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### Summary of Changes


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<tr>
<td>p. 18</td>
<td>Revise Table 2-6 to include newly added heating systems.</td>
</tr>
<tr>
<td>p. 19</td>
<td>Remove “or heat pump” from Section 2.4.2. description for modeling combined hydronic.</td>
</tr>
<tr>
<td>p. 21</td>
<td>Delete Section 2.4.2.3 since heat pump water heaters cannot be modeled in a combined hydronic system.</td>
</tr>
<tr>
<td>p. 25</td>
<td>Revise Table 2-7 to include newly added cooling systems.</td>
</tr>
<tr>
<td>p. 34</td>
<td>Modify Section 2.4.6.2 to correct the description for duct location modeling and reporting in a multi-family building.</td>
</tr>
<tr>
<td>p. 68-69</td>
<td>Water heating distribution systems in Section 2.10 were updated for consistency between the 2013 and 2016 compliance programs.</td>
</tr>
<tr>
<td>p. 70</td>
<td>Modify the standard design description for the recirculation system in buildings with central water heating.</td>
</tr>
</tbody>
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**APPENDIX C**

Revised to match the software for features that result in a special feature note or a HERS verification.

Revise water heating distribution systems to match the software.

**APPENDIX E**

| p. E-21 | Update load dependent energy factor (LDEF) calculations.                                                                                           |
| p. E-21 | Add a calculation for the annual average hourly adjusted load.                                                                                  |
| p. E-23 | Correct the reference to the Appliance Efficiency Regulations.                                                                                 |

**OTHER APPENDICES UNCHANGED**
ACKNOWLEDGMENTS

The Building Energy Efficiency Standards (Standards) were first adopted and put into effect in 1978 and have been updated periodically in the intervening years. The Standards are a unique California asset and have benefitted from the conscientious involvement and enduring commitment to the public good of many persons and organizations along the way. The 2013 Standards development and adoption process continued that long-standing practice of maintaining the Standards with technical rigor, challenging but achievable design and construction practices, public engagement and full consideration of the views of stakeholders.

The revisions in the 2013 Standards were conceptualized, evaluated and justified through the excellent work of Energy Commission staff and consultants. This document was created with the assistance of Energy Commission staff including Martha Brook, PE, Doug Herr, Jeff Miller, PE, Dee Anne Ross, and Danny Tam.

Other key technical staff contributors included Payam Bozorgchami, Tav Commins, Todd Ferris, Larry Froess, PE, Bill Pennington, Maziar Shirakh, PE, and the Energy Commission’s Web Team. Christopher Meyer, Office Manager of the Building Standards Office, and Dave Ashuckian, PE, Deputy Director of the Efficiency Division, provided policy guidance to the Staff. Galen Lemei provided legal counsel to the staff.

Special thanks to our key consultants, including Scott Criswell, Bruce Wilcox, Ken Nittler, Robert Scott, and Jennifer Roberts.
ABSTRACT

The 2013 Building Energy Efficiency Standards for Low-Rise Residential Buildings allow compliance by either a prescriptive or performance method. Performance compliance uses computer modeling software to trade off efficiency measures. For example, to allow more windows, the designer will specify more efficient windows, or to allow more west-facing windows they will install a more efficient cooling system. Computer performance compliance is typically the most popular compliance method because of the flexibility it provides in the building design.

Energy compliance software must be certified by the Energy Commission, following rules established for the modeling software. This document establishes the rules for the process of creating a building model, describing how the proposed design (energy use) is defined, how the standard design (energy budget) is established, and ending with what is reported on the Certificate of Compliance (CF1R). This document DOES NOT specify the minimum capabilities of vendor-supplied software. The Energy Commission reserves the right to approve vendor software for limited implementations of what is documented in this manual.

This Residential Alternative Calculation Methods (ACM) Reference Manual explains how the proposed and standard designs are determined. If the minimum heating system has 78 percent AFUE and the proposed building has a 92 percent AFUE furnace, the standard design is based on 78 percent and the proposed design gets credit for a 92 percent AFUE furnace. The desired result is a positive compliance margin showing how the building performs as compared to the standard design for heating, cooling, water heating, indoor air quality/ventilation, and water heating.

The 2013 Compliance Manager is the simulation and compliance rule implementation software specified by the Energy Commission. The Compliance Manager, called California Building Energy Code Compliance (CBECC), models all features that affect the energy performance of the building. This document establishes the process of creating a building model. Each section describes how a given component, such as a wall, is modeled for the proposed design, standard design, and ends with what is reported on the Certificate of Compliance (CF1R) for verification by the building enforcement agency.

Keywords: ACM, Alternative Calculation Method, Building Energy Efficiency Standards, California Energy Commission, California Building Energy Code Compliance, CBECC, Certificate of Compliance, CF1R, compliance manager, compliance software, computer compliance, energy budget, energy standards, energy use, performance compliance, design, proposed design, standard design

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1 Introduction

1.1 Purpose

This manual documents the rules used for modeling residential buildings for performance compliance under California’s 2013 Building Energy Efficiency Standards for Low-Rise Residential Buildings, similar to the Alternative Calculation Methods (ACM) used in the past to document software rules. This document explains how the standard design (energy budget) is established for a given building.

The 2013 Compliance Manager is the simulation and compliance rule implementation software specified by the Energy Commission. Beginning with the 2013 standards, compliance software requires greater modeling detail for buildings than previous compliance software programs. For example, attics, crawl spaces, basements, and attached unconditioned spaces (garages and storage) are defined in the building modeling software.

Documentation of detailed calculation algorithms is contained in the companion volume:

California Residential Alternative Calculation Method - Algorithms

This document is designed to establish the process of creating a building model. Each section describes how the proposed design (energy use) is defined, how the standard design (energy budget) is established, and ending with what is reported on the Certificate of Compliance (CFIR).

This Reference Manual documents the compliance analysis modeling rules for all aspects of the Energy Commission’s ACM Reference Method. This document DOES NOT specify the minimum capabilities of vendor-supplied software. The Energy Commission reserves the right to approve vendor software for limited implementations of what is documented in this manual.

1.2 Other Documents

The basis of this document is the 2013 Building Energy Efficiency Standards. Documents also relied on include the Reference Appendices for the 2013 Building Energy Efficiency Standards, and the 2013 Residential Compliance Manual.

Detailed modeling information for the software user can be found in the California Building Energy Code Compliance (CBECC) User Manual.
2 The Proposed Design and Standard Design

2.1 Overview

This chapter describes how the proposed design is modeled and how the standard design is established.

2.1.1 Proposed Design

The building configuration is defined by the user through entries for floor areas, wall areas, roof and ceiling areas, fenestration areas, and door areas. Each is entered along with performance characteristics such as U-factors, SHGC, thermal mass, etc. Information about the orientation and tilt is required for walls, fenestration and other elements. The user entries for all of these building elements are consistent with the actual building design and configuration. If the compliance software models the specific geometry of the building by using a coordinate system or graphic entry technique, the data generated is consistent with the actual building design and configuration.

2.1.2 Standard Design

For newly constructed buildings, the standard design building, from which the energy budget is established, is in the same location and has the same floor area, volume, and configuration as the proposed design, except that wall and window areas are distributed equally between the four main compass points, North, East, South and West. For additions and alterations, the standard design shall have the same wall and fenestration areas and orientations as the proposed building. The details are described below.

The space conditioning energy budget for the residential standards is the energy that would be used by a building similar to the proposed design if the proposed building met the requirements of the prescriptive standards. The process of generating the standard design is performed automatically by the compliance software, based on fixed and restricted inputs and assumptions. The process of custom budget generation shall not be accessible to program users for modification when the program is used for compliance purposes or when compliance forms are generated by the program.

The basis of the standard design is prescriptive Package A (from §150.1(c) of the standards, Table 150.1-A). Package A requirements (not repeated here) vary by climate zone. Reference Joint Appendix JA2, Table 2-1, contains the 16 California climate zones and their representative city. The climate zone can be found by city, county and zip code in JA2.1.1.

The following sections present the details on how the proposed design and standard design are determined. For many modeling assumptions, the standard design is the same as the proposed design. When a building has special features, for which the Commission has established alternate modeling assumptions the standard design features will differ from the proposed design so the
building receives appropriate credit for its efficiency. Typically, these measures require verification. Alternate features, such as zonal control, are documented as Special Features on the Certificate of Compliance. Verified features are also documented on the CF1R.

