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PNNL-33183

Building Performance Modeling Tools Physics and Sensitivity Testing in Support of Compliance Modeling

September 2022

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U.S. DEPARTMENT OF ENERGY

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Summary

Energy modeling is increasingly used to document compliance with energy codes and in beyond-code programs such as Leadership in Energy and Environmental Design (LEED), commercial tax deductions, and utility incentive programs. The ANSI/ASHRAE Standard 90.1 Performance Rating Method (PRM) is one of the most prominent[1] modeling protocols that may be used for both beyond-code programs and minimum code compliance. The PRM requires that building performance modeling (BPM) tools used to document compliance be tested using ANSI/ASHRAE Standard 140.[2]

The stated purpose of Standard 140 is to specify test procedures for evaluating the BPM software's technical capabilities and ranges of applicability. Historically, BPM software developers were the primary target audience of the standard and used it to test and diagnose potential issues in their tools. Support of compliance modeling is a distinctly different use case for the standard. Rating authorities and jurisdictions that administer modeling-based programs need a testing framework to gauge variations in the compliance outcomes between approved BPM software tools and to establish BPM software approval procedures that deliver acceptable consistency.

Currently, Standard 140 is limited to ***diagnostic unit tests*** that focus on the capabilities of the BPM software with respect to individual building systems and components, to help identify the impactful parameters and verify the related BPM software algorithms. The California Energy Commission (CEC) Title 24 Alternative Compliance Method (ACM) and the Residential Energy Services Network (RESNET) Home Energy Rating Standard (HERS) prescribe additional sensitivity and physics tests that capture typical systems, components, and designs of buildings in their scope. For example, CEC Title 24 physics tests include medium and large offices, medium retail, and a strip mall. These ***representative building tests*** help gauge variability in results at the whole building level and confirm that the BPM software supports the designs.

This report identifies gaps between systems and components covered by the current Standard 140 diagnostic unit test cases compared to the design elements common in the 90.1 PRM models. Such design elements were identified using the following criteria:

1. Systems found in the minimally code compliant designs were established based on configuration of U.S. Department of Energy and Pacific Northwest National Laboratory (PNNL) prototype models that represent the U.S. commercial building stock.
2. Systems included in the PRM baseline model were established based on the ASHRAE 90.1 Appendix G modeling rules.
3. Systems found in high-performance designs were established based on research studies, design guides, and experience from beyond-code programs.

The recommended new diagnostic unit tests were prioritized based on the percentage of U.S. commercial building stock floor area to which the design element applies, building types that are more commonly modeled, and the anticipated impact of the design element on the overall energy use and the compliance outcome

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[1] Performance-based Code Compliance: A Roadmap to Establishing Quality Control and Quality Assurance Infrastructure, PNNL 30824, April 2021, M. Karpman, M. Rosenberg.
[2] ANSI/ASHRAE Standard 140, Method of Test for Evaluating Building Performance Simulation Software.

Based on the gaps identified, this report recommends adding representative building tests to Standard 140, including the permutations of multifamily and medium office buildings that will be generally based on the corresponding PNNL prototype models. For each occupancy, the representative building tests will include a configuration representing the PRM baseline design, a minimally code-compliant design, and a high-performance design. The recommended diagnostic unit tests and representative building tests and their respective priorities are summarized in Table S.1.

Table S.1. Proposed New Standard 140 Tests

Focus of the New Test		High Priority	Medium Priority	Low Priority
Representative Building Tests				
Multifamily, PRM baseline		x		
Multifamily, minimally code compliant design		x		
Multifamily, high-performance design			x	
Medium office, PRM baseline		x		
Medium office, minimally code compliant design		x		
Medium office, high-performance design			x	
Diagnostic Unit Tests				
Interior daylighting		x		
Exterior daylighting				x
Comparative air-side HVAC tests (Air-side HVAC BESTEST Volume 2)		x		
Exhaust air energy recovery		x		
Air-side HVAC controls				
	Optimal start	x		
	Supply air temperature reset	x		
	Variable speed drives	x		
	Static pressure reset	x		
	Demand-controlled ventilation	x		
Air-side HVAC systems				
	Dedicated outdoor air system	x		
	Perimeter radiation		x	
	Variable air volume with parallel fan power boxes			x
	Radiant panels and chilled/cooled beams			x
Update HVAC BESTEST performance maps with empirical data		x		
Chiller plants				
	Air-cooled centrifugal and positive displacement	x		
	Water-cooled centrifugal and positive displacement		x	
	Heat recovery chillers			x
Hot water boilers		x		
Heat pumps				
	Air-source	x		
	Air-source VRF	x		
	Water-source		x	
	Water-source VRF			x
	Heat recovery VRF			x
	Ground source			x
Water-side HVAC controls and ancillary components				
	Hot water loop arrangement and controls (see Table 10)	x		
	Chilled water loop arrangement and controls (see Table 10)	x		
	Condenser loop arrangement and controls		x	
	Fluid economizers			x

Focus of the New Test		High Priority	Medium Priority	Low Priority
Service water heating				
	Storage water heaters		x	
	Heat pump water heaters		x	
	External storage tanks		x	
	Instantaneous water heaters		x	
	Condenser heat recovery			x
	Thermal solar water heater			x
Envelope				
	Skylights	x		
	Weather-driven infiltration and natural ventilation		x	
	Automatically controlled shades, dynamic and special glazing			x
Transformers				x
Weather data		x		
BESTEST is Building Energy Simulation Test; HVAC is heating, ventilation, and air conditioning; VRF is variable refrigerant flow.				

This report also describes a methodology for quantifying the overall rigor of the Standard 140 testing framework with respect to the PRM based on the breadth of coverage of systems and components relevant to the PRM model, alignment in the boundary conditions and simulation algorithms, and complexity of test cases. The methodology allows the improvement in Standard 140 support of the PRM to be gauged as new tests are added.

Acknowledgments

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Acronyms and Abbreviations

ACM	Alternative Compliance Method
AEDG	Advanced Energy Design Guide
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BESTEST	Building Energy Simulation Test
BPM	building performance modeling
CEC	California Energy Commission
CFM	cubic feet per minute
CHW	chilled water
COMNET	Commercial Energy Services Network
CV	constant-volume
CZ	climate zone
DCV	demand control ventilation
DOAS	dedicated outdoor air system
DOE	U.S. Department of Energy
DX	direct expansion
EPA	U.S. Environmental Protection Agency
FC	fan coil
ft	feet
HERS	Home Energy Rating System
HVAC	heating, ventilation, and air-conditioning
HW	hot water
LEED	Leadership in Energy and Environmental Design
NA	not applicable
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
PRM	Performance Rating Method
PFP	Parallel Fan-Powered
RESNET	Residential Energy Services Network
SWH	service water heating
SZ	single zone
VAV	variable air volume
VRF	variable refrigerant flow
ZE	Zero Energy

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1.0 Background

Energy modeling is increasingly being used to document compliance with energy codes and in beyond-code programs such as Leadership in Energy and Environmental Design (LEED), commercial tax deductions, and utility incentive programs. A fundamental premise of performance-based compliance is that the compliance outcome is driven by the merits of the building design and is largely independent of the building performance modeling (BPM) software used to perform energy modeling, so that using any approved BPM software for a given building design would produce a similar compliance outcome.

Compliance with ASHRAE Standard 90.1, following the Performance Rating Method (PRM) described in Appendix G of the standard, is based on the relative annual energy cost of the baseline vs. proposed design models. Both models are developed by applying the rules of 90.1 Appendix G to the building design being evaluated and may be created either manually by the modeler or automatically by the BPM software based on the manually created model of the building design.

The minimum capabilities of the BPM software tools that may be used for ASHRAE 90.1 Appendix G modeling are listed in 90.1 Section G2.2 and include performing simulations at an hourly timestep; capturing hourly variations in building operation; thermal mass effects and impact of operating conditions on the performance of heating, ventilation, and air conditioning (HVAC) equipment; ability to explicitly model systems and components included in the baseline design; and performing design load calculations, among other capabilities.

In addition, 90.1 Section G2.2.4 requires that the BPM software tools used to develop baseline and proposed design models be tested following Standard 140[1] (90.1 G2.2.4). The reference to Standard 140 is widely interpreted by rating authorities and jurisdictions administering application of the PRM for code compliance and beyond-code programs as a guarantee that the calculations performed by the compliant BPM software are vetted and correct. However, Standard 140 has impactful limitations with respect to the PRM.

Inconsistent compliance outcomes for a given building design modeled in different BPM software tools may be due to the following:

1. Differences in configuration of the models

   The misalignment may be due to modeler error for manually generated models, BPM software error for automatically generated models, or ambiguities in 90.1 requirements resulting in varying interpretations of the rules.

   ASHRAE Standard 229, Protocols for Evaluating Ruleset Implementation in Building Performance Modeling Software, aims to develop processes and tools for verifying that the PRM baseline and proposed design models are configured correctly based on the 90.1 requirements.

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

2. Differences in the simulation results produced by different BPM software tools for the same model configuration

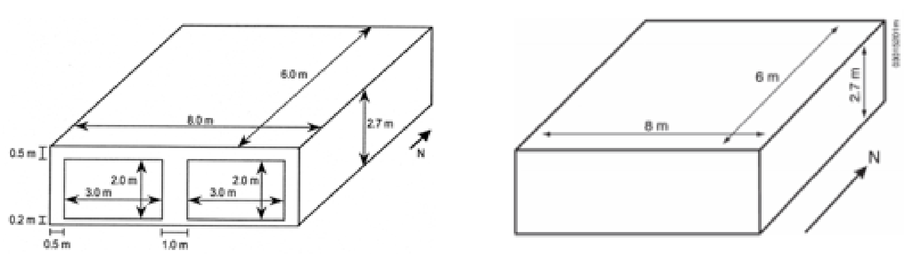
   Standard 140 is traditionally relied on by compliance modeling protocols – such as the California Energy Commission (CEC) Title 24 Alternative Compliance Method (ACM) and the Residential Energy Services Network (RESNET) Home Energy Rating Standard (HERS) – for confirming the technical integrity of BPM software physics calculations.

Software certification requirements of RESNET HERS and California ACM include physics and sensitivity tests in addition to Standard 140, suggesting that administrators of these programs considered the current scope of Standard 140 testing insufficient. This report evaluates physics and sensitivity testing needs of 90.1 PRM, compares them to the current scope of Standard 140, and recommends additional tests and acceptance procedures to address the gaps. The new tests and procedures may be included in Standard 140, Standard 229, or another appropriate standard or guidelines.

2.0 Overview of ASHRAE Standard 140 and Its Limitations with Respect to Compliance Modeling

The stated purpose of Standard 140 is to specify test procedures for evaluating the BPM software's technical capabilities and ranges of applicability. The standard is often compared to the Professional Engineer exam for simulation tools. Historically, BPM software developers were the primary target audience of the standard and used it to effectively isolate and diagnose potential issues in their tools.

Each suite of Standard 140 tests includes multiple permutations of a very simple base case. For example, the base case for comparative cooling system tests (CE300 series) is a near-adiabatic test cell with cooling load driven by the specified internal gains (Figure 1).



Case 600: Thermal envelope and fabrics loads base case

Case CE100: Cooling equipment tests base case

Figure 1. Envelope Geometry of Sample Standard 140 Test Cases

Permutations typically involve changing a single parameter, system, or component to isolate its impact on energy use. For example, test case CE410 is the same as test case CE400 except the economizer is integrated instead of non-integrated; case 610 is the same as case 600 but with an added overhang to help isolate the impact of shading. The evaluated simulation outputs are limited to the end uses being tested – for example, for the heating system tests, the annual heating energy use is compared across the tested software tools.

Rating authorities and jurisdictions that administer compliance modeling protocols such as the 90.1 PRM are a distinctly different user group from BPM software developers. The physics and sensitivity testing framework necessary for compliance modeling must allow gauging of variations in the compliance outcomes between approved BPM software tools to help establish the BPM software approval procedures that deliver acceptable consistency. The gaps in the current content of Standard 140 with respect to compliance modeling are described below.

1. **Many common systems and components found in commercial building designs regulated by Standard 90.1 are not addressed.**

   Since development of Standard 140 was not historically driven by the needs of Standard 90.1 compliance modeling, the existing Standard 140 tests do not support many of the systems and components found in typical commercial buildings, such as daylighting controls, heat pumps, boilers, chillers, and exhaust air energy recovery, among others.

2. **Standard 140 test cases are dramatically simpler than typical building designs modeled following 90.1 PRM.**

   The ***diagnostic unit tests*** included in Standard 140 focus on the BPM software capabilities with respect to individual building systems and components to help identify the impactful parameters and verify the related BPM software algorithms. The CEC ACM and RESNET HERS prescribe additional sensitivity and physics test that capture typical building systems, components, and designs included in their scope. For example, the CEC ACM physics tests include medium and large offices, medium retail, and strip mall (Figure 2). These ***representative building tests*** help gauge variability in results at the whole building level and confirm that the BPM software supports these designs.

3. **There is a misalignment between the level of modeling detail provided in Standard 140 test descriptions and the 90.1 PRM simulation requirements.**

   The scope of modeling inputs specified in Standard 140 for each test case reflects the details necessary for maximizing alignment in the results across the tested BPM software tools, as determined by the simulation trials performed as part of test development. However, many inputs prescribed in Standard 140 test cases are not addressed in the 90.1 PRM, which means that alignment in results among different BPM software tools achieved in Standard 140 testing is not representative of the alignment that would be seen on projects modeled following the PRM.

   In some cases, the PRM requires simulation methods different from those covered by Standard 140 tests. For example, envelope air leakage tests in Standard 140 are based on the fixed annual infiltration rate independent of wind speed, indoor/outdoor temperature difference, and other factors, while the PRM requires that infiltration be adjusted for weather and building operation. There is no evidence that the energy use predicted by these more complex methods is generally aligned among different simulation tools.

4. **Standard 140 does not provide pass/fail criteria to help facilitate BPM software acceptance.**

   Standard 140 does not currently provide the acceptance ranges that may be used to certify BPM software for various compliance modeling protocols. Developing such ranges was traditionally perceived as being outside of the standard's "method of test" purpose. In addition, there are concerns that having such ranges within Standard 140 would restrict advances in state-of-the-art physics calculations, as a BPM software tool that employs more accurate methods than the rest of the pack may be an outlier. As a result, based on the current 90.1 language (90.1 Section G2.2.4), any BPM software that is tested following Standard 140 and publishes results on a publicly available website meets 90.1 physics and sensitivity testing requirements irrespective of results.

   The Standard 90.1 and 140 committees formed a working group to develop a methodology for establishing the acceptance ranges based on the available test results. To avoid conflicts with the Standard 140 scope, the methodology may be included in Standard 140 but the actual acceptance ranges specified in Standard 90.1 or an alternative standard or guideline, such as Standard 229.

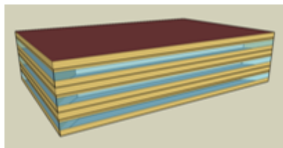
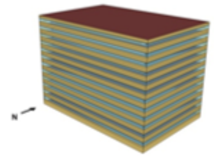
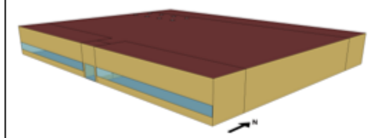
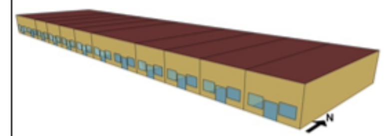
Prototype Description	**Medium Office Building (0300CZ-OffMed)**	**Large Office Building (0400CZ-OffLrg)**	**Retail Medium (0500CZ-RetlMed)**	**Strip Mall-PSZ System (1000CZ-RetlStrp)**
Vintage	New Construction	New Construction	New Construction	New Construction
Location	CZ-6/16	CZ-7/6/16	CZ-6/7/15	CZ-6/15
Fuel Type	gas, electricity	gas, electricity	gas, electricity	gas, electricity
Total Floor Area (sq feet)	53600 (163.8 ft x 109.2 ft)	498,600 (240 ft x 160 ft)	24695 (178 ft x 139 ft)	22,500 ft^2 (300 ft x 75 ft)
Building shape				

Figure 2. Envelope Geometry of California Title 24 Sensitivity Testing Base Cases

3.0 Study Objectives

This study provides recommendations for addressing the first three gaps described in the previous section: (1) lack of support for common systems and components found in commercial building designs, (2) base cases not representative of typical projects modeled following the PRM, and (3) misalignment in the level of detail provided in Standard 140 compared to the modeling inputs prescribed in the PRM. Since development of the acceptance criteria for Standard 140 tests is already underway, it is excluded from the scope of this study. The study focus areas are as follows:

1. Identify design elements common in the 90.1 PRM models that are not currently supported by Standard 140 tests.
2. Recommend new diagnostic unit tests to address the identified gaps and the order of priority for developing these tests.
3. Recommend the representative building tests reflecting typical building designs to complement the diagnostic unit tests.
4. Recommend a methodology for quantifying the rigor of the existing PRM sensitivity and physics testing framework to help understand the current status and set improvement goals.

Section 4.0 of this report identifies building systems and components included in the PRM baseline, typical designs that minimally comply with ASHRAE 90.1 2019, and high-performance designs and compares them to the systems addressed by Standard 140-2020 test cases. Section 4.0 is organized by system type with separate subsections dedicated to envelope, lighting, service water heating (SWH), HVAC, and miscellaneous other equipment. For each system type, new Standard 140 diagnostic unit tests are recommended as high, medium, or low priority based on their prevalence and perceived impact on compliance outcomes.

Section 5.0 assesses the rigor of the Standard 140 testing framework with respect to the PRM, accounting for degree of coverage of building systems and components common in PRM models by Standard 140 tests, alignment in tested algorithms and boundary conditions with the corresponding parameters in the PRM models, and whether unsupported systems have a high impact on the overall building energy use and PRM compliance outcomes. Quantifying the rigor of the physics and sensitivity testing framework helps gauge the current support of the 90.1 PRM by Standard 140 and informs prioritization of new tests.

Section 6.0 proposes representative building tests that may be added to Standard 140 to improve its support of the PRM. Recommendations for additional representative and unit tests, including their relative priorities, are found in Section 7.0.

4.0 Standard 140 Support of the Design Elements Common in the PRM Models

4.1 Methodology

The following methodology was used to identify design elements that are common in the PRM models, their prevalence, and degree of support by Standard 140.

