ASHRAE

STANDARD

ANSI/ASHRAE Standard 140-2017
(Supersedes ANSI/ASHRAE Standard 140-2014)
Includes ANSI/ASHRAE Addendum listed in Annex C

Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs

See Informative Annex C for approval dates.

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NOTE

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FOREWORD

This standard method of test (SMOT) was developed to identify and diagnose differences in predictions from whole-building energy simulation software that may be caused by algorithmic differences, modeling limitations, faulty coding, inadequate documentation, or input errors. These tests are part of an overall validation methodology described in Informative Annex B23. The procedures test software over a broad range of parametric interactions and for a number of different output types, thus minimizing the concealment of algorithmic differences by compensating errors. Different building energy simulation programs, representing different degrees of modeling complexity, can be tested. However, some of the tests may be incompatible with some building energy simulation programs.

The tests are a subset of all the possible tests that could occur. A large amount of effort has gone into establishing a sequence of tests that examines many of the physical and mathematical models relevant to simulating the energy performance of a building and its mechanical equipment. However, because building energy simulation software operates in an immense parameter space, it is not practical to test every combination of parameters over every possible range of function.

The tests consist of a series of carefully described test case building plan, material, and mechanical equipment specifications. Output values for the cases are compared and used in conjunction with diagnostic logic to determine the sources of predictive differences.

The test cases are divided into separate test classes to satisfy different levels of software modeling detail. Such classification allows more convenient citation of specific sections of Standard 140 by other codes and standards and by certifying and accrediting agencies. The Class I test cases (Section 5) are detailed diagnostic tests intended for simulation software capable of hourly or subhourly simulation time steps. The Class II test cases (Section 7) may be used for all types of building load calculation methods, regardless of time-step granularity, and are often favored by those needing to test simplified software for residential buildings. The Class I (Section 5) test cases are designed for more detailed diagnosis of simulation models than the Class II (Section 7) test cases. An overview of the test suites and methodologies that make up Standard 140 follows; Section 4 of the standard provides a detailed road map of the test specifications of Sections 5 and 7, and output requirements of Sections 6 and 8.

Class I Test Procedures (Section 5)

The set of Class I tests included herein consist of

a. *software-to-software comparative tests, in which a program's results may be compared to itself or to the results of other programs in a consistent and repeatable manner, and*
b. *analytical verification tests, in which a program's results may be compared to the results from analytical, quasi-analytical, or verified numerical model solutions (this terminology is elaborated in a subsection below).*

In addition to comparative and analytical verification tests, the overall methodology for model validation and testing described in Informative Annex B23, in the 2017 ASHRAE Handbook—Fundamentals *(see Chapter 19, Section 8), and elsewhere (as cited in Annex B23, Section B23.1.1) includes empirical validation testing, where tested software models are validated to within the uncertainty of experimental input and output data. Such tests can be accommodated within the current title purpose and scope of Standard 140, and additional research on this topic is recommended, as discussed in Informative Annex B23.*

Of the current set of Class I test cases, four test suites were initially developed by the National Renewable Energy Laboratory (NREL) with the International Energy Agency (IEA); one test suite was developed by Natural Resources Canada, also in collaboration with the IEA; and one test suite was based on ASHRAE research and adapted by NREL in collaboration with the ASHRAE Standard 140 project committee (SSPC 140). (See Annex B23, Section B23.1 for reference citations).

For the building thermal envelope and fabric load test cases of Section 5.2, the basic comparative test cases (Sections 5.2.1 and 5.2.2) test the ability of the programs to model such combined effects as thermal mass, direct solar gain windows, window-shading devices, internally generated heat, infiltration, sunspaces, and deadband and setback thermostat control. The in-depth comparative test cases (Section 5.2.3) facilitate diagnosis by allowing excitation of specific heat transfer mechanisms. The ground-coupled slab analytical verification tests of Section 5.2.4 use the results of an analytical solution as a primary mathematical truth standard, and the results from a set of detailed verified numerical models for three-dimensional ground-coupled heat transfer as a secondary mathematical truth standard. These results are then used for comparing to the results of models typically embedded within whole-building energy simulation software. (See Informative Annex B23 for a more complete description of using verified numerical models as a secondary truth standard.) Parametric variations from a steady-state base case include harmonically varying ground surface temperature, floor slab aspect ratio, slab area, water table depth (depth of constant ground temperature), slab interior and ground exterior-surface heat transfer coefficients, and slab and ground thermal conductivity. Informative analytical solution and verified numerical model results are provided for the test cases of this section.