2.2 The Building

**PROPOSED DESIGN**

The building is defined through entries for zones, surfaces, and equipment. Zone types include attic, conditioned space, crawl space, basements, and garages. The roof (such as asphalt shingles or tile) is defined as either part of the attic or as part of a cathedral ceiling (also called a rafter roof). Surfaces separating conditioned space from exterior or unconditioned spaces (such as garage or storage) are modeled as interior walls adjacent to the unconditioned zone, as well as the exterior surfaces of an attached garage or storage space (modeled as an unconditioned zone). See Figure 2-1.

The input file will include entries for floor areas, wall, door, roof and ceiling areas, and fenestration areas, as well as the water heating, space conditioning, ventilation, and distribution systems.

Each area is entered along with performance characteristics, including building materials, U-factor and SHGC. The orientation and tilt (see Figure 2-2) is required for envelope elements.

Building elements are consistent with the actual building design and configuration.

**STANDARD DESIGN**

To determine the standard design for newly constructed buildings, a building with the same general characteristics (number of stories, attached garage, climate zone) with wall and window areas are distributed equally between the four main compass points (north, east, south and west) is created by the software. Energy features are set to be equal to §150.1(c) and Table 150.1-A. For additions and alterations, the standard design shall have the same wall and fenestration areas and orientations as the proposed building. The details are described below.

**VERIFICATION & REPORTING**

All inputs that are used to establish compliance requirements are reported on the CF1R for verification.

2.2.1 Climate and Weather

**PROPOSED DESIGN**

The user specifies either the zip code or the climate zone of the proposed building. If the zip code is specified the software selects the climate zone. Compliance requirements, weather, design temperatures, and Time Dependent Valuation (TDV) of energy factors are a function of the climate zone. Compliance software assumes that the ground surrounding residential buildings has a reflectivity of 20 percent in both summer and winter.
STANDARD DESIGN
The standard design climate zone is the same as the proposed design.

VERIFICATION & REPORTING
The zip code and climate zone of the proposed design is reported on the CF1R for verification.

Figure 2-1: Floor Plan

Figure 2-2: Surface Definitions

- Outside
- Inside

Walls have a tilt greater than 60 but less than 120 degrees from the horizontal

Roofs have a tilt less than 60 degrees from the horizontal

Floors have a tilt of 180 degrees from the horizontal

Garage modeled as an unconditioned zone, w/ walls, slab, roof, and metal roll-up or wood door
2.2.2 Standards Version

This input determines which federal appliance efficiency requirements for cooling equipment apply to the project. It allows the user to choose compliance that will be valid only before the federal requirements change or compliance that will be valid both before and after the change in January 2015. Eligibility for solar electric system credit is only allowed with Compliance 2015.

PROPOSED DESIGN

The user inputs a choice of:

Compliance 2014: valid only through December 2014 (with current federal air conditioning efficiency requirements)

Compliance 2015: valid any time (with 2015 federal air conditioning requirements) and solar credit.

STANDARD DESIGN

The standard design cooling equipment efficiency is based on the specified version of the federal requirements. If Compliance 2015 is selected, a minimum SEER and (if applicable) an EER that meets the 2015 standard for the type and size of equipment modeled.

VERIFICATION & REPORTING

Compliance version is reported on the CF1R.

2.2.3 PV System Credit

For users with single family and town house projects in climate zone 9 through 15 who select Compliance 2015 to comply under the updated federal appliance standards, there is a credit available for photovoltaic (PV) systems that meet the eligibility requirements of Residential Appendix RA4.6.1. The PV systems must be 2 kWdc or larger. The credit is the smaller of:

- PV Generation Rate (kTDV/kWdc) * kWdc
- Max PV Cooling Credit * Standard Design Cooling Energy (kTDV)

Where the factors are shown in Table 2-1.

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>PV Generation Rate (kTDV/kWdc)</th>
<th>Max PV Cooling Credit (% of Standard Design Cooling kTDV/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>09</td>
<td>30269</td>
<td>13%</td>
</tr>
<tr>
<td>10</td>
<td>30342</td>
<td>15%</td>
</tr>
<tr>
<td>11</td>
<td>29791</td>
<td>18%</td>
</tr>
<tr>
<td>12</td>
<td>29556</td>
<td>17%</td>
</tr>
<tr>
<td>13</td>
<td>29676</td>
<td>17%</td>
</tr>
<tr>
<td>14</td>
<td>31969</td>
<td>16%</td>
</tr>
<tr>
<td>15</td>
<td>29536</td>
<td>19%</td>
</tr>
</tbody>
</table>
PROPOSED DESIGN

For users in the applicable climate zone with the appropriate project type and standards version, the software allows the user to input the rated power of the solar system in kilowatts DC. The software automatically calculates the solar credit.

STANDARD DESIGN

The standard design has no PV system

VERIFICATION AND REPORTING

A solar credit is reported as a Special Feature on the CF1R.

2.2.4 Existing Condition Verified

This input is used for additions and alterations. The standard design assumption for existing conditions vary based on whether the existing conditions are verified by a HERS rater prior to construction. See Section 2.11.3 for more information.

PROPOSED DESIGN

The user inputs either yes or no. Yes indicates that the existing building conditions were verified by a HERS rater. Default assumption is no.

STANDARD DESIGN

The standard design assumptions are based on §150.2(b), Table 150.2-B. If the user input is no, or if less than two of the listed components are being altered, the standard design for all existing components is based on the values in the second column. If the proposed design response is yes and two or more of the listed components are being altered, the standard design value for all existing components is the value in the third column.

VERIFICATION & REPORTING

Verification of existing conditions is a special feature and is reported in the HERS Required Verification listings on the CF1R.

2.2.5 Air Leakage and Infiltration

Air leakage is a building level characteristic. The compliance software distributes the leakage over the envelope surfaces in accordance with the building configuration and constructs a pressure flow network to simulate the air flows between the conditioned zones, unconditioned zones and outside.

2.2.5.1 Building Air Leakage and Infiltration (cfm50 and ACH50)

The air flow through a blower door at 50 pascals (Pa) of pressure measured in cubic feet per minute is called cfm50. Cfm50 x 60 minutes divided by the volume of conditioned space is the air changes per hour at 50 Pa, called ACH50. Either cfm50 or ACH50 can be used to describe the building air leakage depending on the circumstances.
Specific data on ACH50 may be entered if the single family house or townhouse will have verified building air leakage testing. In multi-family buildings, due to the lack of an applicable measurement standard, ACH50 is fixed at the above defaults.

User input of an ACH50 less than the default value is a Special Feature that requires post-construction verification of building infiltration testing.

**PROPOSED DESIGN**

ACH50 defaults to 5 for new construction in single family buildings and townhomes and 7 for all other buildings that have heating and/or cooling system ducts outside of conditioned space and for buildings with no cooling system. In single-family buildings and townhomes with no heating and/or cooling system ducts in unconditioned space the default ACH50 is 4.4 and 6.2 for all others.

Specific data on ACH50 may be entered if the single family house or townhouse will have verified building air leakage testing. In multi-family buildings, due to the lack of an applicable measurement standard, ACH50 is fixed at the above defaults and is not a compliance variable. User input of an ACH50 less than the default value is a Special Feature that requires HERS verification.

**STANDARD DESIGN**

The standard design shall have 5 ACH50 for single family buildings and 7 for other buildings (ducted space conditioning).

**VERIFICATION AND REPORTING**

When the user chooses verified building air leakage testing (any value less than the standard design), diagnostic testing for reduced infiltration, with the details and target values modeled in the proposed design, is reported in the HERS Required Verification listing on the CF1R.

**2.2.5.2 Defining Air Net Leakage**

The compliance software creates an air leakage network for the proposed and standard design using the building description. Air leakage is distributed across the envelope surfaces according to the factors in Table 2-2. The air network is insensitive to wind direction. For buildings modeled with multiple conditioned zones, either a 20 square foot open door or 30 square foot open stairwell (in a multi-story building) is assumed between any two conditioned zones.

The only difference between the air network for the proposed and standard designs is the ACH50 if the user specifies a value lower than the default.

Multi-family buildings that have floors between dwelling units, must define each floor as a separate zone or each dwelling unit as a separate zone.
Table 2-2: Air Leakage Distribution

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Ceilings</th>
<th>Floors</th>
<th>Exterior Walls</th>
<th>House to Garage Surfaces</th>
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<tbody>
<tr>
<td>Slab on grade</td>
<td>50</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raised Floor</td>
<td>40</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Garage</td>
<td></td>
<td></td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Attached Garage</td>
<td></td>
<td></td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

2.2.6 Insulation Construction Quality

The compliance software user may specify either standard (unverified) or improved (verified high quality insulation installation, also called Quality Insulation Installation or QII) for the proposed design. Buildings with standard insulation installation are modeled in the program with lower performing cavity insulation in framed walls, ceilings and floors and with added winter heat flow between the conditioned zone and attic to represent construction cavities open to the attic (see Table 2-3). Standard insulation does not affect the performance of continuous sheathing in any construction.