1. Design elements common in the PRM models

The design elements included on projects that use the 90.1 PRM to document code compliance or above-code performance were established using the following criteria.

a. Systems and components common in the minimally code compliant designs

Prototype models (prototypes) from the U.S. Department of Energy (DOE) and Pacific Northwest National Laboratory (PNNL) were used to establish design elements found in common minimally code compliant designs. These prototypes represent 16 common building types, including midrise and high-rise multifamily, hospital, large and small hotels, large, medium, and small office buildings, outpatient healthcare, fast food, sit-down restaurant, standalone retail, strip mall, primary and secondary schools, and warehouse. Configuration of the prototypes, such as HVAC and SWH system types, wall types, window to wall ratio, and number of floors, was informed by the Commercial Building Energy Consumption Survey and research by PNNL and its subcontractors. The mechanical systems were additionally reviewed by the 90.1 mechanical subcommittee, which largely agreed that the HVAC systems reflected the standard practice except for the omission of the variable refrigerant heat pumps.

b. Systems and components included in the PRM baseline

Configuration of the baseline design is prescribed in the 90.1 PRM and is based on building occupancy type (e.g., residential, retail), building size including the floor area and number of stories, and climate zone (CZ). For example, all baseline designs have steel-framed exterior walls; residential spaces (apartments, hotel guest rooms, dormitory rooms, etc.) in the baseline are served by packaged terminal heat pumps for projects in CZs 0 – 3A and by packaged terminal air conditioners with hot water coil for all other locations. Systems and components included in the PRM baseline were established by applying the 90.1 Appendix G rules to each prototype.

c. Systems and components found in high-performance buildings

The following resources were used:

- ASHRAE Advanced Energy Design Guides, Achieving Zero Energy series[1] (AEDG ZE)

  The guides for K-12 school buildings and small to medium office buildings are the only two currently available.

[1] https://www.ashrae.org/technical-resources/aedgs/zero-energy-aedg-free-download

- ASHRAE Research Project 1651,[1] Development of Maximum Technically Achievable Energy Targets for Commercial Buildings

  This research project identified technologies that would result in the highest efficiency levels that are technically achievable now or in the near future (~2030).

- 90.1 Energy Credits proposal being developed by a working group that includes two representatives from each of the 90.1 subcommittees (envelope, lighting, mechanical, etc.)

  This proposal would require projects demonstrating minimum compliance with 90.1 to incorporate high-performance technologies selected from a menu of options.

- Experience of programs for high-performance buildings such as the Energy Star Multifamily Program from the U.S. Environmental Protection Agency (EPA)
- Building Innovation Multifamily[2] design guide by the New Buildings Institute

2. Design elements included in ASHRAE Standard 140–2017 physics and sensitivity tests

Physics and sensitivity tests described in ASHRAE Standard 140 were reviewed to understand their support of the design elements relevant to the PRM models as determined in the previous step. A design element was considered to be supported by Standard 140 if it was either explicitly included in the test cases or implicitly addressed via alternative elements or modeling inputs that rely on fundamentally similar physics algorithms.

For example, the prototypes include mass exterior walls, steel-framed walls, wood-framed walls, and metal buildings (steel-framed walls with metal skin). Standard 140 high-mass building envelope and fabric load tests (cases 900 – 960) explicitly address mass walls. It was considered that the low-mass tests (cases 600 – 650) address all other types of construction including wood- and steel-framed walls and walls in metal buildings. Similarly, lighting and miscellaneous equipment was considered to be addressed by Standard 140 by virtue of internal gains being included in the test cases, including verifying their impact on heating and cooling loads (test case 420).

3. Order of priority for developing the diagnostic unit tests for the design elements that are not currently supported by Standard 140

The priorities were informed by the following factors:

a. *The percentage of U.S. commercial building stock floor area to which the design element applies*

Progress Indicator Analysis[3] of ASHRAE Standard 90.1 conducted by PNNL for each new edition of 90.1 includes the percentage of U.S. building stock floor area represented by each of the 16 prototypes, along with the percentage of floor area in each climate zone for each prototype. In addition, PNNL has provided the new construction rates for different building types represented by the prototypes in U.S. climate zones. This information is included in Appendix A

[1] ASHRAE 1651-RP, Development of Maximum Technically Achievable Energy Targets for Commercial Buildings, J. Glazer https://www.techstreet.com/standards/rp-1651-development-of-maximum-technically-achievable-energy-targets-for-commercial-buildings?product_id=1911167#jumps

[2] https://newbuildings.org/product/multifamily-guide/

[3] https://www.energycodes.gov/sites/default/files/documents/2019EndUseTables.zip

of this report and was used to estimate the percentage of floor area to which the design elements identified in step 1 apply.

For example, following 90.1 Table G3.1, retail buildings two stories or less in CZs 0–3A must be modeled with package single zone heat pumps in the baseline. This baseline would apply to standalone retail and strip mall prototypes. Based on the new construction rates included in Appendix A of this report, the standalone retail prototype represents 10.94% of the U.S. commercial floor area, with 22.9% of it located in CZs 0-3A; the strip mall prototype represents 3.72% of the floor area, with 27.4% in CZs 0-3A. Thus, we may estimate that the PRM baseline for low-rise retail buildings applies to 10.94% × 22.9% + 3.72% × 27.4% = 3.52% of the U.S. commercial floor area. The high-rise multifamily prototype represents ~9.6% of the new construction floor area and has space conditioning provided by a water-source heat pump system. We can use this information to estimate the prevalence of water-source heat pumps in minimally code compliant designs.

b. *Building types that commonly use PRM for documenting the minimum code compliance or beyond-code performance*

Based on a compliance research and stakeholder survey conducted by DOE, PNNL, and the Northwest Energy Efficiency Alliance,[1] projects involving large office buildings, multifamily buildings, schools/universities, and hotels use the performance path more often than other building types.

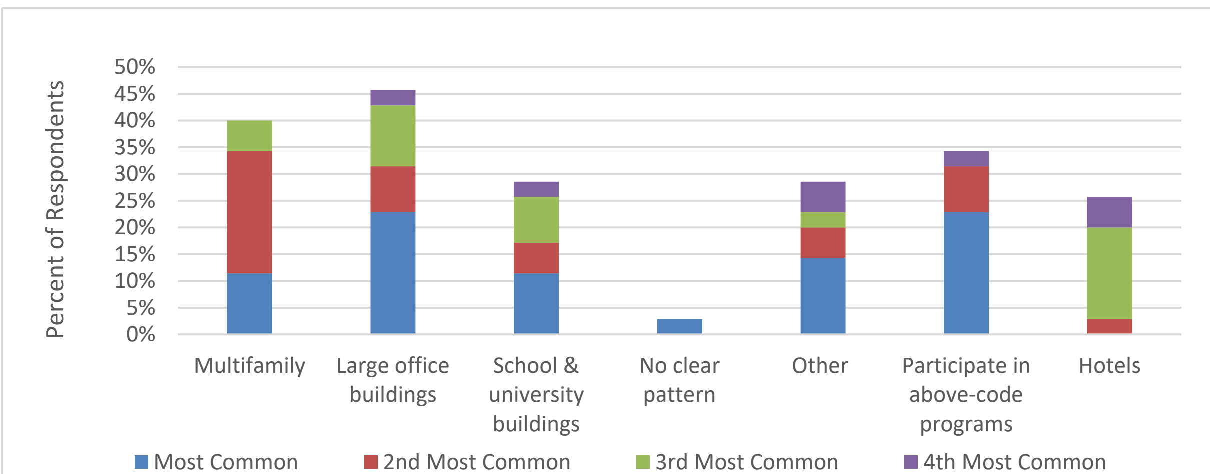


Figure 3. Types of Projects That Use Performance Path Most Often

c. *Anticipated impact of the design element on the compliance outcome*

The impact may be gauged based on the following factors:

- Magnitude of the affected end uses

  Figure 4 shows the contributions of the key end uses toward the overall annual site energy use and cost based on 90.1 2019 prototype models weighted by floor area of U.S. building stock represented by each prototype.

[1] Building Performance Modeling Tools Physics and Sensitivity Testing in Support of Compliance Modeling , M. Karpman, M. Rosenberg, December 2020

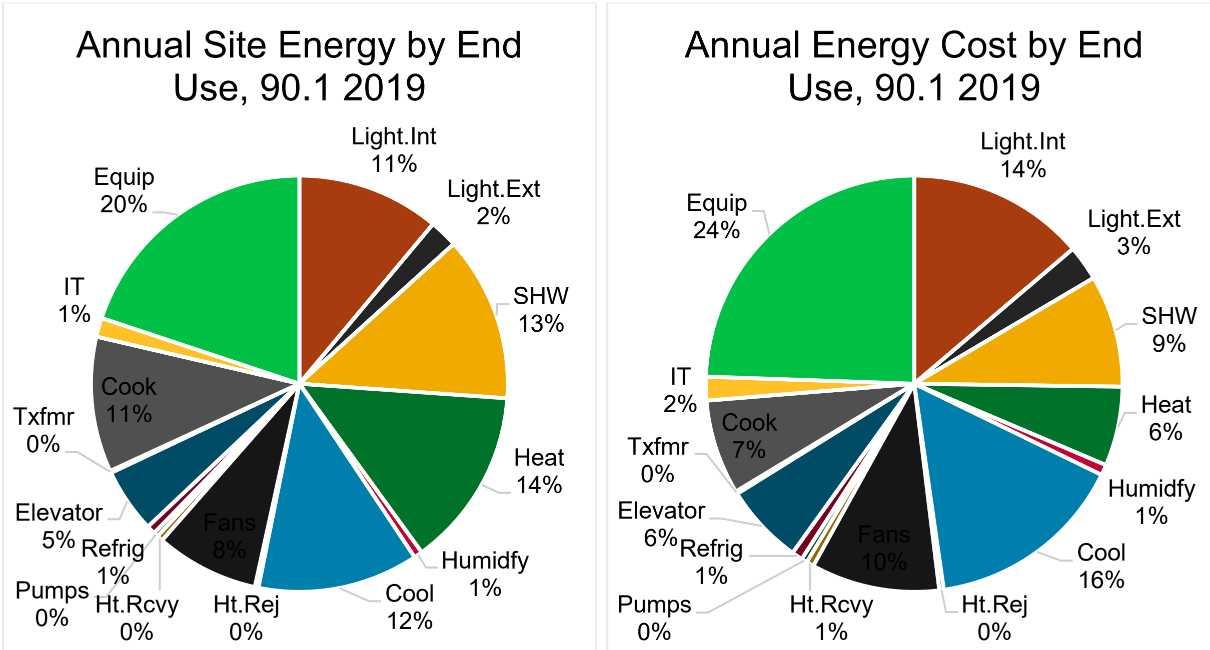


Figure 4. Contribution of Individual End Uses toward Annual Energy Use of 90.1 2019 Prototypes

- Change in stringency with respect to each end use between 90.1-2004 and the current edition of 90.1

  The PRM baseline is representative of a building design that is minimally compliant with Standard 90.1-2004. The proposed designs meet the mandatory provisions of the applicable edition of 90.1 (e.g., 90.1-2019 in jurisdictions that adopt it as the basis of the energy code) and typically also minimally comply with the prescriptive requirements, except for areas where performance tradeoffs are made. Figure 5 illustrates the change in annual site energy consumption of individual end uses between the 90.1 2004 and 2019 versions of the prototypes, which is somewhat representative of the performance tradeoffs that may be expected in the PRM baseline and proposed design models.

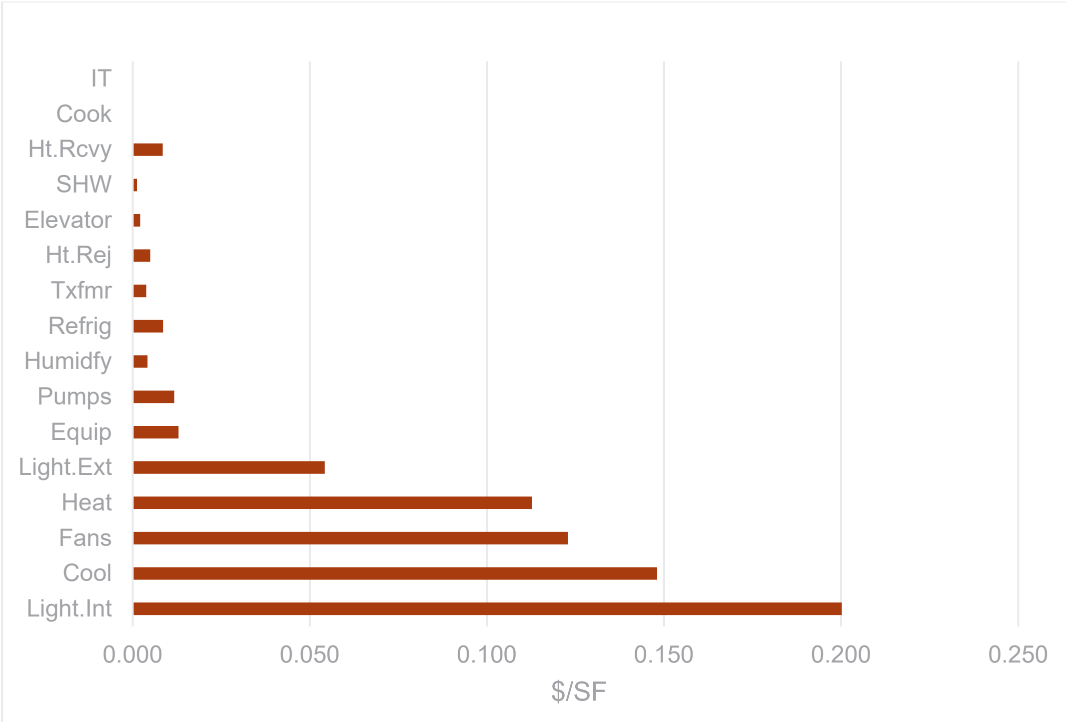


Figure 5. U.S. Average Weighted Annual Energy Cost Savings between 90.1-2004 and 90.1-2019

- Tradeoff opportunities allowed by the PRM

  Figure 5 illustrates that the impact of changes in 90.1 requirements applicable to systems and components offer additional tradeoff opportunities. For example, SWH savings shown in Figure 5 are minimal because SWH equipment efficiency requirements have remained substantially unchanged since 90.1-2004. However, the PRM allows projects to claim performance credit for water conservation measures such as low-flow plumbing fixtures, alternative sanitizing technologies, and preheating water using heat recovery technologies. As a result, projects that use the PRM to demonstrate code compliance or above-code performance often document substantial SWH savings.

- Common tradeoffs on PRM projects

  Experience suggests that common tradeoffs include lighting, fan energy, fenestration area, and economizers.

The sections below list common design elements applicable to building envelope, lighting, SWH, and HVAC. The tables included in each section use the following color-coding:

Design elements supported by existing Standard 140 tests
Design elements for which new tests are recommended as high priority
Design elements for which new tests are recommended as medium priority
Design elements for which new tests are recommended as low priority

4.2 Envelope

4.2.1 Relevant Standard 140 Tests

Standard 140 includes two classes of tests relevant to the building envelope. Class I tests are intended for use with building energy simulation software that has simulation time-steps of one hour or less. Class II test procedures may be used for all simulation tools regardless of time-step granularity.

Class I building thermal envelope and fabric load

The basic tests analyze the software's ability to model building envelope loads in a low-mass configuration with varying window orientation, shading devices, setback thermostat, and night ventilation. The base case is a low-mass, rectangular single zone with no interior partitions (Figure 6).

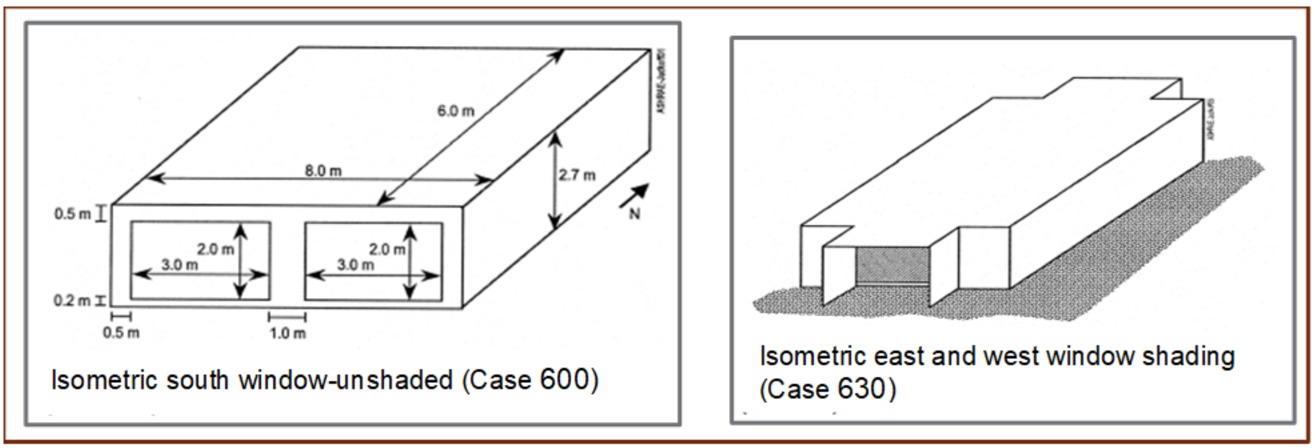


Figure 6. Class I Low Mass Base Case[1]

The following test cases are included:

- Low-mass basic tests (cases 600 – 650) utilize lightweight walls, floor, and roof (Standard 140 Section 5.2.2.1).
- The high-mass basic tests (cases 900 – 960) utilize masonry walls and concrete slab floor and include an additional configuration with a sunspace (Standard 140 Section 5.2.2.2).
- Free-float basic tests (cases 600FF, 650FF, 900FF, and 950FF) have no heating or cooling system and analyze the software's ability to model zone temperature in both low-mass and high-mass configurations with and without night ventilation (Standard 140 Section 5.2.2.3).

Class I building thermal envelope and fabric load in-depth tests

In-depth cases 195 through 320 analyze the ability of software to model building envelope loads for a non-deadband ON/OFF thermostat control. The parametric changes to the base case include no windows, opaque windows, exterior infrared emittance, interior infrared emittance, infiltration, internal gains, exterior shortwave absorptance, south solar gains, interior shortwave absorptance, window orientation, shading devices, and thermostat set points. In-depth cases

[1] Based on Standard 140 Figures 5-1 and 5-5.

395 through 440, 800, and 810 analyze the ability of software to model building envelope loads in a dead-band thermostat control. The parametric changes include no windows, opaque windows, infiltration, internal gains, exterior shortwave absorptance, south solar gains, interior shortwave absorptance, and thermal mass.

