling energy consumption in watt-hours for a refrigerating device over its normal annual usage period as determined using ANSI/ARI Standard 210/240-89.[2] This parameter is commonly used for simplified estimates of energy consumption based on a given load and is not generally useful for detailed simulations of mechanical systems. (Also see *net refrigeration effect* and *cooling energy consumption*.)

sensible heat: the change in enthalpy associated with a change in dry-bulb temperature caused by the addition or removal of heat.

sensible heat ratio (SHR): also known as sensible heat factor (SHF), the ratio of sensible heat transfer to total (sensible + latent) heat transfer for a process. (Also see *sensible heat* and *latent heat*.)

shortwave: refers to the solar spectrum; e.g., in this standard the terms *solar absorptance* and *shortwave absorptance* are used interchangeably.

solar absorptance: the ratio of the solar spectrum radiant flux absorbed by a body to that incident on it.

solar distribution fraction: the fraction of total solar radiation transmitted through the window(s) that is absorbed by a given surface or retransmitted (lost) back out the window(s).

solar fraction: see *solar distribution fraction*.

solar heat gain coefficient (SHGC): a dimensionless ratio of solar heat gains to incident solar radiation, including transmittance plus inward flowing fraction of absorbed solar radiation; for windows, SHGC is dependent on incidence angle.

solar lost through window: the fraction of total solar radiation transmitted through the window(s) that is reflected by opaque surfaces and retransmitted back out the window(s).

standard temperature and pressure (STP) conditions: 0°C and 1 atm.

surface coefficient: see c*ombined radiative and convective surface coefficient*.

zone air temperature: the temperature of just the zone air, not including infrared radiation from the interior surfaces; such a temperature would be measured by a sensor housed in a well-aspirated containment shielded by a material with a solar and infrared reflectance of one; well-mixed air is assumed.

zone cooling loads: sensible heat and latent heat loads associated with heat and moisture exchange between the building envelope and its surroundings as well as internal heat and moisture gains within the building. These loads do not include internal gains associated with operating the mechanical system (e.g., air distribution fan heat).

3.2 Abbreviations and Acronyms Used in This Standard

Abs	absorptance
ach	air changes per hour
ADP	apparatus dew point
ANSI	American National Standards Institute
Apr.	April
ARI	Air-Conditioning and Refrigeration Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BESTEST	Building Energy Simulation Test and Diagnostic Method
BF	bypass factor
BHP	brake horsepower
Cd	degradation coefficient
CDF	coefficient of performance degradation factor
cfm	cubic feet per minute
CIBSE	Chartered Institution of Building Services Engineers
COP	coefficient of performance
COP2	alternative coefficient of performance (see Section 3.1)
Coef	coefficient
Cp	specific heat, J/(kg·K)
DBT	dry-bulb temperature, °C
Dec.	December
E,W,N,S	east, west, north, south
EDB	entering dry-bulb temperature
EER	energy efficiency ratio
EWB	entering wet-bulb temperature
Ext	exterior
FF	free-floating thermostat control strategy (no heating or cooling)
High-mass	heavy mass
HIR	heat input ratio
HVAC	heating, ventilating, and air conditioning
HVAC BESTEST	International Energy Agency Building Energy Simulation Test and Diagnostic Method for Heating, Ventilating, and Air-Conditioning Equipment Models
ID	indoor
I.D.	inside diameter

IDB	indoor dry-bulb temperature
Int	interior
I-P	inch-pound
Jan.	January
k	thermal conductivity, W/(m·K)
Low mass	light mass
Mar.	March
N/A	not applicable
NOAA	National Oceanic and Atmospheric Administration
Nov.	November
NSRDB	National Solar Radiation Database
Oct.	October
O.D.	outside diameter
ODB	outdoor dry-bulb temperature
PLF	part-load factor
PLR	part-load ratio for cooling
PLR_f	part-load ratio for furnace
R	unit thermal resistance, m^2·K/W
Refl	reflectance
SEER	seasonal energy efficiency ratio
SHC	gross sensible capacity, kW thermal
SHGC	solar heat gain coefficient
SHR	sensible heat ratio
SI	Système Internationale
STP	standard temperature and pressure
Surf	surface
t	thickness, m
T	zone air temperature
TC	gross total capacity, kW thermal
TMY	Typical Meteorological Year
TMY2	Typical Meteorological Year 2
Trans	solar transmittance
TUD	Technische Universität Dresden
U	unit thermal conductance or overall heat transfer coefficient, W/(m^2·K)
UA	thermal conductance, W/K
WBAN	Weather Bureau Army Navy
w.g.	water gauge
WYEC2	Weather Year for Energy Calculations 2

4. METHODS OF TESTING

4.1 Applicability of Test Method. The method of test is provided for analyzing and diagnosing building energy simulation software using software-to-software, software-to-analytical-solution, and software-to-quasi-analytical-solution comparisons. The methodology allows different building energy simulation programs, representing different degrees of modeling complexity, to be tested by

- comparing the predictions from other building energy simulation programs to the example simulation results provided in Informative Annex B8, to the example analytical and quasi-analytical solution and simulation results in the informative Annex B16, and/or to other results (simulations or analytical and quasi-analytical solutions) that were generated using this standard method of test;
- checking a program against a previous version of itself after internal code modifications to ensure that only the intended changes actually resulted;
- checking a program against itself after a single algorithmic change to understand the sensitivity between algorithms;
- diagnosing the algorithmic sources of prediction differences; diagnostic logic flow diagrams are included in the informational Annex B9.

4.2 Organization of Test Cases. The specifications for determining input values are provided case by case in Section 5. Weather information required for use with the test cases is provided as described in Annex A1. Annex B1 provides an overview for all the test cases and contains information on those building parameters that change from case to case; Annex B1 is recommended for preliminary review of the tests, but do not use it for defining the cases. Additional information regarding the meaning of the cases is shown in the informational Annex B9 on diagnostic logic. In some instances (e.g., Case 620, Section 5.2.2.1.2), a case developed from modifications to a given base case (e.g., Case 600 in Section 5.2.1) will also serve as the base case for other cases. The cases are grouped as:

a. Building Thermal Envelope and Fabric Load Base Case (see Section 4.2.1)
b. Building Thermal Envelope and Fabric Load Basic Tests (see Section 4.2.2)
   - Low mass (see Section 4.2.2.1)
   - High mass (see Section 4.2.2.2)
   - Free float (see Section 4.2.2.3)
c. Building Thermal Envelope and Fabric Load In-Depth Tests (see Section 4.2.3)
d. Space-Cooling Equipment Performance Analytical Verification Base Case (see Section 4.2.4)
e. Space-Cooling Equipment Performance Parameter Variation Analytical Verification Tests (see Section 4.2.5)
f. Space-Cooling Equipment Performance Comparative Test Base Case (see Section 4.2.6)
g. Space-Cooling Equipment Performance Comparative Tests (see Section 4.2.7)
h. Space-Heating Equipment Performance Analytical Verification Base Case (see Section 4.2.8)
i. Space-Heating Equipment Performance Analytical Verification Tests (see Section 4.2.9)
j. Space-Heating Equipment Performance Comparative Tests (see Section 4.2.10)

4.2.1 Building Thermal Envelope and Fabric Load Base Case. The base building plan is a low mass, rectangular single zone with no interior partitions. It is presented in detail in Section 5.2.1.

4.2.2 Building Thermal Envelope and Fabric Load Basic Tests. The basic tests analyze the ability of software to model building envelope loads in a low mass configuration