**PROPOSED DESIGN**

The compliance software user may specify improved quality insulation installation at the building level. The default is unverified/standard insulation installation. See Section 2.3.3 for information on modeling spray foam insulation.

**STANDARD DESIGN**

The standard design is modeled with standard insulation installation quality.

**VERIFICATION AND REPORTING**

The presence of improved/verified high quality insulation installation is reported in the HERS Required Verification listings on the CF1R. Improved quality insulation installation is certified by the installer and field verified to comply with RA3.5. Credit for verified quality insulation installation is applicable to ceilings/attics, knee walls, exterior walls and exterior floors.

Table 2-3: Modeling Rules for Standard Insulation Installation Quality

<table>
<thead>
<tr>
<th>Component</th>
<th>Modification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walls, Floors, Attic Roofs, Cathedral Ceilings</td>
<td>Multiply the cavity insulation R-value/inch by 0.7</td>
</tr>
<tr>
<td>Ceilings below attic</td>
<td>Multiply the blown and batt insulation R-value/inch by 0.96-0.00347*R</td>
</tr>
<tr>
<td>Ceilings below attic</td>
<td>Add a heat flow from the conditioned zone to the attic of 0.015 times the area of the ceiling below attic times (the conditioned zone temperature - attic temperature) whenever the attic is colder than the conditioned space</td>
</tr>
</tbody>
</table>

For alterations to existing pre-1978 construction, if existing wall construction is assumed to have no insulation, no wall degradation is assumed for the existing wall.
2.2.7 Number of Bedrooms

**PROPOSED DESIGN**

The number of bedrooms in a building is used to establish mechanical ventilation requirements and to determine if a building qualifies as a compact building for purposes of incentive programs.

**STANDARD DESIGN**

The standard design shall have the same number of bedrooms as the proposed design.

**VERIFICATION AND REPORTING**

The number of bedrooms is reported on the CF1R for use in field verification.

2.2.8 Dwelling Unit Types

Internal gains and indoor air quality (IAQ) ventilation calculations depend on the conditioned floor area and number of bedrooms. For multi-family buildings with individual IAQ ventilation systems each different combination of bedrooms and conditioned floor area has a different minimum ventilation cfm that must be verified. A dwelling unit type is one or more dwelling units in the building, each of which has the same floor area, number of bedrooms and appliances.

**PROPOSED DESIGN**

For each dwelling unit type the user inputs the following information:

- Unit name
- Number of this unit in building
- Conditioned floor area (CFA) in square feet per dwelling unit
- Number of bedrooms

**STANDARD DESIGN**

The standard design shall have the same number and type of dwelling units as the proposed design.

**VERIFICATION AND REPORTING**

The number of units of each type and minimum IAQ ventilation for each unit is reported on the CF1R for use in field verification.

2.2.9 Front Orientation

The input for the building front orientation is the actual azimuth of the front of the building. This will generally be the side of the building where the front door is located. The orientation of the other sides of a building viewed from the outside looking at the front door are called front, left, right, back, or a value relative to the front, and the compliance software calculates the actual azimuth from this input. Multiple orientation compliance can be selected for newly constructed buildings only.
PROPOSED DESIGN

The user chooses whether compliance is for all orientations or for a site-specific orientation. For the specific orientation case, input the actual azimuth of the front in degrees.

STANDARD DESIGN

The compliance software constructs a standard design building that has 25 percent of the wall and window area facing each cardinal orientation.

VERIFICATION AND REPORTING

A typical reported value would be "290 degrees (west)". This would indicate that the front of the building faces north 70° west in surveyors terms. The closest orientation on 45° compass points should be reported in parenthesis, e.g., north, northeast, east, southeast, south, southwest, west or northwest. When compliance is shown for multiple orientations, "all orientations" or "cardinal" is reported as a Special Feature on the CF1R.

2.2.10 Natural Gas Availability

The user specifies whether natural gas is available at the site. This is used to establish the TDV values from Reference Appendices JA3 used by the compliance software in determining standard and proposed design energy use.

PROPOSED DESIGN

The user specifies whether natural gas is available at the site.

STANDARD DESIGN

The standard design TDV values for space heating are as defined in Section 2.4 and for water heating are as defined in Section 2.10.

VERIFICATION AND REPORTING

Whether natural gas is or is not available is reported on the CF1R.

2.2.11 Attached Garage

The user specifies whether there is an attached garage. The garage zone is modeled as an unconditioned zone (see Section 2.9).

PROPOSED DESIGN

The user specifies whether there is an attached unconditioned garage.

STANDARD DESIGN

The standard design has the same attached garage assumption as the proposed design.

VERIFICATION AND REPORTING

The presence of an attached garage is reported on the CF1R.
2.2.12 Lighting

The user specifies interior lighting and exterior lighting which are accounted for in internal gain assumptions. There are no tradeoffs between lighting and other building features.

PROPOSED DESIGN

Fraction of portable lighting, power adjustment multiplier and the exterior lighting power adjustment multiplier (Watts/ft²).

STANDARD DESIGN

The standard design lighting is set equal to the proposed lighting.

VERIFICATION AND REPORTING

No lighting information is reported on the CF1R.

2.2.13 Appliances

Appliance data is available for projects other than Title 24, Part 6 compliance. The information impacts internal gains with no effect on the Title 24 energy compliance margin.

PROPOSED DESIGN

The user specifies whether the following appliances are in the building, their fuel consumption or fuel type, and the zone that contains the appliance:

- Refrigerator (default or a specified kWh/yr)
- Dishwasher (default based on number of bedrooms or a specified kWh/yr)
- Clothes washer
- Clothes dryer
- Cooking appliances

STANDARD DESIGN

The standard design appliances are set equal to the proposed appliances.

VERIFICATION AND REPORTING

No appliance information is reported on the CF1R.
2.3 Building Envelope

2.3.1 Materials

Only materials approved by the Commission may be used in defining constructions. Additional materials may be added to the Compliance Manager. Table 2-4 shows the materials currently available for construction assemblies.

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Thickness (in.)</th>
<th>Conductivity (Btu/h·°F·ft)</th>
<th>Coefficient for Temperature Adjustment of Conductivity (°F·1)</th>
<th>Specific Heat (Btu/lb·°F)</th>
<th>Density (lb/ft³)</th>
<th>R-Value per Inch (°F·ft²·h/Btu-in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum Board</td>
<td>0.5</td>
<td>0.09167</td>
<td>0.27</td>
<td>40</td>
<td>0.9091</td>
<td></td>
</tr>
<tr>
<td>Wood layer</td>
<td>0.5</td>
<td>0.06127</td>
<td>0.45</td>
<td>41</td>
<td>1.36</td>
<td></td>
</tr>
<tr>
<td>R4 Synth Stucco</td>
<td>1</td>
<td>0.02083</td>
<td>0.00418</td>
<td>0.35</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>3 Coat Stucco</td>
<td>0.875</td>
<td>0.4167</td>
<td>0.2</td>
<td>116</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Carpet</td>
<td>0.5</td>
<td>0.02</td>
<td>0.34</td>
<td>12.3</td>
<td>4.1667</td>
<td></td>
</tr>
<tr>
<td>Light Roof</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
<td>120</td>
<td>0.0833</td>
<td></td>
</tr>
<tr>
<td>5 PSF Roof</td>
<td>0.5</td>
<td>1</td>
<td>0.2</td>
<td>120</td>
<td>0.0833</td>
<td></td>
</tr>
<tr>
<td>10 PSF Roof</td>
<td>1</td>
<td>1</td>
<td>0.2</td>
<td>120</td>
<td>0.0833</td>
<td></td>
</tr>
<tr>
<td>15 PSF Roof</td>
<td>1.5</td>
<td>1</td>
<td>0.2</td>
<td>120</td>
<td>0.0833</td>
<td></td>
</tr>
<tr>
<td>25 PSF Roof</td>
<td>2.5</td>
<td>1</td>
<td>0.2</td>
<td>120</td>
<td>0.0833</td>
<td></td>
</tr>
<tr>
<td>TileGap</td>
<td>0.75</td>
<td>0.07353</td>
<td>0.24</td>
<td>0.075</td>
<td>1.1333</td>
<td></td>
</tr>
<tr>
<td>SlabOnGrade</td>
<td>3.5</td>
<td>1</td>
<td>0.2</td>
<td>144</td>
<td>0.0833</td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>1</td>
<td>1</td>
<td>0.2</td>
<td>115</td>
<td>0.0833</td>
<td></td>
</tr>
<tr>
<td>Crawl</td>
<td>12</td>
<td>0.16667</td>
<td>0.24</td>
<td>0.075</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>SoftWood</td>
<td>0.08167</td>
<td>0.39</td>
<td>35</td>
<td>1.0204</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>1</td>
<td>0.2</td>
<td>144</td>
<td>0.0833</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1 Sheathing</td>
<td>1</td>
<td>0.08333</td>
<td>0.00418</td>
<td>0.35</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>R2 Sheathing</td>
<td>1</td>
<td>0.04167</td>
<td>0.00418</td>
<td>0.35</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>R3 Sheathing</td>
<td>1</td>
<td>0.02778</td>
<td>0.00418</td>
<td>0.35</td>
<td>1.5</td>
<td>3</td>
</tr>
<tr>
<td>R4 Sheathing</td>
<td>1</td>
<td>0.02083</td>
<td>0.00418</td>
<td>0.35</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>R5 Sheathing</td>
<td>1</td>
<td>0.01667</td>
<td>0.00418</td>
<td>0.35</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>R6 Sheathing</td>
<td>1</td>
<td>0.01389</td>
<td>0.00418</td>
<td>0.35</td>
<td>1.5</td>
<td>6</td>
</tr>
<tr>
<td>R7 Sheathing</td>
<td>1</td>
<td>0.0119</td>
<td>0.00418</td>
<td>0.35</td>
<td>1.5</td>
<td>7</td>
</tr>
<tr>
<td>R8 Sheathing</td>
<td>1</td>
<td>0.01042</td>
<td>0.00418</td>
<td>0.35</td>
<td>1.5</td>
<td>8</td>
</tr>
</tbody>
</table>