Class I ground-coupled slab-on-grade analytical verification tests

These tests are based on a steady-state base case (case GC30b) that has uninsulated slab-on-grade (slab interior surface level with exterior soil surface). Parametric variations include 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. The cases use steady-state and harmonic boundary conditions based on artificially constructed annual weather data and an adiabatic above-grade building envelope to isolate the effects of ground-coupled heat transfer.

Class II building thermal envelope and fabric load base case

The base case is a 1539-ft^2 single-story house with one conditioned zone (the main floor), an unconditioned attic, and a raised floor exposed to air (Figure 7).

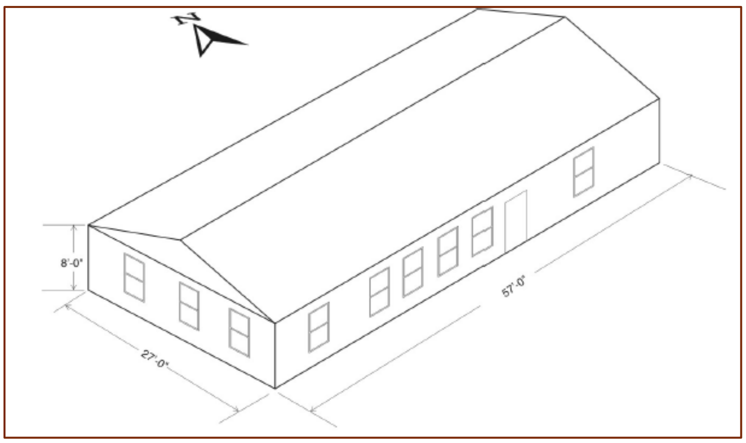


Figure 7. Class II Thermal Envelope and Fabric Load Base Case

The Tier 1 cases test the ability of software to model building envelope loads in the base case with the following variations: infiltration; wall and ceiling R-value; 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 slab-on-grade; uninsulated and insulated basement. The Tier 2 tests cover additional elements related to passive solar design, including variation in mass, glazing orientation, east and west shading, glazing area, and south overhang as applied to the base case that is generally representative of passive solar heating design.

4.2.2 Support of Common Envelope Design Elements by Standard 140

Table 1 provides envelope design components found in the PRM models and their support by the existing Standard 140 tests.

Table 1. Envelope Design Elements Common in the PRM Models and Their Support by Standard 140

Component	System/Component/ Controls Description	ASHRAE 140	ASHRAE 90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Roof	Insulation entirely above deck	Yes	1.00	0.76	Yes
	Metal building	Yes	0.00	0.19	Yes
	Attic and other	Yes	0.00	0.05	Yes
Above-grade Walls	Mass walls	Yes	0.00	0.24	Yes
	Metal building	Yes	0.00	0.19	No
	Steel framed walls	Yes	1.00	0.54	Yes
	Wood framed and other	Yes	0.00	0.04	Yes
Below-grade Walls	Below-grade walls	Yes	0.00	0.13	Yes
Exposed Floor	Mass	Yes	0.00	0.05	Yes
	Steel-Joist	Yes	1.00	0.00	Yes
	Wood-framed and Other	Yes	0.00	0.00	Yes
Foundation	Unheated	Yes	0.87	0.87	Yes
	Heated	No	0.00	0.00	Yes
	Basement	Yes	0.00	0.00	Yes
Opaque Doors	Swinging or non-swinging	Yes	0.00	0.00	No
Fenestration	Vertical	Yes	1.00	1.00	Yes
	Skylights	No	0.45	0.45	Yes
	Special glazing	No	0.00	0.00	Yes
	Automatically controlled dynamic glazing	No	0.00	0.00	No
Shading	Permanent exterior shading (fins, overhangs, and light shelves)	Yes	0.00	0.00	Yes
	Interior shading (shades and blinds)	No	0.00	0.00	Yes
	Automatically controlled fenestration shades or blinds	No	0.00	0.00	Yes
Infiltration	Infiltration	Yes	1.00	1.00	Yes
Exposure	Exposure	Yes	1.00	1.00	Yes

4.2.3 Recommended New Envelope Tests

1. Weather-driven infiltration[1]

90.1 PRM prescribes modeling air leakage of 0.6 cfm/ft^2 in the proposed design for projects that did not perform air-leakage testing, and the measured air-leakage rate for projects that were tests. Baseline air-leakage rate must be modeled at 1.0 CFM/ft^2. (The specified rates are per unit surface area of the envelope pressure boundary at 75 Pa.) Thus, all PRM projects model at least 40% reduction in air leakage rate in the proposed design vs. baseline. The PRM further requires that infiltration be modeled with adjustments for weather and HVAC system operation, including strategies intended to positively pressurize the building (90.1 Table G3.1 #5 and Section G3.1.1.4).

[1] According to Joel Neymark, prior IEA-34/43 work included in the 140 Prioritization Roadmap may be used as the starting point for these tests. In addition, 140-2017, Annex B23, Section B23.2 briefly describes work on validation tests that may be considered for 140.

Infiltration is included in many Standard 140 tests; however, all tests are based on the constant air leakage rate independent of weather. The new tests may be similar to cases 230 and 410 but cover weather-driven infiltration to verify alignment in simulation results between different tools and identify additional simulation inputs that may need to be prescribed in the PRM.

2. Skylights

90.1 2019 requires skylights in most spaces located directly under a roof, such as offices, corridors, and storage rooms, in buildings over 2,500 ft^2. The new tests may be similar to the existing tests for vertical fenestration in low- and high-mass construction (600 and 900 series). Testing scope should include sensitivity to skylight solar and thermal properties, orientation, and shading. Outputs should include heating and cooling energy use.

The new tests would be similar to the existing tests for vertical fenestration in low- and high-mass constructions (600 and 900 series). Testing scope should include sensitivity to skylight solar and thermal properties, orientation, and shading. Outputs should include heating and cooling energy use. Priority for adding skylights is lower than weather-driven infiltration because the physics of angular-dependent optical properties and shading are covered by vertical orientation.

3. Automatically controlled fenestration shades or blinds

The PRM allows performance credit for automatically controlled fenestration shades and blinds (Table G3.1 #5 (a) 4, proposed column). Examples include automated louvers described in AEDG ZE.

4. Special glazing

Special glazing is recommended in AEDG ZE and includes shading, filtering, or reflecting materials integrated into the glazing to reject excessive solar gain. Examples of available technologies include glazing that employs special coatings with selective transmission, and opaque elements integral to the glazing, such as fritted patterns, fiber-fill, aerogel, or blinds-between-glazing panels. 140-2020 Test 670 includes low-e glass.

5. Automatically controlled dynamic glazing

Dynamic glazing can change its tint to respond to real-time solar conditions, which allows the energy performance and glare control to be optimized throughout the day, month, and season, and at different elevations. The technology is recommended in AEDG ZE.

4.3 Lighting

4.3.1 Relevant Standard 140 Tests

Lighting fixtures and controls directly contribute to building electricity use and also interact with space heating and cooling. There are no explicit lighting system tests in Standard 140; however, most existing tests include internal loads, and several tests (e.g., 240, 420) evaluate the sensitivity of heating and cooling energy use to internal gains.

4.3.2 Support of Common Lighting Design Elements by Standard 140

Table 2 lists lighting design components found in PRM models and their support by Standard 140. PRM models commonly include lighting power reduction between baseline and proposed design due to reduced lighting wattage and occupancy sensors, which are modeled by adjusting the hourly lighting schedule by a specified factor (90.1 Table G3.7). Thus, existing Standard 140 tests effectively cover both lighting power and occupancy sensors. Similar considerations apply to exterior lighting power and timers. Daylighting is not currently addressed by Standard 140.

Table 2. Lighting Design Elements Common in PRM Models and Their Support by Standard 140

Component	System/Component/Controls Description	ASHRAE 140	ASHRAE 90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Interior Lighting	Interior lighting power	Yes	1.00	1.00	Yes
	Daylighting	No	0.00	1.00	Yes
	Occupancy sensors	Yes	1.00	1.00	Yes
Exterior Lighting	Exterior lighting power	Yes	1.00	1.00	Yes
	Daylighting	No	1.00	1.00	Yes
	Timer	Yes	0.00	1.00	Yes

4.3.3 Recommended New Lighting Tests

1. Interior daylighting controls

Daylighting is never modeled in the PRM baseline. Starting with 90.1 2013, daylighting is mandatory for the majority of spaces with fenestration, with residential spaces such as dwelling units being the most notable exception. As a result, savings from daylighting affect compliance outcomes for the overwhelming majority of PRM models. Interior lighting is among the most impactful end uses in the 90.1 2019 prototypes, contributing 11% to 14% of the total annual use (Figure 4). It is also the largest contributor to energy savings of the 90.1 2019-compliant prototypes vs. 2004-compliant configurations (Figure 5). 1651-RP lists the optimal daylighting control and daylighting control by fixture among the top 30 measures, and recommends external light shelves that allow daylight to penetrate deeper into the zone than windows without shelves. Adding physics and sensitivity tests for interior daylighting is a high priority.

The tests should include sensitivity to fenestration area, visible transmittance, shading and orientation of the vertical fenestration and skylights, required illuminance, and type of daylighting controls (e.g., stepped control vs. continuous dimming).

2. Exterior daylighting controls

Daylighting controls on exterior fixtures are mandatory and, following the PRM rules, must be modeled for both the baseline and proposed design. Since the baseline and proposed design typically have significantly different exterior lighting power, daylighting controls result in different kilowatt-hour savings in the baseline vs. proposed design. Overall, the impact of exterior daylighting on the compliance outcome is expected to be much less than that of interior daylighting controls, so adding these tests is a low priority.

4.4 Service Water Heating

4.4.1 Support of Common SWH Systems by Standard 140

Standard 140 does not include tests for service hot water heating system design elements. Table 3 shows SWH systems and components applicable to the PRM baseline minimally code compliant and high-performance designs.

Table 3. SWH Design Elements Common in PRM Models and Their Support by Standard 140

Component	System/Component/Controls Description	ASHRAE 140	ASHRAE 90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Water Heater Type	Gas storage water heater	No	0.54	0.60	Yes
	Electric resistance storage water heater	No	0.46	0.40	Yes
	Electric resistance instantaneous water heater	No	0.00	0.00	Yes
	Heat pump water heater	No	0.00	0.00	Yes
	Gas instantaneous water heater	No	0.00	0.00	Yes
	Hot water boiler	No	0.00	0.00	Yes
	Solar thermal	No	0.00	0.00	Yes
	Combined space heating and water heating	No	0.00	0.00	Yes
	Electric booster	No	0.00	0.25	No
	External SWH storage tank	No	0.00	0.00	Yes
	SHW demand	No	1.00	1.00	Yes
Distribution System	SWH distribution system	No	0.00	1.00	Yes
	SWH recirculation pumps	Yes	0.02	0.02	Yes
SWH Heat Recovery	Condenser heat recovery	No	0.05	0.05	Yes
	Hot water (HW) preheat	No	0.00	0.00	Yes

Recirculation pumps are used to ensure prompt availability of hot water at the end use and are common in large hotels and multifamily buildings with central service hot water systems. SWH recirculation pumps are shown as addressed by Standard 140 because their energy use is typically modeled as an externally calculated electricity load, making them analogous to internal loads, which Standard 140 does cover. The need for recirculation is caused by water cooling down in the distribution system; since the PRM requires that the piping losses be ignored (Table G3.1 #11 (i), baseline column), a more accurate physics model of recirculation pumps is not necessary. The PRM requires that modeling of recirculation pumps be the same for the baseline and proposed designs (Table G3.1 #11 (f), baseline column).

4.4.2 Recommended New SWH Tests

PRM rules allow performance credit for reduction in hot water use due to low-flow plumbing fixtures, service hot water preheat or alternative sanitizing technologies (90.1 Table G3.1 #11). In addition, baseline SWH system type and fuel are prescribed based on building occupancy and are often different from the SWH type and fuel specified in the proposed design. For example, all office buildings are modeled with a central electric resistance storage water heater in the baseline, while the proposed design may have a different type of heater such as a central gas water heater or an instantaneous electric heater.

The 64 multifamily projects that participated in the EPA Energy Star Multifamily Program and were modeled following various editions of 90.1 PRM showed a 37% average reduction in SWH energy use for the proposed design relative to the baseline, with SWH accounting for an average of 23% of site energy use. The following SWH tests are recommended for Standard 140, in order of priority.

1. **Storage water heater (electric resistance and gas)**

The PRM baseline prescribes modeling of central electric water heaters for building types where SWH loads are typically not very high (e.g., offices and warehouses) and central storage gas water heaters for other building types. Central storage water heaters are also common in the minimally code compliant building designs based on the PNNL prototype models and are included among recommended technologies in AEDG ZE series. The 90.1 Energy Credits proposal includes fossil fuel water heaters with a minimum efficiency of 95% Et or 0.95 EF. Tests should include sensitivity of water heating energy use to equipment thermal efficiency, standby loss, storage volume, storage tank insulation, temperature of the water entering the heater and leaving the heater, and volume of hot water used. These permutations would implicitly cover technologies that reduce hot water demand, such as low-flow fixtures and service hot water preheat.

2. **Heat pump water heater**

Heat pump water heaters are recommended in AEDG ZE and in the New Buildings Institute multifamily design guide. 1651-RP lists them among systems likely to provide substantial additional savings. They are also included in the 90.1 Energy Credits proposal.

3. **Hot water boiler (atmospheric, forced draft, condensing)**

Dedicated hot water boilers with storage tanks are common on projects participating in the EPA Energy Star Multifamily Projects. Such systems may be addressed by test cases for space heating boiler with prescribed load schedule.

4. **External SWH storage tank**

Test cases involving external storage tanks will help capture performance tradeoffs of central systems with large storage capacity vs. instantaneous water heaters.

5. **Instantaneous water heaters (electric resistance and gas)**

Instantaneous water heaters are recommended in AEDG ZE and may be more efficient compared to central systems due to reduced distribution losses and parasitic loads such as those from recirculation pumps.

6. **Condenser heat recovery**

Condenser heat recovery is included in the PRM baseline for large, non-residential 24-hour-per-day facilities with the total installed heat-rejection capacity of the water-cooled systems exceeding 6,000,000 Btu/h of heat rejection and design SWH load exceeding 1,000,000 Btu/h (Table G3.1 #11 (d), baseline column). The requirement is not commonly triggered, and there is an exception in the PRM that allows projects to not model condenser heat recovery if they can demonstrate compliance with the requirement prescriptively.

7. Solar thermal water heater

Use of solar thermal water heaters is a best practice recommended in the New Buildings Institute multifamily guide. According to the guide, these heaters are not able to fully meet the SWH load in most buildings but are effective for pre-heating water or addressing partial loads, such as laundry.

8. Combined space and service water heating

Such systems are not uncommon on multifamily projects participating in the EPA Energy Star Multifamily Program. The configuration may be essentially addressed by combining tests for space heating boiler operation at a range of part loads, and tests for external SWH storage tank.

4.5 Miscellaneous Other Equipment

This category includes plug loads (e.g., kitchen appliances, consumer electronics); loads from commercial and industrial equipment such as office computers, servers, supermarket refrigeration, and commercial kitchen equipment; and non-HVAC motors such as booster pumps to maintain service water pressure in tall buildings.

Combined, these systems contribute more to the energy use and cost intensity than any other end use (Figure 4). The PRM prescribes the baseline for elevators (Table G3.1 #6), refrigeration equipment rated following AHRI 1200 (Table G3.1 #17), and non-HVAC motors regulated by 90.1 (Table G3.1 #12). Since the baseline is less efficient than the mandatory requirements of the current edition of 90.1, all projects that have this equipment model it at higher efficiency levels than the baseline. The majority of other systems in this category are unregulated and must be modeled identically in the baseline and proposed designs on projects documenting minimum compliance with energy code (Table G3.1 #12). Tradeoffs are allowed on projects demonstrating beyond-code performance if approved by the rating authority. For example, the EPA Energy Star Multifamily Program allows performance credit for major appliances that are Energy Star (e.g., refrigerators, clothes washers).

The energy impact of both regulated systems (non-HVAC motors, refrigeration, elevators) and unregulated systems (e.g. office IT, kitchen appliances, miscellaneous plug loads) is typically captured by performing an external analysis to determine equivalent load (kW) and schedule for the baseline and proposed designs, and incorporating these inputs into energy simulation. Similar to lighting, these systems consume electricity or gas directly and also generate sensible and latent heat gains that interact with heating and cooling. While there are no dedicated tests for such systems in Standard 140, they are largely addressed by physics and sensitivity tests that include internal loads and heat gains (e.g., 240, 420). Table 4 summarizes the design elements included in this category.

Table 4. Miscellaneous Other Elements Common in PRM Models and Their Support by Standard 140

Component	System/Component/Controls Description	ASHRAE 140	ASHRAE 90.1 PRM	Prototype Models	High Performance
Non-HVAC Motors	Non-HVAC motors	Yes	0.53	0.53	Yes
Receptacle	Plug loads	Yes	1.00	1.00	Yes
	Controls	Yes	0.00	0.42	Yes
Elevator/Escalators	Elevator motor	Yes	0.57	0.57	Yes
Refrigeration	Refrigeration systems	Yes	0.26	0.26	No
Transformers	Dry type	No	0.00	0.00	Yes
	Liquid filled	No	0.00	0.00	No

4.5.1 Recommended New Miscellaneous Other Equipment Tests

1. Dry-type transformers

The PRM requires that low-voltage dry-type distribution transformers be modeled only if transformers in the proposed design exceed the minimum efficiency prescribed in 90.1 (Table G3.1 #15). If modeled, the baseline transformer efficiency is based on the minimum required in 90.1 Table 8.4.4, and the proposed efficiency must be modeled as specified. While transformers are included in several prototype models, their prevalence is shown as 0 for both the PRM baseline and minimally code compliant designs to reflect that the PRM requires that minimally code compliant transformers be excluded from modeling. High-performance transformers are not commonly included in PRM models based on author's experience. However, they are discussed in AEDG ZE and included as one of top 30 measures in 1651-RP. Including test cases for transformers is recommended but is a low priority.