The space-cooling equipment cases of Section 5.3 test the ability of programs to model the performance of unitary space-cooling equipment using manufacturer design data presented as empirically derived performance maps. Many whole-building energy simulation programs are designed to work with this type of data, and there is very little manufacturer's data that would support the alternative of first principles (direct physical system component) modeling. In the steady-state analytical verification cases of Sections 5.3.1 *and 5.3.2, which utilize a typical range of performance data, the following parameters are varied: sensible internal gains, latent internal gains, zone thermostat set point (entering dry-bulb temperature), and outdoor dry-bulb temperature. Parametric variations isolate the effects of the parameters singly and in various combinations and isolate the influence of part-loading of equipment, varying sensible heat ratio, dry-coil (no latent load) versus wet-coil (with dehumidification) operation, and operation at typical Air-Conditioning, Heating, and Refrigeration Institute (AHRI) rating conditions. Informative quasi-analytical solution results are provided for the test cases of this section. The comparative test cases of Sections 5.3.3 and 5.3.4 utilize an expanded range of performance data, an outdoor air mixing system, and hourly varying weather data and internal gains. These cases cannot be solved analytically but are more realistic. In these cases, the following parameters are varied: sensible internal gains, latent internal gains, infiltration rate, outdoor air fraction, thermostat set points, and economizer control settings. Through analysis of results, the influence of part-loading of equipment, outdoor dry-bulb (ODB) temperature sensitivity, and dry-coil (no latent load) versus wet-coil (with dehumidification) operation can also be isolated. These cases help to scale the significance of simulation results disagreements more so than the steady-state cases.*

The space-heating equipment cases of Section 5.4 test the ability of programs to model the performance of residential fuel-fired furnaces. These tests are divided into two tiers. The Tier 1 analytical verification test cases (Sections 5.4.1 and 5.4.2) employ simplified boundary conditions and test the basic functionality of furnace models. More realistic boundary conditions are used in the Tier 2 comparative test cases (Section 5.4.3), where specific aspects of furnace models are examined. The full set of space-heating test cases is designed to test the implementation of specific algorithms for modeling the following aspects of furnace performance: furnace steady-state efficiency, furnace part-load ratio, furnace fuel consumption, circulating fan operation, and draft fan operation. These cases also test the effects of thermostat setback and undersized capacity. Informative analytical and quasi-analytical solution results are provided for the Tier 1 test cases of this section.

The air-side heating, ventilating, and air-conditioning (HVAC) equipment cases of Section 5.5 test the ability of programs to model fundamental air distribution system mass flow and heat balance. These test cases are complementary to the test cases of Sections 5.3 and 5.4, respectively, which test the ability to apply performance maps for modeling the working heat-transfer-fluid side and combustion side of HVAC equipment as described above. The Section 5.5 test cases are based on ASHRAE research project RP-865 and were adapted by NREL in collaboration with SSPC 140. These are steady-state analytical verification tests at a variety of constant zone and ambient conditions. The test systems include the following in order of increasing complexity: four-pipe fan coil (FC), single-zone air conditioner (SZ), constant-volume terminal reheat (CV), and variable-air-volume terminal reheat (VAV). In these cases, the FC system is a single-zone system with heating and cooling coils, zone air exhaust, and limited outdoor air (no economizer control), and it does not include a return air fan. The SZ system adds an economizer and a return air fan. The CV system further applies multiple (two) zones, system supply-air temperature control, and terminal reheat coils. Finally, the VAV system further applies a variable airflow supply fan and terminal zone supply-air dampers. The test cases are conducted at five different sets of steady-state outdoor and zone conditions in heating, dry-coil cooling, and wet-coil cooling modes and with temperature and enthalpy economizer outdoor air control strategies applied to selected conditions. Informative quasi-analytical solution results are provided.

Class II Test Procedures (Section 7)

The Class II (Section 7) test cases were adapted from HERS BESTEST, developed by the National Renewable Energy Laboratory (as cited in Annex B23, Section B23.1). This set of test cases formally codifies the Tier 1 and Tier 2 tests for certification of residential energy performance analysis tools.