**Material Name**

The material name is used to select the material for a construction.
**THICKNESS**

Some materials, such as 3-coat stucco, are defined with a specific thickness (not editable by the compliance user). The thickness of other materials, such as softwood used for framing, is selected by the compliance user based on the constructions in the building.

**CONDUCTIVITY**

The conductivity of the material is the steady state heat flow per square foot, per foot of thickness, per degree Fahrenheit temperature difference. It is used in simulating the heat flow in the construction.

**COEFFICIENT FOR TEMPERATURE ADJUSTMENT OF CONDUCTIVITY**

The conductivity of insulation materials varies hourly with their temperature according to the coefficient listed. Other materials have a coefficient of 0 and their conductivity does not vary with temperature.

**SPECIFIC HEAT**

The specific heat is the amount of heat in Btu it takes to raise the temperature of one pound of the material one degree Fahrenheit.

**DENSITY**

The density of the material is its weight in pounds per cubic foot.

**R-VALUE PER INCH**

The R-value is the resistance to heat flow for a 1-inch thick layer.

### 2.3.2 Construction Assemblies

Constructions are defined by the compliance user for use in defining the building. The user assembles a construction from one or more layers of materials as shown in Figure 2-3. For framed constructions there is a framing layer that has parallel paths for the framing and the cavity between the framing members. The layers that are allowed depend on the surface type. The Compliance Manager calculates a winter design U-factor which is compared to a construction that meets the prescriptive standard. The U-factor is displayed as an aid to the user. The calculations used in the energy simulation are based on each individual layer and framing rather than the U-factor.
**ASSEMBLY TYPES**

The types of assemblies are:

- Exterior wall
- Interior wall
- Demising wall
- Knee wall
- Attic roof
- Cathedral roof
- Ceiling below attic
- Interior floor
- Exterior floor (over unconditioned space or exterior)
- Floor over crawl space

**CONSTRUCTION TYPE:**

1. Ceiling below attic (the roof structure is not defined here, but is part of the attic), wood or metal framed. In a residence with a truss roof, the ceiling is where the insulation is located. The structure above that is encompassed by the term attic or roof deck. The roof or attic consists of (moving from inside to outside) the radiant barrier, below deck insulation, framing, above deck insulation, and the asphalt, tile roofing. See more in Section 2.4.5.
2. Cathedral ceiling (with the roof defined as part of the assembly), wood or metal framed. Since there is no attic, the roof structure is connected to the insulated assembly at this point.

3. Roof, structurally insulated panels (SIP).

4. Walls (interior, or exterior), wood or metal framed, or SIP.

5. Floors (over exterior, over crawl space, or interior).

**CONSTRUCTION LAYERS:**

All assemblies have a cavity path and a frame path.

Spray foam insulation may use either default values with no special inspection requirements, or higher values when supported by an ICC report (see details Section 2.3.3 and RA3.5) verified by a HERS rater.

As assemblies are completed, the screen displays whether the construction meets the prescriptive requirement for that component.

**PROPOSED DESIGN**

The user defines a construction for each surface type included in the proposed design. Any variation in insulation R-value, framing size or spacing, interior or exterior sheathing or interior or exterior finish requires the user to define a different construction. Insulation R-values are based on manufacturer’s rated properties rounded to the nearest whole R. Layers such as sheetrock, wood sheathing, stucco and carpet whose properties are not compliance variables are included as generic layers with standard thickness and properties.

Walls separating the house from an attached unconditioned attic or garage are modeled as interior walls with unconditioned space as the adjacent zone, which the compliance manager recognizes as a demising wall. Floors over a garage are modeled as floor over exterior. The exterior walls, floor, ceiling/roof of the garage are modeled as part of the unconditioned garage zone.

**STANDARD DESIGN**

The compliance software assembles a construction that meets the prescriptive standards for each user-defined construction or assembly.

**VERIFICATION AND REPORTING**

All proposed constructions, including insulation, frame type, frame size, and exterior finish or exterior condition are listed on the CF1R. Non-standard framing (e.g., 24” on center wall framing, advanced wall framing) is reported as a special feature.
2.3.3 Spray Foam Insulation

The R-values for spray applied polyurethane foam insulation differs depending on whether the product is open cell or closed cell.

**Table 2-5: Required Thickness Spray Foam Insulation**

<table>
<thead>
<tr>
<th>Required R-values for SPF insulation</th>
<th>R-11</th>
<th>R-13</th>
<th>R-15</th>
<th>R-19</th>
<th>R-21</th>
<th>R-22</th>
<th>R-25</th>
<th>R-30</th>
<th>R-38</th>
</tr>
</thead>
<tbody>
<tr>
<td>Required thickness closed cell @ R5.8/inch</td>
<td>2.00 inches</td>
<td>2.25 inches</td>
<td>2.75 inches</td>
<td>3.50 inches</td>
<td>3.75 inches</td>
<td>4.00 inches</td>
<td>4.50 inches</td>
<td>5.25 inches</td>
<td>6.75 inches</td>
</tr>
<tr>
<td>Required thickness open cell @ R3.6/inch</td>
<td>3.0 inches</td>
<td>3.5 inches</td>
<td>4.2 inches</td>
<td>5.3 inches</td>
<td>5.8 inches</td>
<td>6.1 inches</td>
<td>6.9 inches</td>
<td>8.3 inches</td>
<td>10.6 inches</td>
</tr>
</tbody>
</table>

Additional documentation and verification requirements for a value other than default values shown in Table 2-5 is required (see RA3.5.6).

2.3.3.1 Medium Density Closed-Cell SPF Insulation

The default R-value for spray foam insulation with a closed cellular structure is R-5.8 per inch, based on the installed nominal thickness of insulation. Closed cell insulation has an installed nominal density of 1.5 to less than 2.5 pcf.

2.3.3.2 Low Density Open-Cell SPF Insulation

The default R-value for spray foam insulation with an open cellular structure is calculated as an R-3.6 per inch, calculated based on the nominal required thickness of insulation. Open cell insulation has an installed nominal density of 0.4 to 1.5 pounds per cubic foot (pcf).

**PROPOSED DESIGN**

The user will select either typical values for open cell or closed cell spray foam insulation or higher than typical values, and enter the total R-value (rounded to the nearest whole value).

**STANDARD DESIGN**

The compliance software assembles a construction that meets the prescriptive standards for each assembly type (ceiling/roof, wall, and floor).

**VERIFICATION AND REPORTING**

When the user elects to use higher than typical R-values for open cell or closed cell spray foam insulation, a special features note is included on the CF1R requiring documentation requirements specified in RA4.1.7. Additionally, a HERS verification requirement for the installation of spray foam insulation using higher than default values is included on the CF1R.
2.4 Building Mechanical Systems

The system is made up of the heating system, cooling system (if any), distribution system details and fans. The building ventilation cooling and indoor air quality ventilation systems are also defined at the building level for single family dwellings or as part of the dwelling unit information in multi-family buildings (see also Sections 2.4.9 and 2.4.10).