4.6 Cooling Equipment

4.6.1 Relevant Standard 140 Tests

Space-cooling equipment performance analytical verification tests (140 Section 5.3.2)

The base-case (case CE100) building is a near-adiabatic rectangular single zone with only user-specified internal gains to drive steady-state cooling load. Mechanical equipment represents a simple split-system air-cooled condensing unit with an indoor evaporator coil. Equipment performance is modeled using a performance map. Parameters modified in the steady-state sensitivity tests (cases CE110 – CE200) include sensible internal gains, latent internal gains, zone thermostat set point (entering dry-bulb temperature), and outdoor dry-bulb temperature. The tests isolate the influence of the part-loading of equipment, varying sensible heat ratio, dry coil (no latent load) vs. wet coil (with dehumidification) operation, and operation at typical AHRI rating conditions. These variations allow testing of the models in various domains of the performance map.

Space-cooling equipment performance comparative tests (140 Sections 5.3.3 – 5.3.4)

The base case (case CE300) is a near-adiabatic, rectangular single zone with user-specified internal gains and outdoor air to drive dynamic loads. The cases apply realistic, hourly varying annual weather data for a hot and humid climate. The mechanical system is similar to that used in the analytical tests except that it is a larger system and includes an expanded performance data set covering a wider range of operating conditions (outdoor dry-bulb, entering dry-bulb, and entering wet-bulb temperatures). Also, an air-mixing system is added to test the outdoor air mixing and integrated vs. non-integrated outdoor dry-bulb / indoor dry-bulb economizer.

The following parameters are varied in the sensitivity tests (cases CE310 – CE545): sensible internal gains, latent internal gains, infiltration rate, outdoor air fraction, thermostat set points, and economizer control settings (economizer dry bulb temperature or enthalpy differential / non-differential, and integrated vs. non-integrated control). Analysis of results also isolates the influence of part loading of equipment, outdoor dry-bulb sensitivity, and dry coil (no latent load) vs. wet coil (with dehumidification) operation. These cases help scale the significance of disagreements in simulation results for a realistic context, which is less obvious in the steady-state cases.

4.6.2 Support of Common Cooling Systems by Standard 140

Table 5 illustrates the prevalence of space cooling methods including chilled water (CHW), direct expansion (DX) including cooling-only systems and heat pumps, and evaporative cooling, and the relative occurrence of water-cooled vs. air-cooled condensers for CHW systems. It is assumed that Standard 140 space-cooling equipment performance tests (CE300 series) address cooling provided by both cooling-only and heat pump systems. The recommended new cooling systems tests are included in the following section in order of priority.

Table 5. Space Cooling

Component	System/Component/ Controls Description	ASHRAE 140	ASHRAE 90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Cooling Source	Chilled water	No	0.19	0.24	Yes
	DX	Yes	0.81	0.91	Yes
	Evaporative	No	0.00	0.00	Yes
Chiller Type	Centrifugal	No	0.04	0.04	Yes
	Positive displacement (reciprocating, scroll and screw)	No	0.18	0.24	Yes
	Absorption chiller	No	0.00	0.00	No
	Gas engine driven chiller	No	0.00	0.00	No
	Heat pump chiller	No	0.00	0.00	No
	Heat recovery chiller	No	0.00	0.05	Yes
Chilled Water Condenser Type	Air-cooled	No	0.00	0.15	Yes
	Water-cooled	No	0.19	0.08	Yes
Other	Cooling tower	No	0.19	0.18	No
	Fluid economizer	No	0.00	0.08	Yes

4.6.3 Recommended cooling system tests

1. Air-cooled centrifugal and positive displacement chillers

Chillers are included in the PRM baseline for all nonresidential buildings that are over five stories or have a floor area greater than 150,000 ft^2, public assembly buildings over 120,000 ft^2 (90.1 Table G3.1.1-3), and in buildings with high IT loads (90.1 G3.1.1 g). Based on Table 5, 19% of the new construction floor area has chillers in the baseline; however, the prevalence of such systems in the PRM baseline models is likely higher because large buildings use PRM more often than smaller ones (Figure 3). Water-cooled screw chillers must be modeled in the baseline for projects with a cooling load below 600 tons; water-cooled centrifugal chillers must be modeled for projects with a higher cooling load.

Chillers are also common in minimally code compliant designs and are included in the hospital, large hotel, large office, and secondary school prototypes. Even though, based on the available data, water-cooled chillers are more common than air-cooled chillers in the PRM models, air-cooled chillers are recommended as the first priority for additional tests because they involve fewer components (e.g., there is no heat rejection equipment) and thus would be easier to implement.

2. Water-cooled centrifugal and positive displacement chillers

Based on the available data, water-cooled chillers are more common than air-cooled and are also included in the PRM baseline. The PRM baseline for CHW systems includes an axial-fan open-circuit cooling tower with variable speed fan control (G3.1.3.11). The relevant test suite should cover heat-rejection equipment.

3. Fluid economizers

Fluid economizers must be modeled in the PRM baseline for CHW systems in buildings with high IT loads. They are also included in the hospital and large office prototypes.

4. Heat recovery chillers

Heat recovery chillers are recommended in AEDG ZE for buildings in cooling-dominated climates (CZs 1-2), where they may be more cost effective than a central boiler. 1651-RP listed heat recovery chillers as one of 10 measures with the highest impact on site energy use for hospitals, large hotels, large office buildings, and secondary schools.

4.7 Heating Equipment

4.7.1 Relevant Standard 140 Tests

Space-heating equipment performance analytical verification tests (140 Section 5.4.2)

The base-case (case HE100) building is a rectangular single zone that is near-adiabatic on five faces with one heat exchange surface (the roof) (Figure 8). Mechanical equipment specifications represent a simple unitary fuel-fired furnace with a circulating fan and a draft fan. Equipment performance is modeled using the performance maps (140 Section 5.4.1).

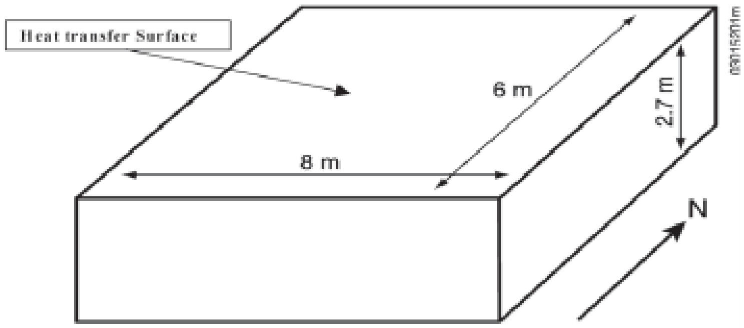


Figure 8. Space Heating Base Case[1]

Sensitivity tests (cases HE110 – HE170) include variations in efficiency, weather (resulting in different load conditions from full load to part load to no load to time-varying load), circulating fan operation, and draft fan operation. This allows testing of the models' basic functionalities in various domains of the performance map.

Space-heating equipment performance comparative tests (140 Section 5.4.3)

In these cases (cases HE210 – HE230), weather (using realistic temperature conditions), thermostat control strategy, and furnace size (undersized furnace) are modified to test performance at more realistic conditions in various domains of the performance map. These cases also test the interactions between furnace, control, and zone models.

4.7.2 Heating Systems

Table 6 illustrates the prevalence of space heating methods, including hot water, electric resistance, heat pumps, and fossil fuel furnaces. The prevalence of different types of boilers that may be used to generate hot water is included in the Boiler Type row of the table. The Heat Pump Type row illustrates the prevalence of different types of heat pumps.

Only furnaces are explicitly addressed in the Standard 140 tests (HE200 series); however, electric resistance heating is also indicated as covered in Table 6 as it is effectively covered by furnace tests as well as all other tests that evaluate heating load. The recommended new heating systems tests are included in the following section in order of priority.

[1] Based on Standard 140 Figure 5-20.

Table 6. Space Heating

Component	System/Component/Controls Description	ASHRAE 140	ASHRAE 90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Heating Source	Hot water	No	0.46	0.41	Yes
	Electric resistance	No	0.08	0.07	Yes
	Heat pump	No	0.18	0.13	Yes
	Furnace	Yes	0.75	0.74	Yes
Boiler Type	Natural (i.e., atmospheric)	No	0.46	0.00	No
	Forced draft	No	0.00	0.41	No
	Condensing	No	0.00	0.00	Yes
Heat Pump Type	Water source heat pump	No	0.00	0.10	Yes
	Variable refrigerant flow heat pump	No	0.00	0.00	Yes
	Ground-source heat pumps	No	0.00	0.00	Yes
	Air source heat pump	No	0.18	0.00	Yes

4.7.3 Recommended Heating System Tests

1. Hot water boilers

Atmospheric hot water boilers are included in the PRM baseline for residential (multifamily, dormitory, hotels) buildings and for non-residential buildings that have more than three stories or more than 25,000 ft^2 of floor area and are located in heating-dominated climates (any climate zone other than 0-3A). Forty-one percent of the prototypes include forced draft space heating boilers. Most of the HVAC system types recommended in AEDG NZ include condensing boilers as either the primary heat source or for backup heat. Thus, the new tests should cover natural draft, forced draft, and condensing boilers, and at minimum include the impact of part load and return water temperature on annual heating energy use.

2. Standard air-source heat pump

Air-source heat pumps are included in the PRM baseline for buildings located in cooling-dominated climates, including residential buildings, which must be modeled with package terminal heat pumps, and public assembly buildings less than 120,000 ft^2 or other non-residential buildings less than 25,000 ft^2, which must be modeled with package rooftop heat pumps.

3. Air-source variable refrigerant flow (VRF) heat pumps

VRF heat pumps are not included in either the PRM baseline or the prototypes. However, they are widely used in modern building designs, and their exclusion from the prototypes was noted as a misrepresentation of the standard practice by the 90.1 mechanical subcommittee. VRF is among the system types recommended by AEDG ZE and is one of the HVAC heating performance improvement options considered in the 90.1 Energy Credits proposal. It is also one of the top 30 measures identified by 1651-RP, which also found that systems with air-cooled condensers are more frequently described in the literature than water-cooled condensers. Adding support of air-source VRF heat pumps to Standard 140 is the first priority.

4. Water-source heat pumps

Water-source heat pumps are included in the high-rise apartment prototype and are one of the system types recommended in AEDG ZE.

5. Water-source VRF heat pumps and heat recovery VRF

Water-cooled VRF systems are less common than air-source VRF but deliver higher efficiency. Heat recovery VRF can simultaneously provide heating and cooling to different zones, depending on the load.

6. Ground-source heat pumps

Ground-source heat pumps are among the systems recommended in AEDG ZE. 1651-RP listed ground-source heat pumps as one of 10 measures with the highest impact on site energy use.

4.8 Air Distribution

4.8.1 Relevant Standard 140 Tests

Air-side HVAC equipment analytical verification tests (140 Section 5.5)

These tests verify the ability of BPM software to model HVAC air distribution system equipment. The cases complement the cooling and heating equipment tests described above. In all air distribution tests, airflow through ducts, coils, and dampers is presumed frictionless such that there are no pressure drops through these components. In addition, HVAC system components, including ducts, mixing boxes, dampers, fans, and coils, are assumed to have no air leakage and no heat exchange (gains or losses) with their external surroundings. Four system types are tested, as described below.

Four-pipe fan-coil (FC) system (140 Section 5.5.1).

A FC system is a single-zone system with heating and cooling coils, zone air exhaust, limited outdoor air (no economizer control), and no return air fan (Figure 9). The tests include three sets of steady-state outdoor and zone conditions in heating, dry-coil cooling, and wet-coil cooling modes. The model is run at specified constant outdoor and indoor conditions. The zone is defined by specifying an ideal steady-state sensible heating load and latent load. The zone sensible heating load may be modeled directly or as negative sensible internal gains within an adiabatic zone. Zone-prescribed latent load can be modeled directly or by specifying the number of occupants in a zone and the latent load per person.

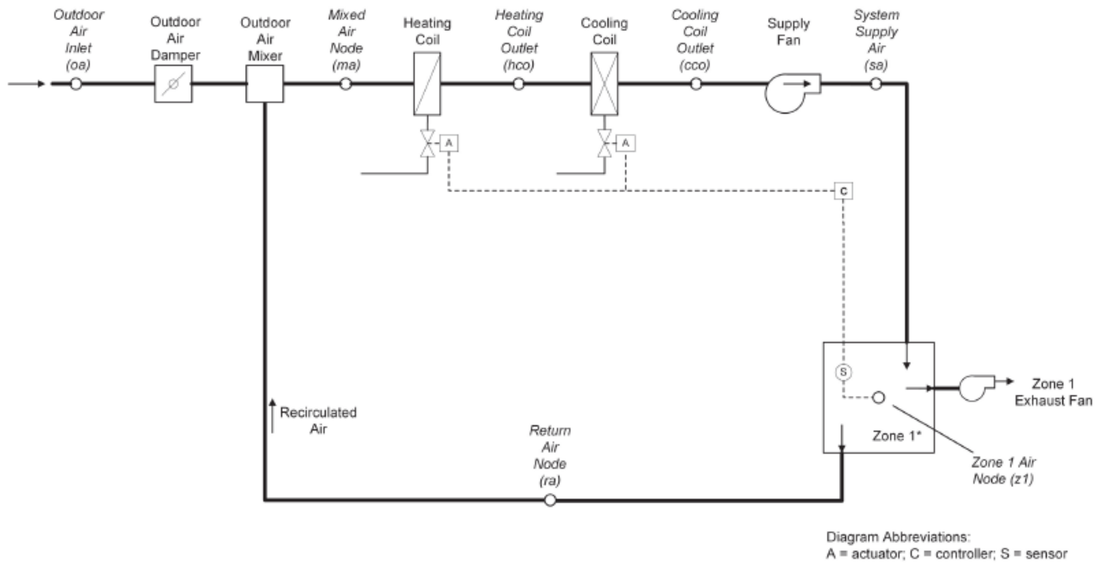


Figure 9. Four-Pipe Fan Coil Schematic[1]

Single-zone (SZ) system (140 Section 5.5.2)

The SZ system is based on the FC system but adds a return air fan and economizer (Figure 10). The SZ system tests include five 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.

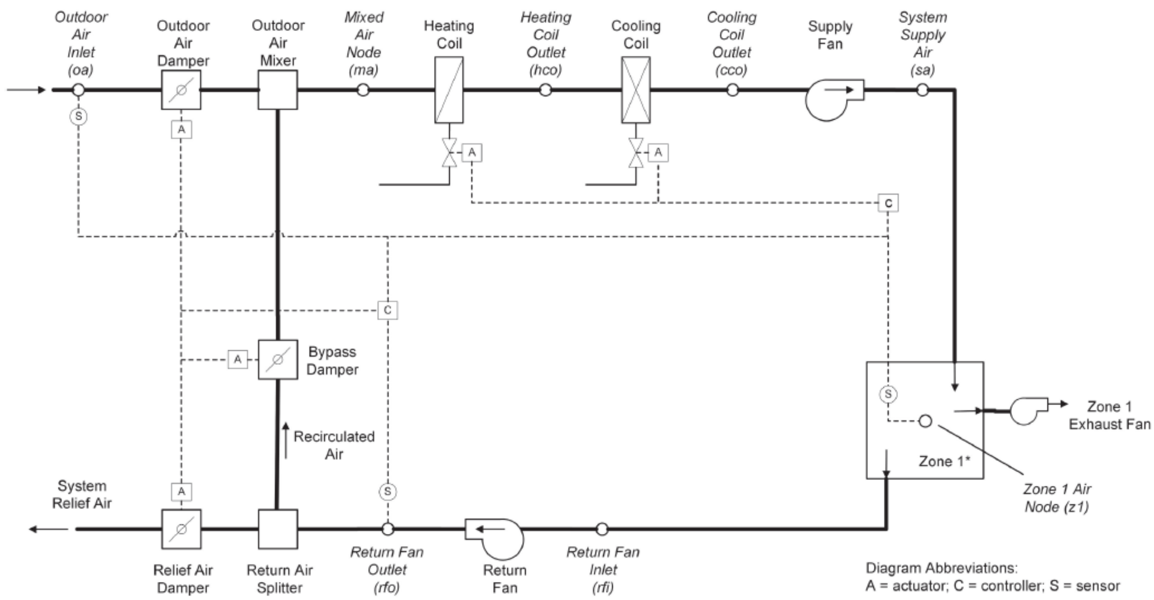


Figure 10. Single-Zone System Schematic[2]

[1] Based on Standard 140 Figure 5-25.
[2] Based on Standard 140 Figure 5-27

Constant-volume terminal reheat (CV) system (140 Section 5.5.3)

The CV system is based on the SZ system but adds multiple (two) zones, system supply air temperature control, and terminal reheat coils (Figure 11). The five sets of CV system test-case conditions are the same as for the SZ system but apply different zone load and temperature set points for the second zone.

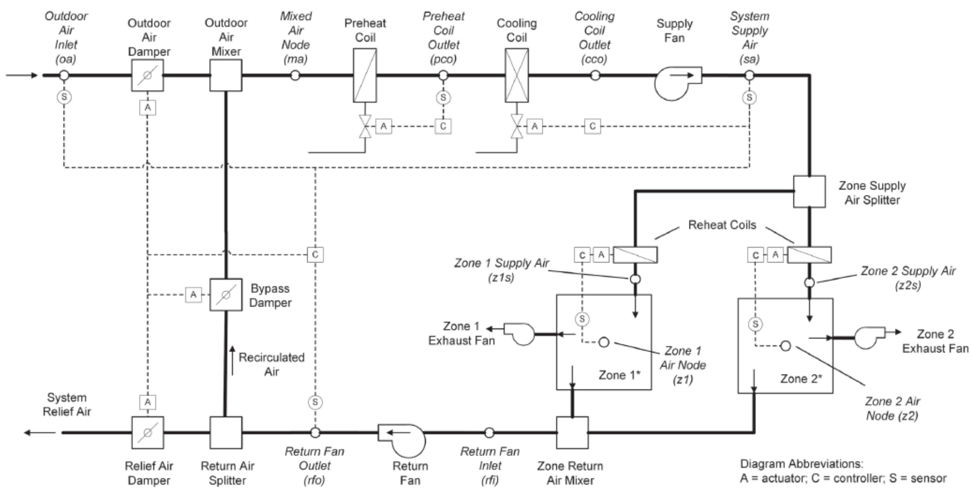


Figure 11. Constant Volume Terminal Reheat System Schematic[1]

Variable air volume terminal reheat (VAV) system (140 Section 5.5.4)

The VAV system is based on the CV system but with a variable airflow supply fan and terminal zone supply air dampers along with terminal reheat coils. Zone VAV terminals are controlled by zone thermostats and maintain zone set points precisely without a throttling range or dead band. The VAV system test-case conditions are the same as those for the CV system.