The Section 7 test cases are divided into Tier 1 and Tier 2 tests. The Tier 1 base building plan (Section 7.2.1) is a single-story house with 1539 ft^2 of floor area, with one conditioned zone (the main floor), an unconditioned attic, a raised floor exposed to air (highly vented crawlspace), and typical glazing and insulation. Additional Tier 1 cases (Section 7.2.2) test the ability of software to model building envelope loads in the base-case configuration with the following variations: infiltration; wall and ceiling R-values; glazing physical properties, area, and orientation; shading by a south overhang; internal loads; exterior surface color; energy inefficient building; raised floor exposed to air; uninsulated and insulated slabs-on-grade; and uninsulated and insulated basements. The Tier 2 tests (Section 7.2.3) consist of the following additional elements related to passive solar design: variation in mass, glazing orientation, east and west shading, glazing area, and south overhang. The Section 7 test cases were developed in a more realistic residential context and have a more complex base building construction than the Section 5 test cases (which have more idealized and simplified construction for enhancement of diagnostic capability). To help avoid user input errors for the Section 7 test cases, the input for the test cases is simple, while remaining as close as possible to typical residential constructions and thermal and physical properties. Typical building descriptions and physical properties published by sources such as the National Association of Home Builders, the U.S. Department of Energy, ASHRAE, and the National Fenestration Rating Council are used for the Section 7 test cases.

Comparing Tested Results

The tests have a variety of uses, including

a. *comparing the predictions from other building energy programs to the example results provided in Informative Annexes B8 and B16 for Class I tests, Informative Annex B20 for Class II tests, and/or to other results that were generated using this SMOT;*

b. *checking a program against a previous version of itself after internal code modifications to ensure that only the intended changes actually resulted;*

c. *checking a program against itself after a single algorithmic change to understand the sensitivity between algorithms; and*

d. *diagnosing the algorithmic sources and other sources of prediction differences. (Diagnostic logic flow diagrams are included in Informative Annex B9.)*

Regarding the example simulation results provided for the comparative test results of selected parts of Annex B8, selected parts of Annex B16, and Annex B20, the building energy simulation 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, B16, and B20 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 sources 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

a. *user input error, where the user misinterpreted or incorrectly entered one or more program inputs;*

b. *inadequate or faulty documentation;*

c. *a problem with a particular algorithm in the program; or*

d. *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.

Informative (nonmandatory) Annex B22 provides an example procedure for establishing acceptance range criteria to assess annual or seasonal heating and cooling load results for software undergoing the Class II tests contained in Section 7. Inclusion of this example is intended to be illustrative only and does not imply in any way that results from software tests are required by Standard 140 to be within any specific limits. However, certifying or accrediting agencies using Section 7 may wish to adopt procedures for developing acceptance range criteria for tested software. Informative Annex B22 presents an example statistically based range setting methodology that may be useful for these purposes.

Importance of Analytical Solutions, Quasi-Analytical Solutions, and Verified Numerical Model Results

In general, it is difficult to develop analytical verification test cases, but such cases are extremely useful. Under the classification of "analytical verification," we define three types of test case solutions: "analytical solutions," "quasi-analytical solutions," and "verified numerical models." Analytical solutions represent a "mathematical truth standard," while quasi-analytical solutions and verified numerical models represent "secondary mathematical truth standards" (as described in Informative Annex B23, Section B23.1.1.2). For selected Class I test cases, Informative Annexes B16 and B8 provide analytical verification test results based on the above solution types, along with simulation results.

For analytical solutions, given the underlying simplified physical assumptions in the case definitions, there is a mathematically correct solution for each case. For quasi-analytical solutions, the assumptions can be somewhat more realistic; however, there is also the possibility for human interpretation to yield solutions that are slightly different but with a much smaller range of disagreement than results from different simulation programs. Verified numerical models allow even more realistic assumptions and cases but must be subjected to a rigorous screening procedure to minimize the possibility of errors. Verified numerical models are first compared to all available analytical solutions and then compared to each other for cases that do not have exact analytical solutions. Once verified, these numerical solutions can be used to test other models as implemented within whole-building energy simulation programs. The ground-coupled slab-on-grade heat transfer test cases of Section 5.2.4 utilize an analytical solution and verified numerical models to extend the analytical verification method beyond the constraints inherent in analytical solutions. All three types of analytical verification solutions provide a basis for greater diagnostic capability than the purely software-to-software comparative test method, and the verified numerical models allow more realistic boundary conditions to be used in the test cases than are possible with pure analytical solutions. See Informative Annex B23 for a more complete description of the analytical verification test methodology.