2.4.1 Heating Subsystems

The heating subsystem describes the equipment that supplies heat to an HVAC System. Heating systems are categorized according to the types show in Table 2-6.

**PROPOSED DESIGN**

The user selects the type and supplies inputs for the heating subsystem in the heating system data screen shown in Figure 2-4 and Figure 2-5. The user inputs the appropriate rated heating efficiency factor. The rated heating capacity is not a compliance variable and is calculated for use in the simulation by the compliance software for all systems except heat pumps. For heat pumps the user inputs the rated heating capacity at 47°F and 17°F for the heat pump compressor to be installed and the software sizes the backup electric resistance heat for use in the simulation.

Systems rated with a Coefficient of Performance (COP) only must calculate the Heating Seasonal Performance Factor (HSPF) for use in performance compliance:

\[
\text{Equation 2-1} \quad \text{HSPF} = (3.2 \times \text{COP}) - 2.4
\]

Until there is an approved compliance option for ductless heat pumps (mini-split, multi-split VRF systems) they are simulated as a split system equivalent to the standard design with default duct conditions.

**STANDARD DESIGN**

When electricity is used for heating, the heating equipment for the standard design is an electric split system heat pump with a Heating Seasonal Performance Factor (HSPF) meeting the Appliance Efficiency Regulations requirements for split systems with default ducts in the attic. The standard design heat pump compressor size is determined by the software based on the compressor size calculated for the air conditioning system.

When electricity is not used for heating, the equipment used in the standard design building is a gas furnace (or propane if natural gas is not available) with default ducts in the attic and an Annual Fuel Utilization Efficiency (AFUE) meeting the Appliance Efficiency Regulations minimum efficiency for central systems. When a proposed design uses both electric and non-electric heat, the standard design is a gas furnace.
**Table 2-6: HVAC Heating Equipment Descriptors**

<table>
<thead>
<tr>
<th>Recommended Descriptor</th>
<th>Heating Equipment Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CntrFurnace</td>
<td>Gas- or oil-fired central furnaces, propane furnaces or heating equipment considered equivalent to a gas-fired central furnace, such as wood stoves that qualify for the wood heat exceptional method. Gas fan-type central furnaces have a minimum AFUE=78%. Distribution can be gravity flow or use any of the ducted systems. (Efficiency metric: AFUE)</td>
</tr>
<tr>
<td>WallFurnGravity</td>
<td>Non-central gas- or oil-fired wall furnace, gravity flow. Equipment has varying efficiency requirements by capacity. Distribution is ductless. (Efficiency metric: AFUE)</td>
</tr>
<tr>
<td>WallFurnFan</td>
<td>Non-central gas- or oil-fired wall furnace, fan-forced. Non-central gas- or oil-fired wall furnace, gravity flow. Equipment has varying efficiency requirements by capacity. Distribution is ductless. (Efficiency metric: AFUE)</td>
</tr>
<tr>
<td>FloorFurnace</td>
<td>Non-central gas- or oil-fired floor furnace. Equipment has varying efficiency requirements by capacity. Distribution is ductless. (Efficiency metric: AFUE)</td>
</tr>
<tr>
<td>RoomHeater</td>
<td>Non-central gas- or oil-fired room heaters. Non-central gas- or oil-fired wall furnace, gravity flow. Equipment has varying efficiency requirements by capacity. Distribution is ductless. (Efficiency metric: AFUE)</td>
</tr>
<tr>
<td>WoodHeat</td>
<td>Wood-fired stove. In areas with no natural gas available, a wood heating system with any back-up heating system, is allowed to be installed if exceptional method criteria described in the Residential Compliance Manual are met. (Efficiency Metric: N/A)</td>
</tr>
<tr>
<td>Boiler</td>
<td>Gas or oil boilers. Distribution systems can be Radiant, Baseboard or any of the ducted systems. Boiler may be specified for dedicated hydronic systems. Systems in which the boiler provides space heating and fires an indirect gas water heater (IndGas) may be listed as Boiler/CombHydro Boiler and is listed under “Equipment Type” in the HVAC Systems listing. (Efficiency metric: AFUE)</td>
</tr>
<tr>
<td>SplitHeatPump</td>
<td>Heating side of a split heat pump heating system that has one or more outdoor units supply heat to each habitable space in the dwelling unit. Heat is at least partly distributed using one of the ducted systems. (Efficiency metric: HSPF)</td>
</tr>
<tr>
<td>SDHVSplitHeatPump</td>
<td>Heating side of a small duct, high velocity, split system that produces at least 1.2 inches of external static pressure when operated at the certified air volume rate of 220–350 CFM per rated ton of cooling and uses high velocity room outlets generally greater than 1,000 fpm that have less than 6.0 square inches of free area. (Efficiency Metric: HSPF)</td>
</tr>
<tr>
<td>DuctlessMiniSplitHeatPump</td>
<td>Heating side of a heat pump system that has single outdoor section and one or more ductless indoor sections. The indoor section(s) cycle on and off in unison in response to a single indoor thermostat (Efficiency Metric: HSPF)</td>
</tr>
<tr>
<td>DuctlessMultiSplitHeatPump</td>
<td>Heating side of a heat pump system that has a single outdoor section and two or more ductless indoor sections. The indoor sections operate independently and can be used to condition multiple zones in response to multiple indoor thermostats. (Efficiency Metric: HSPF)</td>
</tr>
<tr>
<td>DuctlessVRFHeatPump</td>
<td>Heating side of a variable refrigerant flow (VRF) heat pump system that has one or more outdoor sections and two or more ductless indoor sections. The indoor sections operate independently and can be used to condition multiple zones in response to multiple indoor thermostats. (Efficiency Metric: HSPF)</td>
</tr>
<tr>
<td>RoomHeatPump</td>
<td>Same as DuctlessHeatPumpSystem except that heat is not supplied to each habitable space in the dwelling unit. (Efficiency metric: COP)</td>
</tr>
<tr>
<td>PkgHeatPump</td>
<td>Heating side of central packaged heat pump systems. Central packaged heat pumps are heat pumps in which the blower, coils and compressor are contained in a single package, powered by single phase electric current, air cooled, rated below 65,000 Btuh. Distribution system is one of the ducted systems. (Efficiency metric: HSPF)</td>
</tr>
<tr>
<td>LrgPkgHeatPump</td>
<td>Heating side of large packaged units rated at or above 65,000 Btu/hr (heating mode). Distribution system is one of the ducted systems. These include water source and ground source heat pumps. (Efficiency metric: COP)</td>
</tr>
<tr>
<td>Electric</td>
<td>All electric heating systems other than space conditioning heat pumps. Included are electric resistance heaters, electric boilers and storage water heat pumps (air-water) (StoHP). Distribution system can be Radiant, Baseboard or any of the ducted systems.</td>
</tr>
<tr>
<td>CombHydro</td>
<td>Water heating system can be storage gas (StoGas, LgStoGas), storage electric (StoElec) or heat pump water heaters (StoHP). Distribution systems can be Radiant, Baseboard, or any of the ducted systems and can be used with any of the terminal units (FanCoil, RadiantFlr, Baseboard, and FanConv).</td>
</tr>
</tbody>
</table>
VERIFICATION AND REPORTING

The proposed heating system type and rated efficiency are reported in the compliance reports. The rated heating capacity of each proposed heat pump is reported on the CF1R so that installed size can be verified to be at least as large.

2.4.2 Combined Hydronic Space/Water Heating

Combined hydronic space/water heating is a system whereby a water heater is used to provide both space heating and water heating. Dedicated hydronic space heating systems are also an optional capability. Space heating terminals may include fan coils, baseboards, and radiant surfaces (floors, walls or ceilings).

For combined hydronic systems, the water heating portion is modeled in the normal manner. For space heating, an effective AFUE is calculated for gas water heaters. For electric water heaters, an effective HSPF is calculated. The procedures for calculating the effective AFUE or HSPF are described below.
Combined hydronic space conditioning cannot be combined with zonal control credit.

**PROPOSED DESIGN**

When a fan coil is used to distribute heat, the fan energy and the heat contribution of the fan motor must be considered. The algorithms for fans used in combined hydronic systems are the same as those used for gas furnaces and are described in Chapter 3.

If a large fan coil is used and air distribution ducts are located in the attic, crawlspace or other unconditioned space, the efficiency of the air distribution system must be determined using methods consistent with those described in Section 2.4.6. Duct efficiency is accounted for when the distribution type is ducted.