[1] Based on Standard 140 Figure 5-28

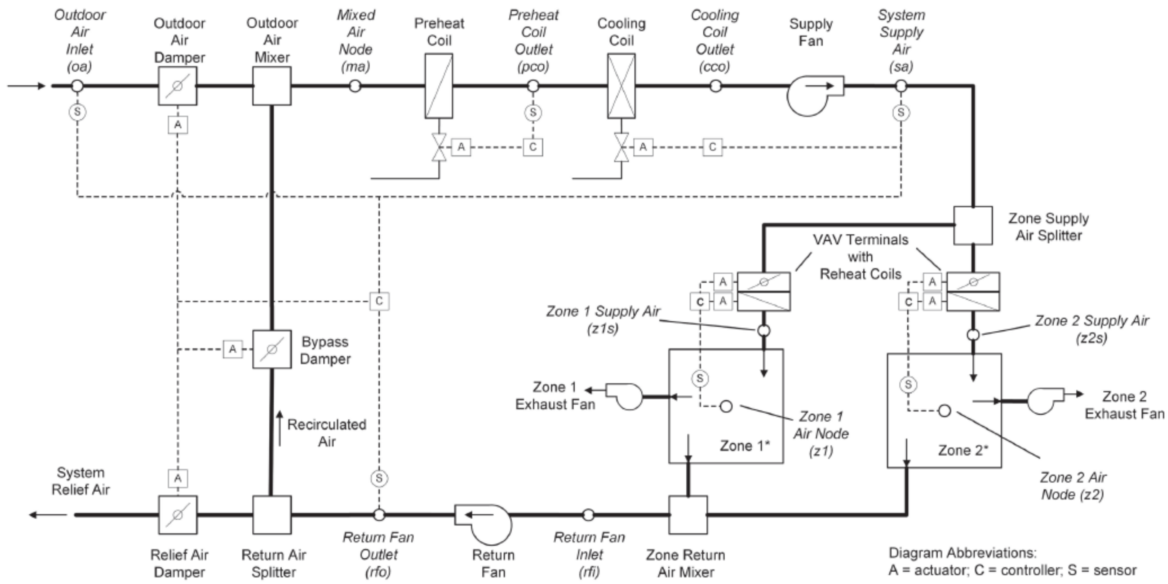


Figure 12. Variable Air Volume Reheat System Schematic[1]

4.8.2 Support of Common Air-side System Types by Standard 140

The PRM baseline may include CV systems, VAV systems with reheat, and VAV systems with parallel fan-powered boxes. Constant volume systems apply to residential occupancies (e.g., multifamily, hotels), which, depending on the climate zone, are modeled with either a constant volume package terminal air conditioner or a packaged terminal heat pump. In addition, non-residential buildings with three stories or less and an less than 25,000 ft^2, certain public assembly buildings, and retail buildings must be modeled with packaged CV rooftop air conditioner or heat pump (Table G3.1.1-3). Constant volume systems are also typically modeled for some HVAC zones in larger buildings, such as IT rooms or security offices that have substantially different internal loads or schedules from other zones on the same floor (G3.1.1 c).

For larger buildings, the PRM baseline includes VAV systems with hot water reheat for projects in heating-dominated climate zones or VAV systems with parallel fan-powered boxes and electric resistance reheat in cooling-dominated climates (CZs 0 – 3A). Table 7 illustrates common air-side system types and their support by Standard 140. The recommended new air-side systems tests are included in the following section in order of priority.

Table 7. Air Distribution Systems

System/Component/Controls Description	ASHRAE 140	ASHRAE 90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Dedicated OA System	No	0.00	0.04	Yes
Perimeter Radiation	No	0.00	0.00	Yes
Constant Volume	Yes	1.00	0.95	Yes
Variable Volume with reheat	Yes	0.25	0.37	Yes
Variable Volume with PFP Boxes	No	0.08	0.00	No
Radiant Panels	No	0.00	0.00	Yes

[1] Based on Standard 140 Figure 5-29

4.8.3 Recommended New Air-side System Tests

1. Dedicated outdoor air system (DOAS)

DOASs simplify ventilation control and design, improve humidity control, and allow for sensible-cooling-only terminal equipment. A DOAS also can be equipped with high-efficiency filtration systems with static pressure requirements above the capability of zone-terminal HVAC equipment. Energy-saving features of DOAS include separation of ventilation air conditioning from zone air conditioning and ease of implementation of exhaust air energy recovery.

DOASs are never modeled in the PRM baseline and are only included in the large hotel prototype. However, DOAS is included in three out of four HVAC system types recommended in AEDG ZE for small to medium office buildings and is also recommended in 1651-RP for all building types.

2. Perimeter radiation

Perimeter radiation, while not included in the prototypes, is commonly used in commercial designs. The most common application is in perimeter zones that may include either electric resistance or hot water baseboards.

3. VAV with PFP boxes

This system type is suggested as medium priority because even though it applies to the PRM baseline it’s not included in prototypes or recommended in AEDG ZE.

4. Radiant panels and chilled/cooled beams

Radiant heating and cooling systems improve occupant comfort. Active chilled beams are among the top 30 measures identified by 1651-RP.

4.9 Mechanical Ventilation

4.9.1 Support of Common Air-side System Elements by Standard 140

Standard 140 support of mechanical ventilation includes test cases with fixed outdoor air fraction (e.g., 15% for the CE300 base case), exploring sensitivity to changes in the amount of outdoor air (e.g., CE330), night ventilation (case 650), and economizer (CE400 series). The recommended new tests related to mechanical ventilation are described in the following section in order of priority.

Table 8. Outdoor Air / Ventilation Design

Component	System/Component/Controls Description	ASHRAE 140	ASHRAE 90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Ventilation	Fixed flow	Yes	1.00	0.97	Yes
	Demand-control	No	0.22	0.37	Yes
	Night ventilation	Yes	0.00	0.00	No
	Natural ventilation	No	0.00	0.00	Yes
Exhaust Air Energy Recovery	Sensible energy recovery	No	0.00	0.00	Yes
	Enthalpy recovery	No	0.09	0.52	Yes

4.9.2 Recommended New Mechanical Ventilation Tests

1. Exhaust air energy recovery

PRM baseline HVAC systems that have a design supply air capacity of 5000 cfm or greater and a minimum design outdoor air supply of 70% or greater must have an energy recovery system with at least 50% enthalpy recovery ratio (G3.1.2.10). Depending on project location, design air flow rate, and outdoor air fraction, building designs may be required to have energy recovery in order to meet 90.1 prescriptive requirements (90.1 Section 6.5.6). Energy recovery is included in the multifamily, large office, large hotel, and primary and secondary school prototypes. Energy recovery ventilators are included in 1651-RP both as a standalone measure and in combination with DOAS.

2. Demand control ventilation

Demand control ventilation (DCV) is included in the PRM baseline for systems with an outdoor air capacity of more than 3000 cfm serving areas with an average design capacity of greater than 100 people per 1000 ft^2 (90.1 G3.1.2.5, Exception 1). With few exceptions, DCV is also required by 90.1 for all spaces larger than 500 ft^2 with a design occupant density of more than 25 people per 1000 ft^2 (90.1 Section 6.4.3.8), which commonly applies to spaces such as classrooms, conference rooms, and auditoriums. DCV/CO_2 controls measure is included in 1651-RP as applicable to any building type, and it is also recommended in AEDG ZE.

3. Natural ventilation

Natural ventilation strategies are recommended in AEDGs, which also mention that BPM software has various levels of sophistication for modeling natural ventilation. This may also be addressed by including weather-driven infiltration tests.

4.10 Air-side System Controls

4.10.1 Support of Common Air-side System Controls by Standard 140

Standard 140 covers integrated and non-integrated economizers, including fixed dry bulb, differential dry bulb, and differential enthalpy. There are tests for zone temperature controls including setback, but no tests for humidity controls. Table 9 shows common air-side controls, their prevalence, and their support by Standard 140. The recommended new tests related to air-side controls are included in the following section in order of priority.

Table 9. Air-side Controls

Component	System/Component/ Controls Description	ASHRAE 140	ASHRAE 90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Economizer	Fixed dry bulb	Yes	0.71	0.00	Yes
	Differential dry bulb	Yes	0.00	0.73	Yes
	Differential enthalpy	Yes	0.00	0.73	No
	Non-integrated	Yes	0.00	0.00	No
	Integrated	Yes	0.00	1.00	No
Zone Climate	Temperature	Yes	1.00	1.00	Yes
	Humidity	No	0.05	0.05	Yes
Other	Optimal start/stop	No	0.71	0.77	Yes
	Supply air temperature reset	No	0.33	0.37	Yes
	Variable-flow, variable speed drive	No	0.33	0.37	Yes
	Variable-flow, static pressure reset	No	0.00	0.37	Yes

4.10.2 Recommended New Air-side Control Tests

1. Optimal start

Optimal start uses a system-level controller to determine the time required to bring each zone from the current temperature to the occupied set-point temperature and delays starting the system so that the temperature in each zone reaches the occupied set point just in time for occupancy. Optimal start capability is a mandatory requirement of 90.1 for systems with setback controls and DDCs. Optimal start controls are commonly modeled in both PRM baseline and proposed design models.

2. Supply air temperature reset

PRM baseline VAV systems must be modeled with supply air temperature reset under the minimum cooling load conditions. 90.1 prescriptive requirements call for multi-zone HVAC systems to have controls to automatically reset the supply air temperature in response to representative building loads, or to outdoor air temperature (90.1 Section 6.5.3.5). Alternatively, controls that adjust the reset based on zone humidity are allowed in certain climate zones. Such controls are common for both PRM baseline and proposed design models.

3. Variable speed drives

PRM baseline VAV systems must have fans with variable speed drives (G3.1.3.15), and they are also common in proposed designs. 90.1 sets limits on the minimum flow that a VAV system must be able to achieve and the maximum power draw at this speed – for example, DX and chilled-water cooling units that control the cooling capacity directly based on space temperature must have at least two stages of fan control, with the minimum speed not exceeding 66% of full speed with no more than 40% of the fan power at full fan speed (90.1 6.5.3.2.1). Fans must also have variable-speed control or other devices that will result in a total return/relief fan system demand of no more than 30% of total design power at 50% of total design fan flow (90.1 Section 6.5.3.2.4).

4. Static pressure reset

The PRM provides a part load performance curve for VAV fan systems that, according to the PNNL Performance Rating Method Reference Manual, corresponds to multi-zone VAV with fixed static pressure set point. Static pressure reset controls are required by 90.1 for multiple-zone VAV systems with a total fan system motor nameplate horsepower exceeding 5 hp with DDC of individual zones, and involve resetting the static pressure set point based on the zone requiring the most pressure; i.e., the set point is reset to be lower until one zone damper is nearly wide open (90.1 Section 6.5.3.2.3). Thus, for many commercial projects, static pressure reset is included in the proposed design but not in the baseline, directly contributing to performance tradeoffs.

5. Zone humidity control

The PRM requires that temperature and humidity control set points and schedules be the same in the proposed and baseline designs. Thus, humidity control must be included in both models on projects where it is specified.

4.11 Hydronic Loops

4.11.1 Support of Hydronic Loops by Standard 140

There are no tests in Standard 140 related to water-side HVAC. The recommended new tests are included in the following section in order of priority.

Table 10. Hydronic Loops

Component	System/Component/Controls Description	ASHRAE 140	ASHRAE 90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
HW Loop	Primary only	No	0.33	0.41	Yes
	Primary/secondary	No	0.00	0.00	No
	Constant flow	No	0.00	0.03	No
	Variable flow	No	0.33	0.38	Yes
	T reset based upon demand	No	0.00	0.41	Yes
	T reset based upon OAT	No	0.33	0.41	Yes
CHW Loop	Primary/secondary	No	0.19	0.24	No
	Primary only	No	0.00	0.00	No
	Constant	No	0.19	0.24	No
	Variable	No	0.19	0.24	Yes
	T reset based upon demand	No	0.00	0.24	No
	T reset based upon OAT	No	0.19	0.24	No
Pumps	Fixed speed, variable flow (riding pump curve)	No	0.33	0.00	No
	Variable speed, variable flow	No	0.42	0.28	Yes

4.11.2 Recommended New Hydronic Loop Tests[1]

1. Hot Water loop arrangement and controls

The PRM baseline hot water pumping system must be modeled as primary-only with continuous variable flow. Hot-water systems serving 120,000 ft^2 or more must be modeled with variable-speed drives, and systems serving less than 120,000 ft^2 must be modeled as riding the pump curve (90.1 G3.1.3.5).

Hot water supply temperature must be reset based on outdoor dry-bulb temperature following a prescribed schedule (G3.1.3.4). The new tests should address these loop configurations and controls.

2. CHW loop arrangement and controls

PRM baseline CHW systems must be modeled as primary/secondary with a constant flow primary loop and variable-flow secondary loop. For systems with a cooling capacity of 300 tons or more, the secondary pump must be modeled with variable speed drives; for lower capacity systems, the secondary pump must be modeled as riding the pump curve (90.1 G3.1.3.10). CHW supply temperature must be reset higher based on outdoor dry-bulb temperature, except in CHW systems serving computer rooms, where the reset must be baseline on the HVAC system requiring the most cooling; i.e., the CHW set point is reset to be higher until one cooling-coil valve is nearly wide open (90.1 G3.1.3.9). The new tests should address these loop configurations and controls.

[1] There is some relevant IEA 34/43 work on hydronic systems that may be applicable, as described in 140-2017, B23.2.14.

5.0 Rigor of Standard 140 Testing Framework in Respect to PRM

5.1 General Approach

The rigor of the BPM software testing frameworks with respect to a compliance modeling protocol may be assessed based on the following criteria:

1. Breadth of system and components addressed by the testing framework relative to systems and components common on projects modeled following the compliance protocol (e.g., PRM). A testing framework with broad coverage increases confidence in the consistency of compliance outcomes across the universe of modeled projects.
2. Degree of alignment between the boundary conditions and algorithms exercised in the test cases vs. boundary conditions and algorithms used on projects modeled following the compliance ruleset. For example, test cases based on simplified weather files may miss discrepancies that would arise with real weather data; test cases with a fixed infiltration rate do not fully support projects that use weather-adjusted infiltration algorithms.
3. Whether building systems and components that are not supported by the testing framework are associated with impactful end uses and are often improved in the proposed designs compared to the PRM baseline, resulting in significant impact of such elements on PRM compliance outcomes.

5.2 Breadth of Coverage

The following methodology was used to quantify the Standard 140 breadth of coverage of design elements common in the PRM baseline designs, minimally code compliant designs, and high-performance designs.

1. For each design element supported by Standard 140, prevalence shown in the corresponding cell of the PRM Baseline or Minimally Code Compliant Design columns in Table 1 through Table 10 was multiplied by 100 to convert to percentage. Due to insufficient data, the prevalence fraction could not be determined for high-performance design elements, so the corresponding cells in Table 1 through Table 10 were set to "Yes" if the design element was recommended in any of the relevant references (ASHRAE AEDG ZE, 1651-RM, etc.) or "No" otherwise. To convert to the numeric prevalence values, "Yes" was replaced with 1, and "No" was replaced with 0.
2. To quantify support by Standard 140, the percent prevalence in each cell was multiplied by 0 if the design element was not supported by Standard 140. If the design element did not apply (had 0 prevalence), the value in the cells was set to N/A.
3. The overall support for each type of model (PRM baseline, minimally code compliant design, and high-performance design) was calculated by summing the percentage support for all design elements in the corresponding column for each category of system and dividing the total by the sum of prevalences.

This is illustrated in Figure 13 using an interior lighting example. The 90.1 PRM baseline includes interior lighting power and lighting occupancy sensor design elements, each of which has a prevalence of 1 (100%) and is supported by Standard 140. Thus, the overall Standard 140 support is 100% for this example. For minimally code compliant designs and high-performance designs, Standard 140 supports two out of three relevant design elements, resulting in (100+0+100)/(100+100+100) = 67% support. The approach may be refined by assigning weighing factors to individual design elements, e.g., to reflect the relative importance of interior lighting power, daylighting controls, and occupancy sensors. (Lighting occupancy sensors area is assumed to be supported since, following 90.1 PRM, they are modeled through schedule adjustment, and Standard 140 does include test cases that vary internal gain schedule.)

Category	Design Element Description	Support by Std 140	Prevalence		
			90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Interior Lighting	Interior lighting power	Yes=1	1.00	1.00	Yes
	Daylighting	No=0	0.00	1.00	Yes
	Occupancy sensors	Yes=1	1.00	1.00	Yes

Category	Design Element Description	Support by Standard 140		
		90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Interior Lighting	Interior lighting power	100%	100%	100%
	Daylighting	N/A	0	0
	Occupancy sensors	100%	100%	100%
Overall Std 140 Support		100%	67%	67%

Figure 13. Methodology for Evaluating Standard 140 Support of the PRM Models

The methodology allows quantification of the degree of applicability of a generic, ruleset-neutral software testing protocol (such as Standard 140) to a specific ruleset (such as Standard 90.1 Appendix G and RESNET HERS). Since the design elements are ruleset specific, the same ruleset-neutral testing protocol may have different breadths of coverage for different rulesets. For example, Standard 140 tests cover a much greater number of systems and components found on projects in the scope of RESNET HERS than on projects in the scope of ASHRAE 90.1 Appendix G. Thus, Standard 140 has a greater breadth of coverage with respect to RESNET HERS than with respect to 90.1 Appendix G.

5.3 Alignment Between Tested and Prescribed Boundary Conditions and Algorithms

An informative annex to Standard 140 describes the following methodologies for validating BPM software:

1. Analytical verification tests, in which BPM software results are compared to the results from analytical, quasi-analytical, or verified numerical model solutions. Analytical solutions rely on simplified physical assumptions and case definitions, so that a mathematically correct solution can be derived. 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 rigorously screened to minimize the possibility of errors. All three types of analytical

verification solutions provide a basis for greater diagnostic capability than the purely software-to-software comparative tests described below.

2. Software-to-software comparative tests involve comparing BPM software results to themself or to the results of other programs. Such tests support any desired level of test case complexity and allow multiple diagnostic comparisons. However, there is no absolute truth standard, so only statistically based acceptance ranges are possible and diagnosing reasons for discrepancy in results may be non-trivial.
3. Empirical validation testing involves using experimental input and output data to validate the BPM software results. The simplest empirical validation compares a building's actual long-term energy use to energy use predicted by the BPM software, similar to how BPM tools are used in practice for predictive modeling. However, with this validation method, results may be difficult to interpret because any simulation input or algorithm may be erroneous. Even if there is good agreement between measured and predicted performance, possible offsetting errors prevent a definitive conclusion about the model accuracy. Disadvantages of this method include imperfect knowledge of the building being simulated, high cost of detailed measurements and site work, measurement errors, and difficulty of diagnosing sources of inaccuracy. In addition, only a limited number of test conditions and sensitivity test cases are practical.