It is important to understand the difference between a "mathematical truth standard" and an "absolute truth standard." When applying mathematical truth standards, 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. For example a one-dimensional conduction model may be properly solved mathematically, but inappropriate where two-dimensional conduction dominates. By contrast, an "approximate truth standard" from an experiment tests both the solution process and the appropriateness of the model within experimental uncertainty. The ultimate or "absolute" validation truth standard would be comparison of simulation results with data from a perfectly performed empirical validation experiment, with all simulation inputs perfectly defined.

We include simulation results for the cases where analytical verification results (analytical, quasi-analytical, or verified *numerical model solutions) exist. This allows simulationists to compare their relative agreement (or disagreement) versus the analytical verification results to that for other simulation results. Perfect agreement among simulations and analytical verification results is not necessarily expected because sometimes simulations cannot perfectly match the specified simplifying assumptions or boundary conditions required for developing the analytical verification solutions. The provided results give an indication of the degree of agreement that is possible between simulation results and the analytical verification results. Therefore, a tested program may disagree with analytical verification solutions without necessarily being incorrect. However, it is worthwhile to investigate the sources of such differences, as noted previously.*

Supporting Files

The supporting electronic files to be used with Standard 140-2017 are called out as described in README-140-2017.docx, provided in the root folder of the accompanying files package. Accompanying files are organized by a separate file folder for each set of tests. Each of the test-set-specific file folders is further subdivided by separate subfolders for normative files and informative files. Normative files include weather data, output report templates, and equipment performance data (for those test cases that apply such data). Informative files include example results, example entries for documentation reports, and other supporting information. ***Electronic files can be downloaded online at http://www.ashrae.org/140-2017***.

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

adiabatic: without loss or gain of heat. ***Informative Note:*** For example, an adiabatic boundary does not allow heat to flow through it.

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

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

altitude: vertical elevation above sea level.

analytical solution: a mathematical solution of a model of reality that has an exact result for a given set of parameters and simplifying assumptions.

analytical verification: where outputs from a program, subroutine, algorithm, or software object are compared to results from a known analytical solution or to results from a set of closely agreeing quasi-analytical solutions or verified numerical models. (See *analytical solution*, *quasi-analytical solution*, and *verified numerical model*.)

annual heating load: the heating load for the entire one-year simulation period. ***Informative Note:*** For example, 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 floor conduction: the hourly floor conduction that represents the maximum for the final year of the simulation period; used for tests of Section 5.2.4.

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 integrated peak zone load: the hourly zone load that represents the maximum for the final year of the simulation period; used for tests of Section 5.2.4.

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

annual incident unshaded total solar radiation (diffuse and direct): the 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. ***Informative Note:*** For example, 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. ***Informative Note:*** For example, for hourly simulation programs, this is the average of the hourly zone air temperatures for the one-year simulation period.

annual sensible cooling load: the sensible cooling load for the entire one-year simulation period. ***Informative Note:*** For example, 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): the 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. ***Informative Note:*** 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. 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 (SHR) (ratio of sensible heat transfer to total [sensible + latent] heat transfer for a process). For the test cases of Section 5.3, SHR is calculated as SHR = (Gross sensible capacity)/(Gross total capacity). (See *sensible heat ratio*, *gross sensible capacity*, and *gross total capacity*.) ***Informative Note:*** The ADP is the temperature to which all the supply air would be cooled if 100% of the supply air contacted the coil.

aspect ratio (AR): the ratio of the floor slab length to the floor slab width.

building thermal envelope and fabric: elements of a building that enclose spaces and that control or regulate heat and mass transfer between the interior spaces and the building exterior, the internal thermal capacitance, and heat and mass transfer between internal zones.

bypass factor (BF): 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 *apparatus dew point*.)

cavity albedo: see *solar lost through window*.