### 2.4.2.1 Large or Small Storage Gas Water Heater

When storage gas water heaters are used in combined hydronic applications, the effective AFUE is given by the following equation:

\[
AFUE_{\text{eff}} = RE - \frac{PL}{RI}
\]

Where:

- **AFUE_{\text{eff}}** = The effective AFUE of the gas water heater in satisfying the space heating load.
- **RE** = The recovery efficiency (or thermal efficiency) of the gas water heater. A default value of 0.70 may be assumed if the recovery efficiency is unknown. This value is generally available from the Energy Commission appliance directory.
- **PL** = Pipe losses (kBtu/h). This can be assumed to be zero when less than 10 feet of piping between the water heater storage tank and the fan coil or other heating elements are located in unconditioned space (see Equation RI).
- **RI** = The rated input of the gas water heater (kBtu/h) available from the Energy Commission’s appliance directory.

### 2.4.2.2 Storage Electric Water Heater

The HSPF of storage water heaters used for space heating in a combined hydronic system is given by the following equations.

\[
HSPF_{\text{eff}} = 3.413 \left[ 1 - \frac{PL}{3.413 kW_i} \right]
\]

Where:

- **HSPF_{\text{eff}}** = The effective HSPF of the electric water heater in satisfying the space heating load.
PL = Pipe losses (kBtu/h). This can be assumed to be zero when less than 10 feet of piping between the water heater storage tank and the fan coil or other heating elements are located in unconditioned space (see Equation).

RI = The kilowatts of input to the water heater available from the Energy Commission’s appliance directory.

**STANDARD DESIGN**

When electricity is used for heating, the heating equipment for the standard design is an electric split system heat pump with a Heating Seasonal Performance Factor (HSPF) meeting the Appliance Efficiency Regulations requirements for split systems, unless the proposed design is a room heat pump, in which case the standard design is the same. The standard design heat pump compressor size is determined by the software based on the compressor size calculated for the air conditioning system.

When electricity is not used for heating, the equipment used in the standard design building is a gas furnace (or propane if natural gas is not available) with default ducts in the attic and an Annual Fuel Utilization Efficiency (AFUE) meeting the Appliance Efficiency Regulations minimum efficiency for central systems. When a proposed design uses both electric and non-electric heat, the standard design is a gas furnace.

When propane is used for a combined hydronic system, the water heater is electric.

**2.4.3 Special Systems – Hydronic Distribution Systems and Terminals**

**PROPOSED DESIGN**

This listing is completed for hydronic systems that have more than 10 feet of piping (plan view) located in unconditioned space. As many rows as necessary may be used to describe the piping system.

**STANDARD DESIGN**

The standard design is established for a hydronic system in the same way as for a central system, as described in Section 2.4.1.

**VERIFICATION AND REPORTING**

A hydronic or combined hydronic system is reported in the *Special Features* listing on the CF1R.

Other information reported includes:

- **Piping Run Length (ft).** The length (plan view) of distribution pipe located in unconditioned space, in feet, between the primary heating/cooling source and the point of distribution.
- **Nominal Pipe Size (in.).** The nominal (as opposed to true) pipe diameter in inches.
- **Insulation Thickness (in.).** The thickness of the insulation in inches. Enter "none" if the pipe is uninsulated.
• **Insulation R-value (hr-ft²-°F/Btu).** The installed R-value of the pipe insulation. Minimum pipe insulation for hydronic systems is as specified in §150.1(j).

### 2.4.4 Ground Source Heat Pump

Until there is an approved compliance option for ground source heat pump systems to accurately represent this system, which uses the earth as a source of energy for heating and as a heat sink for energy when cooling, a split system equivalent to the standard design with default duct conditions is substituted for the proposed system. The mandatory efficiencies for ground water source heat pumps are a minimum Coefficient of Performance (COP) for heating and EER for cooling.

### 2.4.5 Cooling Subsystems

The cooling subsystem describes the equipment that supplies cooling to an HVAC System.

**Figure 2-6: Cooling System Data**

<table>
<thead>
<tr>
<th>Cooling System Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Currently Active Cooling System: Cooling Component 1</td>
</tr>
<tr>
<td>Name: Cooling Component 1</td>
</tr>
<tr>
<td>Type: SplitAirCond - Split air conditioning system</td>
</tr>
<tr>
<td>SEER: 13.0 [kBtu/h]/kW</td>
</tr>
<tr>
<td>EER: 11.3 [kBtu/h]/W</td>
</tr>
<tr>
<td>CFM per Ton: 360 [CFM/ton]</td>
</tr>
<tr>
<td>AC Charge: Verified</td>
</tr>
<tr>
<td>Refrigerant Type: R410A</td>
</tr>
</tbody>
</table>

**PROPOSED DESIGN**

The user selects the type of cooling equipment from Table 2-7 and enters basic information to model the energy use of the equipment. At a minimum, enter the cooling equipment descriptor, zoning type (Table 2-8), and SEER. The default is NotZonal. For ducted cooling systems the cooling air flow from the conditioned zone through the cooling coil is an input. The rated cooling capacity is not a compliance variable.

Until there is an approved compliance option for ductless heat pumps (mini-split, multi-split VRF systems) they are simulated as a split system equivalent to the standard design with default duct conditions.

See sections below for the details of specific inputs.

**STANDARD DESIGN**

The cooling system for the standard design building is a non zonal control split system air conditioner or heat pump meeting the minimum requirements of §150.1(c) and Table 150.1-A. The
standard design system shall assume verified refrigerant charge in climate zones 2 and 8 through 15 for all ducted split systems, ducted package systems, and mini-split systems. Mandatory fan efficacy is assumed in all climate zones.

**VERIFICATION AND REPORTING**

Information shown on the CF1R includes cooling equipment type, cooling efficiency (SEER and/or EER). Measures requiring verification are listed on the in the HERS Verification section of the CF1R.

### 2.4.5.1 Verified Refrigerant Charge or Charge Indicator Display

Proper refrigerant charge is necessary for electrically driven compressor air conditioning systems to operate at full capacity and efficiency. Software calculations set the compressor efficiency multiplier to 0.90 to account for the impact of improper refrigerant charge or 0.96 for proper charge.

**PROPOSED DESIGN**

The software allows the user to indicate if systems will have diagnostically tested refrigerant charge or a field verified charge indicator display (CID). This applies only to ducted split system and packaged air conditioners and heat pumps, as well as mini-split heat pumps.

**STANDARD DESIGN**

The standard design building is modeled with either diagnostically tested refrigerant charge or a field verified charge indicator display if the building is in climate zone 2 or 8 through 15, and is required by §150.1(c) and Table 150.1-A for the proposed cooling system type.

**VERIFICATION AND REPORTING**

These features require field verification or diagnostic testing and are reported in the HERS Required Verification listings on the CF1R. Details on refrigerant charge measurement are discussed in Reference Appendices, Residential Appendix RA. Information on the requirements for charge indicator displays is located in Reference Appendices, Joint Appendix JA6.1.
### Table 2-7: HVAC Cooling Equipment Descriptors