Standard 140 includes analytical and comparative tests, as illustrated in Table 11.

Table 11. Standard 140 Tests by Type

	Analytical Tests	**Comparative Tests**
Building Thermal Envelope and Fabric Load	Std 140 Section 5.2.4 ground-coupled heat transfer for slab-on-grade	Std 140 Section 5.2.1-5.2.3 Low mass (600-650) High mass (900-960) Free float (600FF-950FF) In-depth (195 – 440, 800 and 810) Does not include slab-on-grade
Space Cooling Equipment	Std 140 Section 5.3.1 – 5.3.2 Cases CE100-CE200	Std 140 Section 5.3.2-5.3.4 Cases CE300-CE545
Space Heating Equipment	Std 140 Section 5.4.1-5.4.2 Cases HE100 – HE170	Std 140 Section 5.4.3 Cases HE210 – HE230
Air-side HVAC Equipment	Std 140 Section 5.5 • Four-pipe fan-coil (AE200 series, Section 5.5.1) • Single-zone (AE 200 series, Section 5.5.2) • Constant-volume terminal reheat system (AE300 series, 140 Section 5.5.3) • Variable-air-volume terminal reheat system (AE 400 series, Section 5.5.4)	

The method for assessing breadth of coverage discussed in the previous section counts a design element as fully supported by Standard 140 as long as it is covered in any of the tests, irrespective of type. For example, as seen in Table 11, space heating and cooling equipment test suites include both analytical and comparative tests, while only analytical tests are available for air-side HVAC equipment.

To account for that, a more nuanced Standard 140 support metric than a simple Yes/No may be used. For example, design elements that are included only in the analytical tests may be counted as 35% supported; design elements for which there are both analytical and simple comparative tests may be counted as 70% supported. Design elements included in analytical tests, simple comparative tests, and representative buildings comparative tests may be counted as 100% supported. Where more complex tests produce sufficient alignment in results across different tools based on Standard 140 committee judgement, the lower-level tests may not be necessary and thus the score may be set based on the highest level of tests included in Standard 140 for the system or component. For example, a score of 70% may be used for opaque envelope, for which there are simple comparative tests but no analytical tests.

Similarly, support for a design element may be downgraded to account for misalignment between the tested algorithms and the algorithms prescribed in the compliance protocol. For example, even though infiltration is included in the comparative tests, it may be counted as 35% supported, equivalent to analytical-only tests.

Table 12 compares specifications of the Standard 140 600 and 900 series test cases to the envelope properties common in the PRM compliance models, indicating that Standard 140 thermal fabric tests generally cover the range of envelope properties found in the PRM baseline and proposed designs based on the evaluation of the high-rise multifamily and medium office prototypes. Thus, no additional downgrading was used.

Table 12. Range of Envelope Properties in Std 600 and 900 Series Test Cases vs. 90.1 PRM

Input Parameter	Std 140	90.1 PRM Baseline (2)	90.1 2019 Requirement (2)
Exterior Walls			
U-factor (1)	0.025/0.074 (11)	0.084/0.064	0.055 (6)
Heat capacity			
Roof			
U-factor (1)	0.016/0.049 (11)	0.063	0.032 (5)
Heat capacity			
Thermal emittance		0.9 (13)	
Solar reflectance		**0.3 (13)**	
Windows			
Window to wall ratio	16%	6% - 40% (5) Multifamily: ≤40% Office: 19% small, 31% medium, 40% large	≤40% (3)
U-factor (1)	0.21-0.91 (12)	0.57	0.36/0.45 (10)
Solar heat gain coefficient (SHGC)	0.44 – 0.86 (12)	0.39	0.38/0.33 (10)
Air Leakage			
Air changes per hour	0.5 – 1.0	Multifamily: 0.46 Office: 0.55 (7)	Multifamily: 0.19 Office: 0.22 (8)
Internal Gains			
Rate, W/ft^2	1.32	Multifamily: 1.32 Office: 1.75 (4)	Multifamily: 1.07 Office: 1.39 (9)

Notes

1. U-factor is air-to-air.
2. Requirements for conditioned envelope in CZ5B (Denver), based on the location of Std 140 600-900 test cases. Values separated by a slash (/) represent requirements for residential/non-residential conditioned envelope.
3. Projects typically use the performance path to document compliance with 90.1 because they have greater than 40% fenestration area.
4. Sum of lighting loads from 90.1 Table G3.8 and miscellaneous loads prescribed for 90.1 Appendix C:
   Multifamily: 0.7 + 0.62 = 1.32
   Office: 1.0 + 0.7 5= 1.75
5. From 90.1 Table 5.5-5, insulated entirely above deck.
6. From 90.1 Table 5.5-5, steel-framed.
7. Calculated by applying the formula in Section G3.1.1.4 and the baseline infiltration of 1 CFM/ft^2 @ 75Pa per 90.1 Table G3.1 #5 b to the geometry of PNNL high-rise multifamily and medium office prototypes.
8. Calculated by applying the formula in Section G3.1.1.4 and the baseline infiltration of 0.4 CFM/ft^2 @ 75Pa 90.1 Section 5.4.3.1.1 to the geometry of PNNL high-rise multifamily and medium office prototypes.
9. Sum of lighting loads from 90.1 Table 9.5.1 and miscellaneous loads prescribed for 90.1 Appendix C:
   Multifamily: 0.45 + 0.62 = 1.07
   Office: 0.64 + 0.75 = 1.39
10. U-factor and SHGC for fixed/operable windows from 90.1 Table 5.5-5.
11. Higher value for all test cases except 680, which increases wall and roof insulation.
12. Lower values for all test cases except 670, which includes single pane window.
13. 90.1 Table G3.1 #5 (f), Baseline column.

Table 13 illustrates Standard 140 support by system type, accounting for types of existing test suites. It covers common systems and components found in the 90.1 PRM baseline, in the minimally code compliant designs, and in high-performance designs. This classification framework may evolve in parallel with test case development.

Table 13. Standard 140 Support of PRM Models by System Type Without Accounting for System Impact

System Type	System Sub-type	90.1 PRM Baseline	Minimally Code Compliant Designs	High-Performance Designs
Envelope	Opaque envelope	70%	70%	65%
	Fenestration	48%	48%	35%
	Shading	N/A	N/A	23%
	Infiltration	35%	35%	35%
	Exposure	70%	70%	70%
Envelope Overall		56%	56%	46%
Lighting	Interior lighting	70%	47%	47%
	Exterior lighting	47%	47%	47%
Lighting Overall		58%	47%	47%
Service Water Heating	Water heater type	0%	0%	0%
	External SWH storage	N/A	N/A	0%
	SWH demand	0%	0%	0%
	SWH heat recovery	0%	0%	0%
Service Water Heating Overall		0%	0%	0%
Miscellaneous Other Equipment	Non-HVAC motors	70%	70%	70%
	Receptacle	70%	70%	70%
	Elevator/escalators	70%	70%	70%
	Refrigeration	70%	70%	70%
	Transformers	N/A	N/A	0%
Miscellaneous other Equipment Overall		70%	70%	56%
Heating/Cooling Source	Space cooling	56%	56%	23%
	Space heating	36%	38%	18%
Heating/Cooling Source Overall		46%	47%	20%
HVAC System Types	Dedicated OA system	N/A	0%	0%
	Perimeter radiation	N/A	N/A	0%
	Constant volume	35%	33%	35%
	Variable volume with reheat	9%	13%	35%
	Variable volume with PFP boxes	0%	N/A	N/A
	Radiant panels	N/A	N/A	0%
HVAC System Types Overall		15%	15%	14%
HVAC Air-side Controls and Ancillary Components	Ventilation controls	29%	25%	12%
	Exhaust air energy recovery	0%	0%	0%
	Economizer	35%	35%	35%
	Zone temperature/humidity	33%	33%	18%
	Optimal start	0%	0%	0%
	Supply air temperature reset	0%	0%	0%
	Variable-flow, variable speed drive	0%	0%	0%
	Variable-flow, Static Pressure Reset	N/A	0%	0%
HVAC Controls and Ancillary Components Overall		14%	12%	8%
HVAC Water-side Controls and Ancillary Components	Hot water loop	0%	0%	0%
	Chilled water loop	0%	0%	0%
	Condenser loop	0%	0%	0%
	Pumps	0%	0%	0%
	Heat rejection equipment	0%	0%	N/A
	Fluid economizer	N/A	0%	0%
HVAC Water-side Components and Controls Overall		0%	0%	0%

5.4 Accounting for System Impact

Overall support of PRM models by Standard 140 may be calculated as a simple average of support for individual system types (envelope, lighting, etc.) shown in Table 13, effectively assuming that each system type has approximately equal impact on the PRM compliance outcomes. However, this is not the case. As discussed above, since the PRM baseline is generally aligned with 90.1 2004, the difference between the 90.1 2004 and 90.1 2019 prototypes is somewhat representative of the difference in the PRM baseline and proposed design performance, and based on Figure 5, interior lighting, cooling, and fan energy cost savings between 90.1 2004 and 2019 are substantially greater than savings from miscellaneous equipment or pump end uses.

To address that, end uses reported for the prototype models in the PNNL analysis may be mapped to the system types in Table 13 to establish the weighing factors for the system types. In some cases, the mapping is intuitively obvious – e.g., equipment, refrigeration, transformers, elevators, cooking, and IT end uses reported for the prototypes all belong under the miscellaneous other equipment system type. In other cases, judgement was used and the allocation can be further adjusted. For example, cooling end use reported for the prototypes was allocated to system types in Table 13 as follows: 20% to envelope, 30% to space cooling, 30% to HVAC system type, and 20% to HVAC air-side controls and ancillary. The allocations may be refined with additional research. In addition, the weighting may be based on site or source energy by end use for the prototypes instead of energy cost. The initial mapping was developed based on energy cost and is shown in Table 14. Column headings in Table 14 are based on the categories included in the System Type column of Table 13.

Table 14. Mapping Between Prototype End Uses and System Types

Prototypes' Reported End Uses	US Average Weighted Annual Energy Cost Savings 2004 - 2019	Envelope	Interior Lighting	Exterior Lighting	SWH	Misc. other Equipment	Space Cooling	Space Heating	HVAC System Types	HVAC Air-side Controls and Ancillary Components	HVAC Water-side Controls and Ancillary Components	Total
Light.Int	0.200		100%									100%
Cool	0.148	20%					30%		30%	20%		100%
Fans	0.123	10%							40%	50%		100%
Heat	0.113	20%						30%	30%	20%		100%
Light.Ext	0.054			100%								100%
Equip	0.013					100%						100%
Pumps	0.012										100%	100%
Humidfy	0.004						100%					100%
Refrig	0.009					100%						100%
Txfmr	0.004					100%						100%
Ht.Rej	0.005										100%	100%
Elevator	0.002					100%						100%
SHW	0.001				100%							100%
Ht.Rcvy	0.008									100%		100%
Cook	0.000					100%						100%
IT	0.000					100%						100%
Annual Energy Savings \$/ft^2		0.064	0.200	0.054	0.001	0.028	0.049	0.034	0.127	0.122	0.017	0.696

Since PRM projects often claim higher SWH savings than suggested by the 90.1 2004 – 90.1 2019 prototypes comparison, SWH weight was determined assuming 20% reduction in the 90.1 2004 prototype's U.S. average weighted annual cost, or 0.102 x 20% = 0.020 \$/ft^2 instead of the value shown in Table 14. The resulting weighting factors and PRM support by Standard 140 based on the above methodology are given in Table 15. In most cases, Standard 140 support is the highest for the 90.1 PRM baseline, which includes fewer design elements. The support decreases for the minimally code compliant designs and is the lowest for high-performance designs. However, in some cases, support of the PRM baseline may be less than support of a minimally code compliant design – for example, many types of projects are required to have boilers in the PRM baseline; boilers are not supported by Standard 140 and are less prevalent in commercial building stock based on PNNL prototype models.

Table 15. Standard 140 Support of PRM Accounting for System Impact

System Type	System Type Weight	Standard 140 Support by System Type		
		90.1 PRM Baseline	Min. Code Compliant Designs	High-Performance Designs
Envelope	9%	56%	56%	46%
Interior Lighting	28%	70%	47%	47%
Exterior Lighting	8%	47%	47%	47%
SWH	3%	0%	0%	0%
Misc. Other Equipment	4%	70%	70%	56%
Space Cooling	7%	56%	56%	23%
Space Heating	5%	36%	38%	18%
HVAC System Types	18%	15%	15%	14%
HVAC Air-side Controls and Ancillary Components	17%	14%	12%	8%
HVAC Water-side Controls and Ancillary Components	2%	0%	0%	0%
Overall Weighted Support		41%	35%	29%

6.0 Representative Buildings Comparative Tests

PRM support by Standard 140 may be improved by expanding the Standard 140 comparative test suites to include base cases and parametric variations representative of building designs modeled following the PRM.

6.1 Base Cases

Building occupancy types

The following factors were considered:

a. Building types with the highest new construction floor area include multifamily (23.3% total for high- and mid-rise apartments), non-refrigerated warehouses (18.6%), primary and secondary schools (15.75% combined), and office buildings (12.67% total including 3.86% large, 5% medium, and 3.8% small) (Appendix A).

b. Building types with the highest area-weighted site energy use intensity for 90.1 2019-compliant stock include standalone retail, outpatient healthcare, hospital, mid-rise and high-rise apartment, and secondary school (PNNL 2019 End Use Tables, see Appendix B)

c. Buildings types most commonly modeled following the PRM include multifamily, large office building, school and university building, and hotel (Figure 3).

d. Building types that provide good coverage of design elements found in the PRM baseline.

e. Avoid inherently complex building types such as medical facilities.

f. To simplify test development, maximize use of systems addressed by the existing Standard 140 unit tests.

CEC ACM software certification requirements include sensitivity tests involving large and medium offices, medium retail, and strip mall. COMNET (Commercial Energy Services Network) sensitivity testing requirements included large and medium office, retail/supermarket, manufacturing/warehouse, and mixed-use retail/office/multifamily base cases. Having base cases representing many different building types results in a more comprehensive testing framework and allows for more accurate prioritization of the unit diagnostic tests that should be added to Standard 140. However, it increases the effort necessary to formulate the tests and the effort on the part of the BPM software developers who would need to test their tools.

To simplify test case development, the representative building base cases may be aligned with the whole building test cases that are being planned for Standard 229. Since these tests are not yet developed, it is recommended that the representative buildings sensitivity tests include a residential building such as multifamily or hotel, and at least one non-residential building. Retail buildings, while accounting for the highest area-weighted site energy use intensity, do not typically use a performance path to document compliance, and based on the available data, are not common in programs for high-performance buildings. Based on these considerations, high-rise multifamily and medium office building are recommended as the first priority implementation. To mitigate the effort, a test suite for one of the two building types may be developed first.

Climate zones

The tests should be completed in the representative climate zones, including cooling-dominated and heating-dominated. The recommended climate zones are given in Table 16 and were established based on the construction volumes across U.S. included in Appendix A of this report and to cover a variety of representative climates. The specific locations for each climate zone align with the locations used for the prototype analysis.

Table 16. Climate Zones for Representative Building Tests

Climate Zone	New Construction Volume	Climate Description	Location	Notes
2B	16.85%	Hot, dry	Tucson, Arizona	
4A	3.39%	Mixed, humid	New York City, New York[1]	Humid CZ ("A") with one of the highest construction volumes
4B	20.94%	Mixed, dry	Albuquerque, New Mexico	
5B	17.6%	cool, dry	Denver, Colorado[2]	
5C	4.59%	cool, marine	Port Angeles, Washington	Marine CZ ("C") with the highest construction volume
6B	3.17%	cold, dry	Great Falls, Montana	Cold CZ with the highest construction volume

1. Chicago may be used as an alternative location for mixed humid climate.
2. Denver location may be used for developing the initial test cases as it is representative of a mixed climate.

Design elements to be included

The following criteria were used to establish systems and components included in the base cases:

a. Reflect PRM baseline for the selected building type and location.

b. Cover the key design elements included in the PRM baseline.

c. When possible, give preference to the design elements addressed by the diagnostic unit tests.

6.2 Parametric Variations

Similar to the existing Standard 140 tests, changes to the individual design elements of the base cases should be modeled as separate parametric tests. Parametric test cases would step-by-step transform the base case into the minimally code compliant design and then into a high-performance design. For example, the first set of parametric tests may transform the base case envelope to the envelope minimally compliant with 90.1 2019, the next set of parametric tests would incorporate changes to the lighting system, and so on.

6.3 High-rise Multifamily

The multifamily base case is based on the apartment high-rise prototype (Figure 14). The design features of the base case and parametric runs are summarized in the following tables.