<table>
<thead>
<tr>
<th>Recommended Descriptor</th>
<th>Cooling Equipment Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NoCooling</td>
<td>Entered when the proposed building is not cooled or when cooling is optional (to be installed at some future date). Both the standard design equivalent building and the proposed design use the same default system (refer to section 2.4.8.3). (Efficiency metric: SEER)</td>
</tr>
<tr>
<td>SplitAirCond</td>
<td>Split air conditioning systems. Distribution system is one of the ducted systems. (Efficiency metric: SEER and EER)</td>
</tr>
<tr>
<td>PkgAirCond</td>
<td>Central packaged air conditioning systems less than 65,000 Btu cooling capacity. Distribution system is one of the ducted systems. (Efficiency metric: SEER and EER)</td>
</tr>
<tr>
<td>LrgPkgAirCond</td>
<td>Large packaged air conditioning systems rated at or above 65,000 Btu/hr (cooling capacity). Distribution system is one of the ducted systems. (Efficiency metric: EER)</td>
</tr>
<tr>
<td>SDHVSplitAirCond</td>
<td>Small duct, high velocity, split A/C system. (Efficiency Metric: SEER)</td>
</tr>
<tr>
<td>DuctlessSplitAirCondSystem</td>
<td>One or more split air conditioning outdoor units that use refrigerant to transport cooling to at least one terminal in each habitable space in the dwelling unit. These include small ductless mini-split and multiple-split heat air conditioners and packaged terminal (commonly called “through-the-wall”) units. Cooling is not distributed using ducts either inside or outside of the conditioned space. (Efficiency metric: EER)</td>
</tr>
<tr>
<td>RoomAirCond</td>
<td>Same as DuctlessSplitAirCondSystem except that cooling is not supplied to each habitable space in the dwelling unit. (Efficiency metric: EER)</td>
</tr>
<tr>
<td>SplitHeatPump</td>
<td>Cooling side of split heat pump systems. Distribution system is one of the ducted systems. (Efficiency metric: SEER and EER&lt;65,000 Btu/hr EER&gt;65,000 Btu/hr)</td>
</tr>
<tr>
<td>PkgHeatPump</td>
<td>Cooling side of central single-packaged heat pump systems with a cooling capacity less than 65,000 Btu/hr. Distribution system is one of the ducted systems. (Efficiency metric: SEER)</td>
</tr>
<tr>
<td>LrgPkgHeatPump</td>
<td>Cooling side of large packaged heat pump systems rated at or above 65,000 Btu/hr (cooling capacity). Distribution system is one of the ducted systems. (Efficiency metric: EER)</td>
</tr>
<tr>
<td>GasCooling</td>
<td>Gas absorption cooling. Three descriptors, COP95 (the rated COP for the gas portion), CAP95 (the rated capacity), and PPC (the parasitic electric energy at rated conditions in Watts).</td>
</tr>
<tr>
<td>SDHVSplitHeatPump</td>
<td>Cooling side of a small Duct, High Velocity, heat pump system (Efficiency Metric: SEER)</td>
</tr>
<tr>
<td>DuctlessMiniSplitAirCond</td>
<td>Ductless mini-split A/C system. (Efficiency Metric: SEER)</td>
</tr>
<tr>
<td>DuctlessMultiSplitAirCond</td>
<td>Ductless multi-split A/C system. (Efficiency Metric: SEER)</td>
</tr>
<tr>
<td>DuctlessVRFAirCond</td>
<td>Ductless variable refrigerant flow (VRF) A/C system. (Efficiency Metric: SEER)</td>
</tr>
<tr>
<td>DuctlessMiniSplitHeatPump</td>
<td>Cooling side of a heat pump system that has single outdoor section and one or more ductless indoor sections. The indoor section(s) cycle on and off in unison in response to a single indoor thermostat. (Efficiency Metric: SEER)</td>
</tr>
<tr>
<td>DuctlessMultiSplitHeatPump</td>
<td>Cooling side of a heat pump system that has a single outdoor section and two or more ductless indoor sections. The indoor sections operate independently and can be used to condition multiple zones in response to multiple indoor thermostats. (Efficiency Metric: SEER)</td>
</tr>
<tr>
<td>DuctlessVRFHeatPump</td>
<td>Cooling side of a variable refrigerant flow (VRF) heat pump system that has one or more outdoor sections and two or more ductless indoor sections. The indoor sections operate independently and can be used to condition multiple zones in response to multiple indoor thermostats. (Efficiency Metric: SEER)</td>
</tr>
<tr>
<td>RoomHeatPump</td>
<td>Same as DuctlessHeatPumpSystem except that cooling is not supplied to each habitable space in the dwelling unit. (Efficiency metric: SEER)</td>
</tr>
<tr>
<td>EvapDirect</td>
<td>Direct evaporative cooling systems. Assume minimal efficiency air conditioner. The default distribution system location is DuctAttic; evaporative cooler duct insulation requirements are the same as those for air conditioner ducts. (Efficiency metric: SEER)</td>
</tr>
<tr>
<td>EvapIndirDirect</td>
<td>Indirect-direct evaporative cooling systems. Assume energy efficiency ratio of 13 EER. Requires air flow and media saturation effectiveness from the CEC directory.</td>
</tr>
<tr>
<td>EvapIndirect</td>
<td>Indirect cooling systems. The default distribution system location is DuctAttic; evaporative cooler duct insulation requirements are the same as those for air conditioner ducts. Assume energy efficiency ratio of 13 EER. Requires air flow and media saturation effectiveness from the CEC directory.</td>
</tr>
<tr>
<td>Evap/CC</td>
<td>Evaporatively Cooled Condensers. A split mechanical system, with a water-cooled condenser coil. (Efficiency metric: EER)</td>
</tr>
</tbody>
</table>
Table 2-8: Cooling Zonal Control Descriptors

<table>
<thead>
<tr>
<th>Zoning Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZonalSingleSpeed</td>
<td>A ducted cooling system with a single speed compressor and zone control dampers</td>
</tr>
<tr>
<td>ZonalMultiSpeed</td>
<td>A ducted cooling system with a multiple speed or variable speed compressor and zone control dampers</td>
</tr>
<tr>
<td>ZonalSingleSpeedBypass</td>
<td>A zonally controlled HVAC system with a bypass duct</td>
</tr>
<tr>
<td>ZonalSingleSpeedNoBypass</td>
<td>A zonally controlled HVAC system with no bypass duct</td>
</tr>
<tr>
<td>NotZonal</td>
<td>Any cooling system that has no zone control dampers</td>
</tr>
</tbody>
</table>

Table 2-9: Summary of Air Conditioning Measures Requiring Verification

<table>
<thead>
<tr>
<th>Measure</th>
<th>Description</th>
<th>Procedures (Need Update)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verified Refrigerant Charge</td>
<td>Air-cooled air conditioners and air-source heat pumps be diagnostically tested to verify that the system has the correct refrigerant charge. The system must also meet the system airflow requirement.</td>
<td>RA3.2, RA1.2</td>
</tr>
<tr>
<td>Verified Charge Indicator Display</td>
<td>A Charge Indicator Display can be installed as an alternative to refrigerant charge testing.</td>
<td>RA3.4.2</td>
</tr>
<tr>
<td>Verified System Airflow</td>
<td>When compliance requires verified System Airflow greater than or equal to a specified criterion.</td>
<td>RA3.3</td>
</tr>
<tr>
<td>Verified Air-handling Unit Fan Efficacy</td>
<td>To verify that Fan Efficacy (Watt/cfm) is less than or equal to a specified criterion.</td>
<td>RA3.3</td>
</tr>
<tr>
<td>Verified EER</td>
<td>Credit for increased EER by installation of specific air conditioner or heat pump models.</td>
<td>RA3.4.3, RA3.4.4.1</td>
</tr>
<tr>
<td>Verified SEER</td>
<td>Credit for increased SEER.</td>
<td>RA3.4.3, RA3.4.4.1</td>
</tr>
<tr>
<td>Evaporatively Cooled Condensers</td>
<td>Must be combined with duct leakage testing, refrigerant charge, and verified EER.</td>
<td>RA3.1, RA3.1.4.3, RA3.2, RA1.2, RA3.4.3, RA3.4.4.1</td>
</tr>
</tbody>
</table>

2.4.5.2 Verified System Airflow

Adequate airflow from the conditioned space is required to allow ducted air conditioning systems to operate at their full efficiency and capacity. Efficiency is achieved by the air distribution system design, by improving the efficiency of motors or air distribution systems with less resistance to airflow. Software calculations account for the impact of airflow on sensible heat ratio and compressor efficiency.

PROPOSED DESIGN

The default cooling airflow is 150 cfm/ton for ZonalSingleSpeed systems and 350 cfm/ton for all other ducted cooling systems. Users may model a higher airflow and receive credit in the compliance calculation if greater verified system airflow is diagnostically tested using the procedures of Reference Appendices, Residential Appendix RA3.
If no cooling system is installed, this value is assumed to be 16.8 cfm/1000 Btu furnace nominal output specified by the manufacturer.

**STANDARD DESIGN**

The standard design shall assume a system that complies with mandatory and prescriptive requirements for the applicable climate zone.

**VERIFICATION AND REPORTING**

The airflow rate verification compliance target (cfm or cfm/ton) is reported in the *HERS Required Verification* listings of the CF1R. When there is no cooling system it is reported on the CF1R as a special feature.

### 2.4.5.3 Verified Air Handling Unit Fan Efficacy

The mandatory requirement in §150.0(m)13 is for an air-handling unit fan efficacy less than or equal to 0.58 Watts/cfm as verified by a HERS rater. The alternative to HERS verification of 0.58 Watts/cfm is HERS verification of a return duct design that conforms to the specification given in Table 150.0-C or D. However, if a value less than 0.58 Watts/cfm is modeled by the software user for compliance credit, the system fan efficacy value modeled by the user shall be verified by a HERS Rater, and the alternative return duct design method using Table 150.0(m)13 is not allowed for use in demonstrating compliance.

**PROPOSED DESIGN**

The software shall allow the user to enter the fan efficacy. The default mandatory value is 0.58 W/cfm. However, users may specify a lower value and receive credit in the compliance calculation if verified and diagnostically tested using the procedures of Reference Appendices, Residential Appendix RA3.3.

If no cooling system is installed, this value is assumed to be 0.58 W/cfm.

**STANDARD DESIGN**

The standard design shall assume a verified fan efficacy complying with the mandatory requirement for less than or equal to 0.58 Watts/cfm.