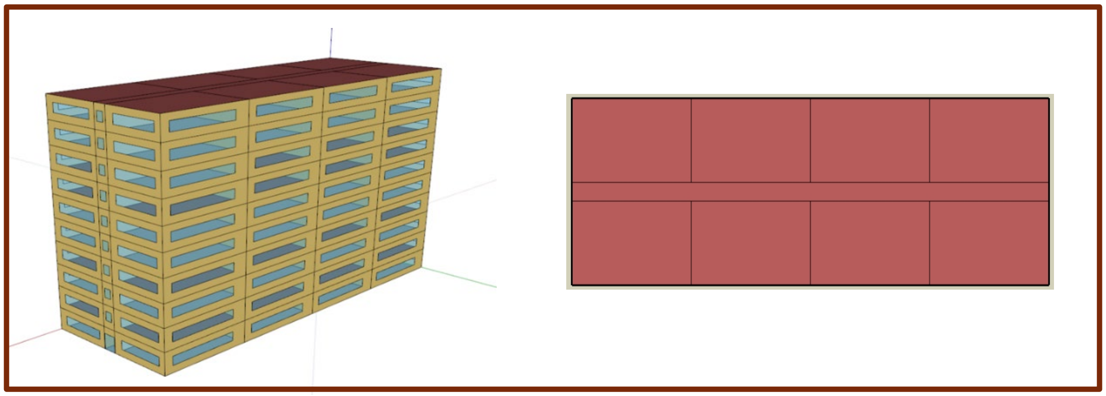


Figure 14. Multifamily Base Case Elevation and Thermal Zones

Table 17. Multifamily Base Case Attributes Not Changed in Parametric Runs

Item	Base Case Attributes that Remain Unchanged
Total Floor Area (ft^2)	84,360 (152 ft x 55.5 ft)
Number of Floors	10
Thermal Zoning	Perimeter zone depth: 15 ft
Exterior Wall Construction	Steel-Frame walls (2X4 16IN OC) 0.4 in. stucco+5/8 in. gypsum board + wall insulation+5/8 in.
Roof Construction	Built-up roof
Foundation Type	Slab-on-grade floors (unheated)
Infiltration	Infiltration rate @75Pa per unit area of envelope pressure boundary; adjusted by wind and building operation

Table 18. Multifamily Envelope Base Case and Parametric Changes

Item	Base Cases Set: PRM Baseline for CZ	Parametric Set 1: Minimally Code Compliant Design	Parametric Set 2: High-Performance Design
Window-to-Wall Ratio	30% on each exposure (per prototype)	Same as base case if <40%, per PRM rules	60%?
Shading	None	None (per prototypes)	Add overhangs/side fins? Site shading?
Exterior Walls U-factor	PRM baseline for CZ	90.1 requirements for CZ	PH levels for CZ
Roof U-factor	PRM baseline for CZ	90.1 requirements for CZ	PH levels for CZ
Window U-factor	PRM baseline for CZ	90.1 requirements for CZ	PH levels for CZ
Window SHGC (all)	PRM baseline for CZ	90.1 requirements for CZ	PH levels for CZ
Window Visible Transmittance	90.1 requirements for CZ	90.1 requirements for CZ	PH levels for CZ
Skylight Dimensions	None (or 3% roof area?)	None (or 3% roof area?)	5% of roof area?
Infiltration	1.0 CFM/ft^2	0.6 CFM/ft^2 (PRM default for proposed design)	PH levels for CZ

Table 19. Multifamily HVAC Base Case and Parametric Changes

Item	Base Cases Set: PRM Baseline for CZ	Parametric Set 1: Minimally Code Compliant Design	Parametric Set 2: High-Performance Design
System Type			
Heating	CZs 0 - 3a: packaged terminal heat pump Other CZs: packaged terminal AC (hot water coil)	Same as base case? Water source heat pump?	VRF? PSZ DOAS?
Cooling Type	DX	Same as base case	VRF?
Distribution and Terminal Units	Constant volume CZs 0 - 3a: System 2 - packaged terminal heat pump Other CZs: System 1 - packaged terminal AC	Same as base case? Water source heat pump?	VRF? PSZ DOAS?
HVAC Efficiency			
Cooling	PRM baseline	Min. required by 90.1	AEDG ZE
Heating	PRM baseline	Min. required by 90.1	AEDG ZE
HVAC Control			
Supply Air Temperature	NA	NA	AEDG ZE
CHW Supply T	NA	NA	NA
HW Supply T	180°F supply, 130°F return, OA reset	Per prototype, min. required by 90.1	AEDG ZE
Economizers	No	Not required	AEDG ZE for CZ
Ventilation	ASHRAE Standard 62.1 or International Mechanical Code, same as prototype	Same as base case	Same as base case
DCV	No	No	No
Energy Recovery	No	As required by 90.1 for CZ	AEDG ZE
Supply Fan			
Supply Fan Power	PRM baseline allowance	Per prototype	AEDG ZE
Pumps			
HVAC Pumps	NA	Per prototype	AEDG ZE
Cooling Tower			
Type/Effy	NA	Per prototype	AEDG ZE

Table 20. Multifamily SWH Base Case and Parametric Changes

Item	Base Cases Set: PRM Baseline for CZ	Parametric Set 1: Minimally Code Compliant Design	Parametric Set 2: High-Performance Design
SWH Type and Fuel	Electric resistance storage (G3.1.1-2)	Natural gas storage (prototype)	AEDG ZE
Thermal Efficiency (%)	PRM baseline	As required by 90.1	AEDG ZE
Standby Loss	PRM baseline	As required by 90.1	
SWH Pump	Per prototype with motor efficiency per 90.1 G3.9.1	Per prototype	AEDG ZE

Table 21. Multifamily Internal Loads Base Case and Parametric Changes

Item	Base Cases Set: PRM Baseline for CZ	Parametric Set 1: Minimally Code Compliant Design	Parametric Set 2: High-Performance Design
Lighting Power Density	Table G3.7	90.1 Section 9 allowance	AEDG ZE
Daylighting Controls	None	Yes, min. required in 90.1 Section 9	AEDG ZE
Occupancy Sensors	None	Reduced schedule fraction per Table G3.7	AEDG ZE
Plug Loads	Per prototype	Per prototype	Per prototype

6.4 Medium Office

The medium office base case is based on the corresponding prototype (Figure 15). The key design features are summarized in the following tables.

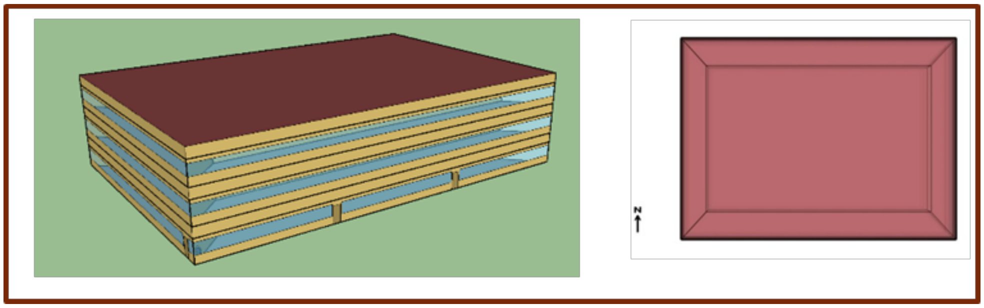


Figure 15. Medium Office Base Case Elevation and Thermal Zones

Table 22. Medium Office Base Case Attributes Not Changed in Parametric Runs

Item	Base Case Attributes that Remain Unchanged
Total Floor Area (ft^2)	53,600 (163.8 ft x 109.2 ft)
Number of Floors	3
Thermal Zoning	Perimeter zone depth: 15 ft.
Exterior Wall Construction	Steel-frame walls (2x4 16 in. OC) 0.4 in. Stucco+5/8 in. gypsum board + wall insulation+5/8 in.
Roof Construction	Built-up roof
Foundation Type	Slab-on-grade floors (unheated)
Infiltration	Infiltration rate @75Pa per unit area of envelope pressure boundary; adjusted by wind and building operation

Table 23. Medium Office Envelope Base Case and Parametric Changes

Item	Base Cases Set: PRM Baseline for CZ	Parametric Set 1: Minimally Code Compliant Design	Parametric Set 2: High-Performance Design
Window-to-Wall Ratio	40%	33% (per prototype)	60%?
Shading	None	None (per prototypes)	Add overhangs/side fins? Site shading?
Exterior Walls U-factor	PRM baseline for CZ	90.1 requirements for CZ	PH levels for CZ
Roof U-factor	PRM baseline for CZ	90.1 requirements for CZ	PH levels for CZ
Window U-factor	PRM baseline for CZ	90.1 requirements for CZ	PH levels for CZ
Window SHGC (all)	PRM baseline for CZ	90.1 requirements for CZ	PH levels for CZ
Window Visible Transmittance	90.1 requirements for CZ	90.1 requirements for CZ	PH levels for CZ
Skylight Dimensions	None (or 3% roof area?)	None (or 3% roof area?)	5% of roof area?
Infiltration	1.0 CFM/ft^2	0.6 CFM/ft^2 (PRM default for proposed design)	PH levels for CZ

Table 24. Medium Office HVAC Base Case and Parametric Changes

Item	Base Cases Set: PRM Baseline for CZ	Parametric Set 1: Minimally Code Compliant Design	Parametric Set 2: High-Performance Design
System Type			
Heating	Gas preheat coil CZ 0 – 3a: electric resistance reheat Other CZ: hot water reheat coil	Same as base case	Same as base case? VRF?
Cooling Type	DX	Same as base case	Same as base case? VRF?
Distribution and Terminal Units	CZ 0 – 3a: System 6 – Packaged VAV with PFP boxes Other CZ: System 5 – Packaged VAV with reheat	VAV terminal box with damper and electric reheat coil	DOAS?
HVAC Efficiency			
Cooling	PRM baseline	Min. required by 90.1	Per AEDG ZE
Heating	PRM baseline	Min. required by 90.1	Per AEDG ZE
HVAC Control			
Supply Air Temperature	Reset up by 5°F under the minimum cooling load	Max. 104°F, Min. 55°F	Reset control per AEDG ZE
CHW Supply T	NA		
HW Supply T	NA		
Economizers	Integrated dry bulb, based on CZ (G3.1.2.7)	90.1 prescriptive requirements for CZ	Per AEDG ZE for CZ
Ventilation	ASHRAE Standard 62.1 or International Mechanical Code, same as prototype	Same as base case	Same as base case
DCV	No	No	Yes
Energy Recovery	No	As required by 90.1 for CZ	Per AEDG ZE
Supply Fan			
Supply Fan Power	PRM baseline allowance	Per prototype	Per AEDG ZE
Pumps			
HVAC Pumps	NA	NA	NA
Cooling Tower			
Type/Effy	NA		

Table 25. Medium Office SWH Base Case and Parametric Changes

Item	Base Cases Set: PRM Baseline for CZ	Parametric Set 1: Minimally Code Compliant Design	Parametric Set 2: High-Performance Design
SWH Type and Fuel	Electric resistance storage (G3.1.1-2)	Natural gas storage (prototype)	Per AEDG ZE
Thermal Efficiency (%)	PRM baseline	As required by 90.1	Per AEDG ZE
Standby Loss	PRM baseline	As required by 90.1	
SWH Pump	Per prototype with motor efficiency per 90.1 G3.9.1	Per prototype	AEDG ZE

Table 26. Medium Office Internal Gains Base Case and Parametric Changes

Item	Base Cases Set: PRM Baseline for CZ	Parametric Set 1: Minimally Code Compliant Design	Parametric Set 2: High-Performance Design
Lighting Power Density	Table G3.7	90.1 Section 9 allowance	Per AEDG ZE
Daylighting Controls	None	Yes, min. required in 90.1 Section 9	Per AEDG ZE
Occupancy Sensors	None	Reduced schedule fraction per Table G3.7	Per AEDG ZE
Plug Loads	Per prototype	Per prototype	Per prototype

7.0 Proposed New Test Suites

7.1 Internal Standard 140 Test Suite Development Roadmap

The Standard 140 committee initiated the work to prioritize new test suite development at the ASHRAE January 2018 meeting and released the roadmap in June of 2019.[1] As part of the roadmap development, the potential test suites were briefly described, including the test suite purpose, parts of the BPM software being tested, and how far along the test suite is (e.g., completely new, modification of existing tests). The roadmap was conceived as a living document. In the most recent prioritization poll of voting and non-voting members of the Standard 140 committee, conducted in June 2019, participants were asked to rank the identified test suites from 10 (the highest priority) to 1 (the lowest priority). The priorities established by the poll are given in Table 27. The scope of tests that were included in the poll and are relevant to the PRM are summarized below based on the Standard 140 Roadmap Appendices A and B. The summaries also include the expected test development effort (low/medium/high).

Table 27. Test Suite Prioritization by Standard 140 Committee

Test Suite	Average Score
Air-side HVAC BESTEST Volume 2	7.13
Weather-driven Infiltration and Natural Ventilation	6.80
Update HVAC BESTEST Performance Maps with Empirical Data	6.73
Weather Drivers	6.60
Analytical Building Fabric Tests – 1052-RP	6.53
Multi-zone Non-airflow (MZ) Test Cases (IEA 34/43)	6.53
Empirical Test Set from LBNL Flexlab and ORNL FRP	6.40
Domestic Hot Water	6.07
Ground Coupling (expand Section 5.2.4)	5.73
Empirical Test Set from NREL Indoor/Outdoor Modular Apartment	5.53
Standard 205 Performance Map Tests	5.40
ETNA BESTEST Empirical Validation	5.07
Thermal Bridging (2-D/3-D conduction)	4.67

1. Airside HVAC Building Energy Simulation Test (BESTEST) Volume 2

Standard 140 Section 5.5 currently includes in-depth diagnostic analytical verification tests for modeling airside HVAC equipment. These tests apply steady-state weather data and other idealizations and provide the foundation for establishing realistic comparative tests. The proposed new tests would apply hourly-varying annual weather data and add new physics tests. Adding the airside HVAC comparative tests would follow the precedent of the Standard 140 cooling and heating equipment tests (Standard 140 Sections 5.3 and 5.4), which include both analytical and comparison tests and will complement the existing analytical tests with respect to acceptance criteria because they will allow scaling of differences between the tools based on realistic annual weather data. The following tests may be included:

[1] http://data.ashrae.org/standard140/Standard%20140%20Prioritization-Roadmap-2019Jun24-070119.pdf

- Non-idealized bypass factor (BF): Volume 1 tests apply BF = 0; new tests would apply realistic value (e.g., BF = 0.05) and corresponding apparatus dew point, geometry, and other equivalent inputs.
- Apply annual (non-steady-state) weather data to existing test cases to allow scaling of differences among programs with annual and peak energy use, important for qualification tests.
- Dry-bulb and enthalpy economizer controls for robust net energy savings in hot dry and humid climates.
- Duct heat gain/loss.
- Fan energy consumption.

The test case development effort is expected to be medium. Airside systems have high impact on the PRM compliance outcomes of typical projects. Since only analytical tests are currently included for such systems in Standard 140, adding comparative tests will increase support of these design elements from 35% to 70% based on the methodology for quantifying PRM support described in the previous section.

2. Analytical building thermal fabric tests

The analytical thermal fabric tests would be based on ASHRAE 1052-RP.[1] Each test would focus on a specific heat transfer mechanism, such as conduction, solar gains and shading, infiltration including fixed and stack effect, long wave radiation, convective and radiative heat gains, and ground coupling. The analytical solutions were implemented in an interactive program with user inputs to generate a variety of cases for each test type (e.g., varying wall material properties for conduction tests). All tests use single-zone, 3m x 3m x 3m. The test case development effort is expected to be medium. The envelope is already better supported than other design elements common in PRM models; this test suite is not a high priority for PRM.

3. Service water heating tests

These tests would largely investigate service hot water systems in an isolated context, outside of the whole-building energy simulation, but may also include tests focusing on basic energy balance in a zone containing a water heating system. Tests may be developed in collaboration with RESNET, which already has some tests for modeling of water heating systems, and with SSPC 118. The follow types of tests are included in the summary description:

- Various tank sizes (including tankless)
- Electric, gas, and heat pump water heater
- Empirical-test-based laboratory-grade [2]
- Range of environmental conditions (simulating standby losses)
- Range of tests under a wide variety of draw scenarios

[1] Development of an Analytical Verification Test Suite for Whole Building Energy Simulation Programs – Building Fabric, Spitler, J.D., Rees, S.J., and Dongyi, X., ASHRAE 1052-RP Final Report, April 2001
[2] That's how it's worded in 140 roadmap, not clear what it means

The test case development effort is expected to be medium. This test suite is directly relevant to the PRM and has similar scope to what is described in the section on Standard 140 Support of Design Elements Common in PRM Models. However, since SWH system weight in Table 15 is low, these tests are a medium priority.

4. Multi-zone non-airflow (MZ) test cases[1]

These new tests would expand the thermal fabric test cases in Standard 140 Section 5.2 to include multi-zone tests to achieve an improved agreement for the shading cases vs. the current Section 5. Examples of new tests include three-zone steady-state conduction analytical verification tests and multi-zone shading tests, including unshaded base case, multi-zone fin shading, and multi-zone automated building self-shading. The test suite development effort is expected to be small. This test suite is not a priority for the PRM since envelope is already better supported than other design elements.

5. Standard 205 performance map tests

Standard 205 defines the format of manufacturer's performance data to be transmitted to BEM programs. The data will be supplied as performance maps of the complete performance envelope for the equipment. There could be multiple maps per piece of equipment representing different operation states or levels. BPM software tools will need to properly read the Standard 205 files and interpret the performance data and performance states, which require developing new functionality for most tools. Standard 205 has not yet been published. A parallel project to create a Standard 205 toolkit may simplify the required coding for BEM programs, but testing to verify that the toolkit routines are properly applied would still be necessary. The test suite development effort is expected to be large.

This test suite is not a priority for the PRM since Standard 205 has not yet been published, performance data for commercial systems is not yet available from equipment manufacturers, and the common BPM software tools do not support this input format.

6. Thermal bridging

These tests would focus on multi-dimensional heat transfer through exterior building components, which may be tested in isolation (i.e., simulated hot-box performance with defined boundary conditions), and in the context of whole-building energy simulation (as part of the thermal fabric test suite). The tests will establish detailed verified numerical reference models similar to the ground coupling test cases. The test development effort is expected to be medium. This test suite is not a priority since the PRM does not currently require capturing thermal bridging. The Standard 90.1 envelope subcommittee is developing an addendum to account for thermal bridging; however, the model will be based on the simplified methods involving derating of thermal properties of surfaces.

7. Update HVAC BESTEST performance maps with empirical data

The current Standard 140-2017 Section 5.3 addresses a very simple constant speed unitary split system based on a combination of measured and modeled data provided by Trane & Carrier and does not support the new generation of high-efficiency variable equipment. The new tests would include a 5-ton rooftop unit with a seasonal energy efficiency ratio of 17 and a 6-ton

[1] NREL 2008 final report https://www.nrel.gov/docs/fy08osti/43827.pdf

rooftop unit with an integrated energy efficiency ratio of 23, both with different degrees of fan and compressor variability. The measured performance maps used in the new tests would include realistic part load conditions not available with the previous performance maps. The new tests would be similar to those already included in Standard 140-2017 Section 5.3 but would focus on modeling of variable speed fans and compressors such as the following:

- Multi-stage scroll compressor, single-speed condenser fan, direct drive variable supply air fan with high-efficiency motor, low leak dampers, hot gas re-heat humidity control, economizer
- Variable speed everything, direct drive compressor

The test development effort is expected to be medium. The test suite is useful for the PRM but is a low priority since performance maps for commercial equipment are not commonly available from equipment manufacturers and BPM software tools do not typically accept such inputs.

8. Weather-driven infiltration and natural ventilation

The current test in Standard 140 Section 5 specifies air changes per hour independent of weather conditions (constant for most cases, varying for 650 and 950). The proposed new tests would expand the Standard 140 Section 5.2 thermal fabric test cases to include weather-driven infiltration tests. The cases will test the ability of BPM software to apply simulation inputs including but not limited to aperture, leakage, or crack area to calculate hourly infiltration air-flow rate as a function of wind speed, ΔT, and orientation. The tests may include varying wind speed, zone temperature, and outdoor temperature, separately and in some combination; and separate tests with mechanical fan, single zone tests with different aperture heights on windward and leeward sides, multi-zone tests with different aperture heights on windward and leeward sides, and inter-zone apertures. The tests would apply realistic weather to gauge the impact of differences in BPM software results on annual energy use. The test case development effort is expected to be medium.

This test suite is useful for the PRM, which requires accounting for the impact of weather and building operation on infiltration. However, to fully realize the benefits of the test suite, the PRM would need to prescribe additional modeling inputs found to be impactful in the simulation trials.

9. Weather drivers

These tests would confirm the ability of the BPM software to read and interpret the weather file formats correctly, such as applying altitude correction and time zone, determining solar radiation for tilted walls and windows, etc. The test case development effort is expected to be small. The tests are useful for PRM models.

7.2 Proposed New Test Suites in Support of PRM

The recent Standard 140 test development largely followed a bottom-up approach. For example, analytical verification tests for heating and cooling equipment (Standard 140 Sections 5.3.1, 5.3.2, 5.4.1, and 5.4.2) were developed first, followed by comparative tests in sections 5.3.3, 5.3.4, and 5.4.3. The same sequence is now used for air-side HVAC tests – the current scope of Standard 140 includes analytical verification tests (Standard 140 Section 5.5), and developing the corresponding comparative tests (Air-side HVAC BESTEST Volume 2) is the planned next step. While a bottom-up approach makes intuitive sense (start simple and increase complexity), it is does not inform priorities and so it is not conducive to rapid test development in support of a given modeling use case. For example, resolving misalignment in results between the BPM tools participating in the simulation trials should not be a priority if the misalignment has a small impact on the compliance outcome.

An alternative top-down approach involves developing tests for representative building models starting with the base case (the PRM baseline) and transforming the base case, component by component, first into the minimally code compliant design and then into high-performance design. This process would help identify impactful disagreements that could then be explored in the simplified comparative unit tests as necessary. The top-down approach was used in the HERS BESTEST, which was developed by the National Renewable Energy Laboratory (NREL) in support of RESNET Mortgage Industry National Home Energy Rating Standards. The base cases for this test suite, now included in Section 7 of Standard 140, involved a single-zone structure with an attic and either a slab-on-grade or basement foundation (Figure 7) that is representative of single family homes, which are the main focus of the RESNET HERS ruleset.

In addition to informing prioritization, representative building tests offer a framework for developing test case descriptions. For example, the existing Standard 140 tests typically evaluate impact of changes in efficiency levels of given components – e.g., change in infiltration rates, or thermal properties of the wall, or cooling system efficiency. The range or parameters included in the unit tests should reflect properties of the design elements of the PRM baseline model vs. minimally code compliant and high-performance designs. In addition, the PRM's "independent baseline" typically results in qualitative differences between baseline and proposed design models – e.g., changes from lightweight to mass walls, from constant volume to VAV systems, etc. The diagnostic unit tests should evaluate the sensitivity of results to such qualitative changes in test case configurations.

The proposed new tests are summarized in Table 28. Test suites involving multifamily and medium office prototypes are recommended as the first priority. While both building types should be supported, it will be more efficient to develop a test suite for one of the two first to inform development of the test suite for the second one. The representative building tests involving high-performance design are recommended as a medium priority, but some of the relevant design elements such as VRF heat pumps and DOAS units may be moved to high priority given the prevalence of these systems in commercial designs. The priorities for diagnostic unit tests included in Table 28 account for the prevalence of systems and components in the PRM models illustrated in Table 1 through Table 10 of this report, the relative impact of design elements on the PRM compliance outcome (system type weights) in Table 15, and the prioritization completed by the Standard 140 committee. However, these priorities may need to be adjusted based on findings from the representative building tests. The minimally code compliant designs category in Table 27 refers to designs having systems and components meeting but not exceeding the requirements of 90.1 2019 for the applicable system types.

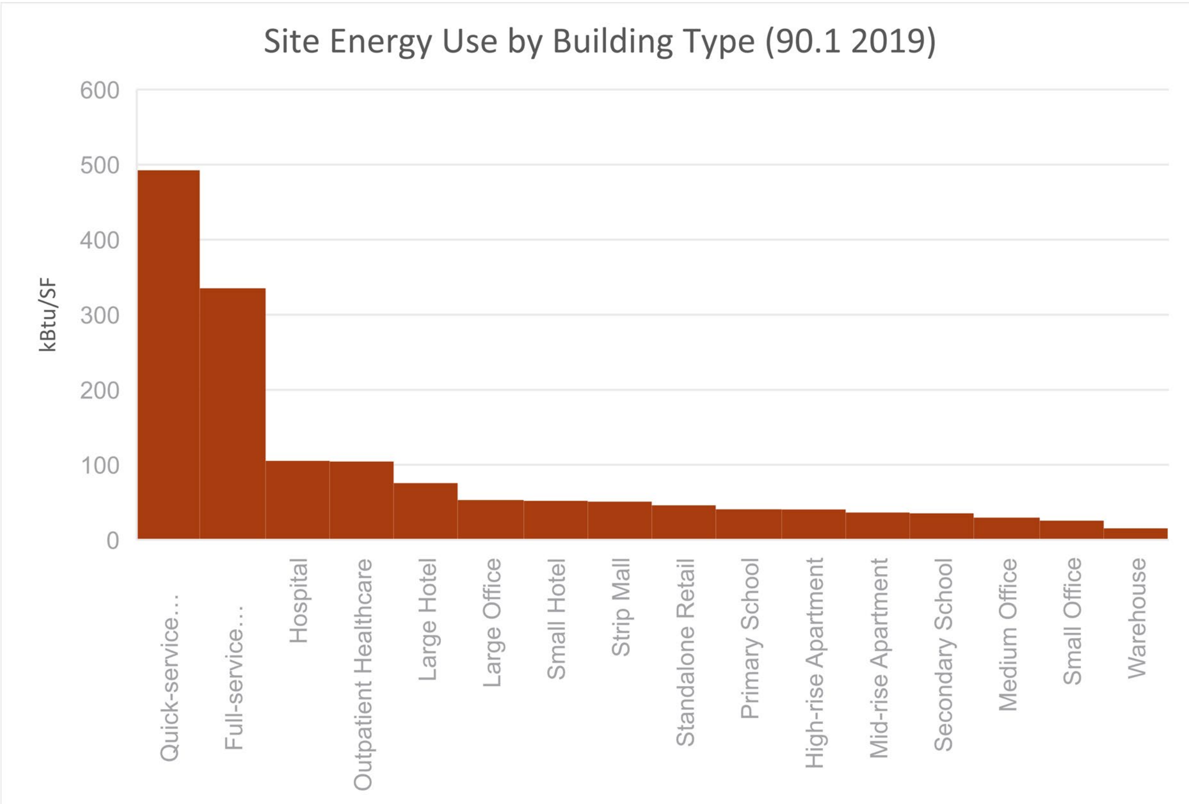
Table 28. Proposed New Standard 140 Tests and Priorities

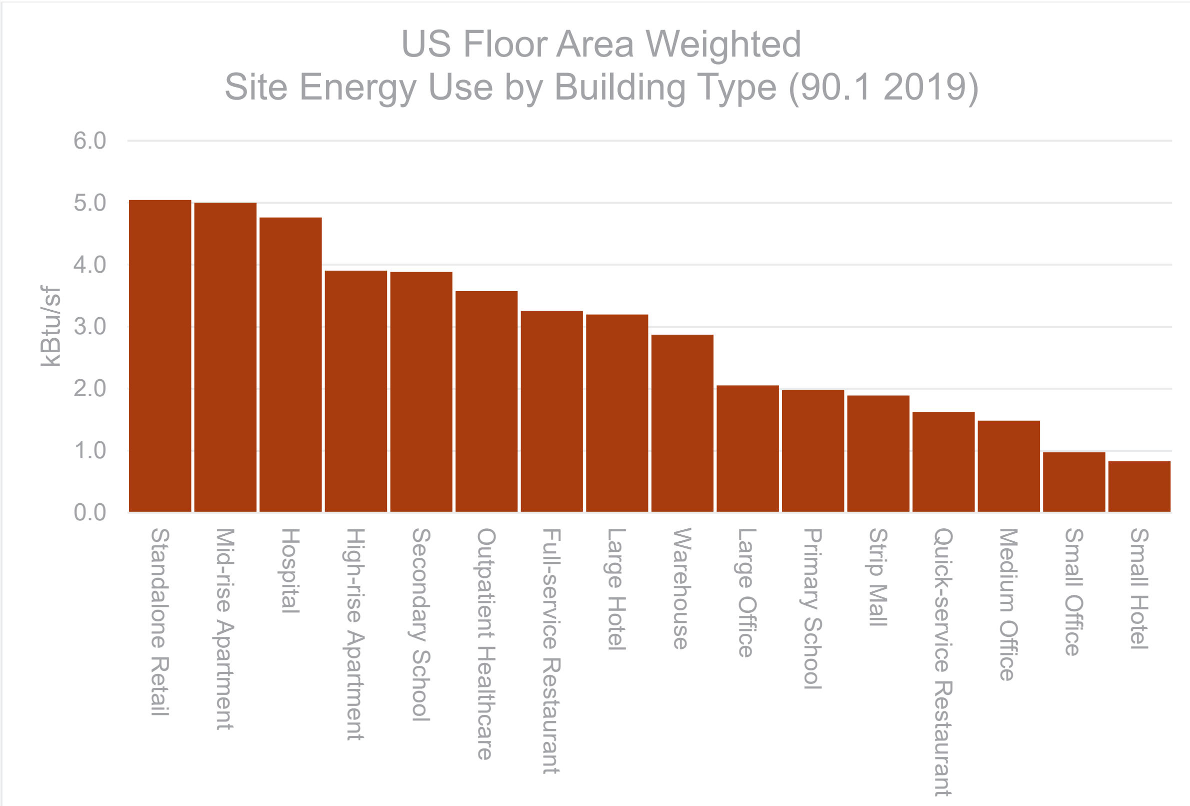
Focus of the New Test		High Priority	Medium Priority	Low Priority
Representative Building Tests				
Multifamily, PRM baseline		x		
Multifamily, minimally code compliant design		x		
Multifamily, high-performance design			x	
Medium office, PRM baseline		x		
Medium office, minimally code compliant design		x		
Medium office, high-performance design			x	
Diagnostic Unit Tests				
Interior daylighting		x		
Exterior daylighting				x
Comparative aid-side HVAC tests (Air-side HVAC BESTEST Volume 2)		x		
Exhaust air energy recovery		x		
Air-side HVAC controls				
	Optimal start	x		
	Supply air temperature reset	x		
	Variable speed drives	x		
	Static pressure reset	x		
	DCV	x		
Air-side HVAC systems				
	Dedicated outdoor air system	x		
	Perimeter radiation		x	
	VAV with parallel fan power boxes			x
	Radiant panels and chilled/cooled beams			x
Update HVAC BESTEST performance maps with empirical data		x		
Chiller plants				
	Air-cooled centrifugal and positive displacement	x		
	Water-cooled centrifugal and positive displacement		x	
	Heat recovery chillers			x
Hot water boilers		x		
Heat pumps				
	Air-source	x		
	Air-source VRF	x		
	Water-source		x	
	Water-source VRF			x
	Heat recovery VRF			x
	Ground source			x
Water-side HVAC controls and ancillary components				
	Hot water loop arrangement and controls (See Table 10)	x		
	Chilled water loop arrangement and controls (See Table 10)	x		
	Condenser loop arrangement and controls		x	
	Fluid economizers			x
Service water heating				
	Storage water heaters		x	
	Heat pump water heaters		x	
	External storage tanks		x	
	Instantaneous water heaters		x	
	Condenser heat recovery			x
	Thermal solar water heater			x
Envelope				
	Skylights	x		
	Weather-driven infiltration and natural ventilation		x	
	Automatically controlled shades, dynamic and special glazing			x
Transformers				x
Weather Data		X		

Appendix A – New Construction Building Area by Building Type and Climate Zone

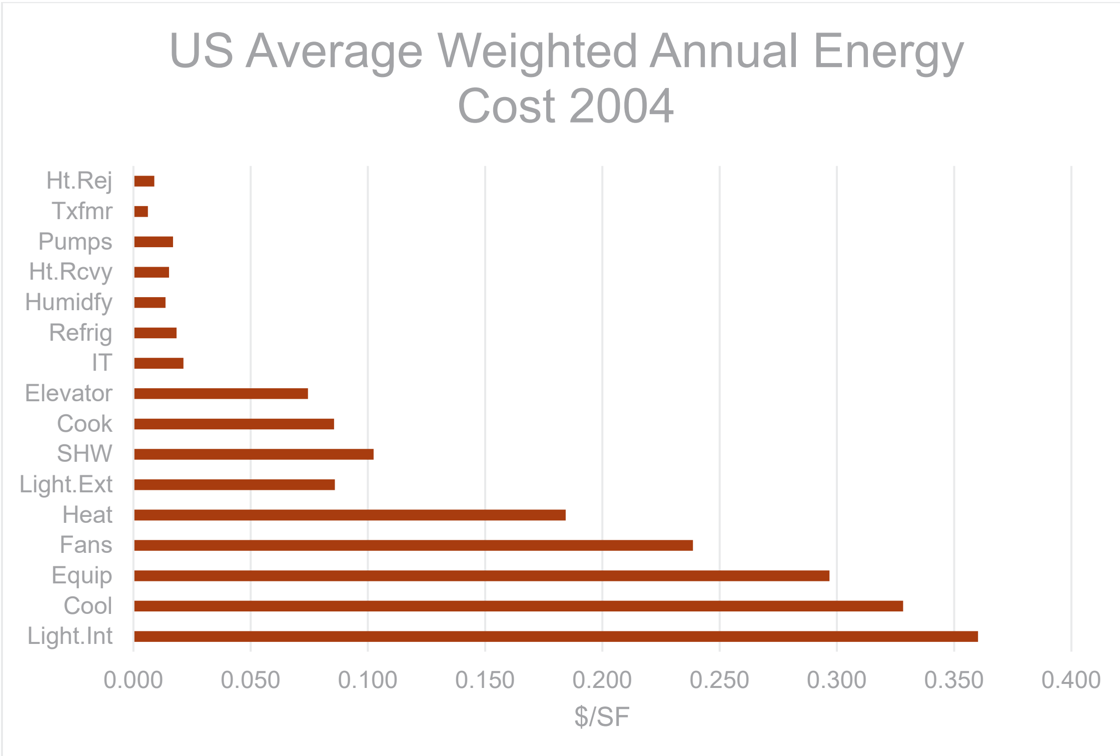
	1A	2B	2A	3B	3C	3A	4B	4C	4A	5B	5C	5A	6B	6A	7	8	Weights by Bldg Type
Large Office	0.11	0.54	0.07	0.54	0.26	0.23	1.13	0.00	0.24	0.48	0.15	0.00	0.09	0.00	0.01	0.00	3.86
Medium Office	0.14	0.78	0.19	0.73	0.45	0.16	0.95	0.03	0.17	0.88	0.31	0.00	0.17	0.03	0.02	0.00	5.01
Small Office	0.11	0.77	0.15	0.70	0.27	0.05	0.58	0.03	0.09	0.67	0.21	0.00	0.13	0.02	0.02	0.00	3.80
Stand-alone Retail	0.29	1.79	0.31	1.78	0.85	0.12	1.92	0.08	0.26	2.37	0.54	0.01	0.49	0.06	0.06	0.01	10.94
Strip Mall	0.16	0.63	0.14	0.70	0.42	0.09	0.66	0.02	0.09	0.61	0.12	0.00	0.06	0.01	0.01	0.00	3.71
Primary School	0.13	0.98	0.12	0.94	0.36	0.04	0.88	0.03	0.12	0.77	0.23	0.00	0.16	0.05	0.02	0.00	4.83
Secondary School	0.26	1.86	0.19	2.16	0.77	0.14	1.98	0.07	0.27	2.18	0.51	0.01	0.37	0.09	0.06	0.01	10.92
Hospital	0.09	0.75	0.11	0.63	0.32	0.10	0.92	0.03	0.13	0.95	0.23	0.01	0.20	0.03	0.03	0.00	4.52
Outpatient Healthcare	0.05	0.54	0.09	0.53	0.17	0.04	0.62	0.02	0.10	0.80	0.20	0.00	0.18	0.03	0.03	0.00	3.42
Full Service Restaurant	0.03	0.18	0.03	0.17	0.08	0.01	0.16	0.01	0.02	0.19	0.04	0.00	0.03	0.00	0.00	0.00	0.97
Quick Service Restaurant	0.01	0.07	0.01	0.06	0.02	0.00	0.06	0.00	0.00	0.07	0.02	0.00	0.01	0.00	0.00	0.00	0.33
Large Hotel	0.18	0.71	0.10	0.56	0.55	0.09	0.82	0.02	0.13	0.65	0.19	0.00	0.14	0.04	0.02	0.00	4.22
Small Hotel	0.03	0.30	0.02	0.27	0.11	0.02	0.30	0.01	0.03	0.27	0.10	0.00	0.08	0.03	0.02	0.00	1.59
Non-Refrigerated Warehouse	0.53	3.53	0.63	2.77	2.23	0.18	3.69	0.05	0.54	3.14	0.82	0.00	0.37	0.03	0.04	0.00	18.56
High-rise Apartment	1.44	1.19	0.08	0.57	0.63	0.29	3.26	0.00	0.49	1.36	0.19	0.00	0.11	0.01	0.00	0.00	9.64
Mid-rise Apartment	0.36	2.24	0.27	1.78	1.18	0.49	3.02	0.03	0.71	2.22	0.73	0.01	0.57	0.05	0.04	0.00	13.69
Weights by Zone	3.94	16.85	2.52	14.89	8.67	2.06	20.94	0.43	3.39	17.60	4.59	0.05	3.17	0.49	0.38	0.03	100.00

Appendix B – Site Energy Use by Building Type (PNNL 2019 end use tables)




US Floor Area Weighted
Site Energy Use by Building Type (90.1 2019)
kBtu/sf
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Standalone Retail
Mid-rise Apartment
Hospital
High-rise Apartment
Secondary School
Outpatient Healthcare
Full-service Restaurant
Large Hotel
Warehouse
Large Office
Primary School
Strip Mall
Quick-service Restaurant
Medium Office
Small Office
Small Hotel

Appendix C – US Average Annual Energy Cost and Cost Savings by End Use



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