**VERIFICATION AND REPORTING**

For user inputs lower than the default mandatory 0.58 Watts/cfm, fan efficacy is reported in the *HERS Required Verification* listings of the CF1R.

For default mandatory 0.58 Watts/cfm, the choice of either Fan Efficacy or Alternative Return duct design according to Table 150.0-C,D is reported in the *HERS Required Verification* listings of the CF1R.

When there is no cooling system it is reported on the CF1R as a special feature.
2.4.5.4 Verified Energy Efficiency Ratio (EER)

**PROPOSED DESIGN**

Software shall allow the user the option to enter an EER rating for central cooling equipment in “compliance 2014” mode (a HERS verified measure). For equipment that is rated only with an EER (some evaporative coolers, room air conditioners), the user will enter the EER as an SEER. For “compliance 2015,” the Appliance Efficiency Regulations require a minimum SEER and EER for central cooling equipment. When using compliance 2015, only if a value higher than 11.7 EER is shown for central cooling equipment, is it reported as a HERS verified measure.

**STANDARD DESIGN**

The standard design for 2014 does not include an EER rating for cooling equipment. For compliance 2015, the standard design for central air conditioning equipment is 11.7 EER.

**VERIFICATION AND REPORTING**

Verified EER is reported in the HERS Required Verification listings on the CF1R for 2014 compliance. For 2015, EER verification is only required if higher than 11.7 EER is modeled. The EER rating is verified using rating data from AHRI Directory of Certified Product Performance at [www.ahridirectory.org](http://www.ahridirectory.org) or another directory of certified product performance ratings approved by the Commission for determining compliance.

2.4.5.5 Verified Seasonal Energy Efficiency Ratio (SEER)

**PROPOSED DESIGN**

The software allows the user to specify the SEER value.

**STANDARD DESIGN**

The standard design is based on the default minimum efficiency SEER for the type of cooling equipment modeled in the proposed design, based on the applicable Appliance Efficiency Regulations. For central cooling equipment, the minimum efficiency becomes 14 SEER and 11.7 EER in 2015.

**VERIFICATION AND REPORTING**

If a SEER higher than the default minimum efficiency is modeled in software, the SEER requires field verification. The higher than minimum SEER rating is verified using rating data from AHRI Directory of Certified Product Performance at [www.ahridirectory.org](http://www.ahridirectory.org) or another directory of certified product performance ratings approved by the Commission for determining compliance. Verified SEER is reported in the HERS Required Verification listings on the CF1R.
2.4.5.6 Verified Evaporatively-Cooled Condensers

**PROPOSED DESIGN**
Software shall allow users to specify an evaporatively-cooled condensing unit. The installation must comply with the requirements of RA4.3.2 to ensure the predicted energy savings are achieved. This credit must be combined with verified refrigerant charge testing, EER, and duct leakage testing.

**STANDARD DESIGN**
The standard design is based on a split system air conditioner meeting the requirements of §150.1(c) and Table 150.1-A.

**VERIFICATION AND REPORTING**
An evaporatively-cooled condensing unit, verified EER, and duct leakage testing are reported in the HERS Required Verification listings on the CF1R.

2.4.5.7 Evaporative Cooling
Evaporative cooling technology is best suited for dry climates where direct and/or indirect cooling of the supply air stream can occur without compromising indoor comfort. Direct evaporative coolers are the most common system types currently available, but provide less comfort and deliver more moisture to the indoor space. They are assumed to be equivalent to a minimum split system air conditioner. The evaporative cooling modeling methodology addresses two performance issues. The first performance issue is rising indoor relative humidity during periods with extended cooler operation. Since modeling of indoor air moisture levels is beyond the capability of simulation models, a simplified algorithm is used to prohibit evaporative cooler operation during load hours when operation is expected to contribute to uncomfortable indoor conditions. The algorithm disallows cooler operation when outdoor wet bulb temperatures are 70°F, or above. The second performance issue relates to evaporative cooler capacity limitations. Since evaporative coolers are 100 percent outdoor air systems, their capacity is limited by the outdoor wet bulb temperature. Each hour with calculated cooling load, the algorithm will verify that the cooling capacity is greater than the calculated house cooling load.

**PROPOSED DESIGN**
Software shall allow users to specify one of three types of evaporative cooling: (1) direct evaporative cooler is the most commonly available system type, (2) indirect, or (3) indirect-direct. Product specifications and other modeling details are found in the Energy Commission appliance directory for evaporative cooling. Direct system types are assigned an efficiency of 13 SEER (or minimum appliance efficiency standard for split system cooling). The default system type is evaporative direct. For indirect or indirect-direct, select the appropriate type, from the Energy Commission appliance directory and input a 13 EER as well as the air flow and media saturation effectiveness or cooling effectiveness from the Energy Commission appliance directory.

**STANDARD DESIGN**
The standard design is based on a split system air conditioner meeting the requirements of §150.1(c) and Table 150.1-A.
VERIFICATION AND REPORTING

When a direct evaporative cooling system is modeled, the system type and minimum efficiency are shown in the appropriate section of the CF1R. When indirect or indirect-direct evaporative cooling is modeled, the EER verification is shown in the HERS verification section of the CF1R along with the system type, air flow and system effectiveness.

2.4.6 Distribution Subsystems

If multiple HVAC distribution systems serve a building each system and the conditioned space it serves may be modeled in detail separately or the systems may be aggregated together and modeled as one large system. If the systems are aggregated together they must be the same type and all meet the same minimum specifications.

For the purposes of duct efficiency calculations, the supply duct begins at the exit from the furnace or air handler cabinet.

Figure 2-7: Distribution System Data

<table>
<thead>
<tr>
<th>Distribution System Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Currently Active Distribution System:</td>
</tr>
<tr>
<td>Name:</td>
</tr>
<tr>
<td>Type:</td>
</tr>
<tr>
<td>Has Bypass Duct</td>
</tr>
<tr>
<td>Low Leakage Air Handler</td>
</tr>
<tr>
<td>Use all distribution system defaults</td>
</tr>
<tr>
<td>Duct Leakage:</td>
</tr>
<tr>
<td>Duct Insulation R-value:</td>
</tr>
</tbody>
</table>

2.4.6.1 Distribution Type

PROPOSED DESIGN

The compliance software shall allow the user to select from the basic types of HVAC distribution systems and locations listed in Table 2-10. For ducted systems, the default location of the HVAC ducts and the air handler are in conditioned space for multi-family buildings and in the attic for all other buildings.

The software will allow users to select default assumptions or specify any of the verified or diagnostically tested HVAC distribution system conditions in the proposed design (see Figure 2-7)
and Table 2-11), including duct leakage target, R-value, supply and return duct area, diameter and location.

Until there is an approved compliance option for ductless heat pumps (mini-split, multi-split VRF systems) they are simulated as a split system equivalent to the standard design with default duct conditions.
### Table 2-10: HVAC Distribution Type and Location Descriptors

<table>
<thead>
<tr>
<th>Recommended Descriptors</th>
<th>HVAC Distribution Type and Location Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Distribution Systems</td>
<td>Fan-powered, ducted distribution systems that can be used with most heating or cooling systems. When ducted systems are used with furnaces, boilers, or combined hydronic/water heating systems the electricity used by the fan is calculated. R-value is specified in &quot;Duct R-value&quot; column when a ducted system is specified.</td>
</tr>
<tr>
<td>Ducts located in unconditioned attic</td>
<td>Ducts located overhead in the unconditioned attic space.</td>
</tr>
<tr>
<td>Ducts located in a crawl space</td>
<td>Ducts located under floor in the crawl space.</td>
</tr>
<tr>
<td>Ducts located in a garage</td>
<td>Ducts located in an unconditioned garage space.</td>
</tr>
<tr>
<td>Ducts located within the conditioned space (except &lt; 12 lineal ft)</td>
<td>Ducts located within the conditioned floor space except for less than 12 linear feet of duct, furnace cabinet and plenums, typically an HVAC unit in the garage mounted on return box with all other ducts in conditioned space.</td>
</tr>
<tr>
<td>Ducts located entirely in conditioned space</td>
<td>HVAC unit or systems with all HVAC ducts (supply and return) located within the conditioned floor space. Location of ducts in conditioned space eliminates conduction losses but does not change losses due to leakage. Leakage from either ducts that are not tested for leakage or from sealed ducts is modeled as leakage to outside the conditioned space.</td>
</tr>
<tr>
<td>Distribution system without ducts</td>
<td>Air distribution systems without ducts such as ductless split system air conditioners and heat pumps, window air conditioners, through-the-wall heat pumps, wall furnaces, floor furnaces, radiant electric panels, combined hydronic heating equipment, electric baseboards or hydronic baseboard finned-tube natural convection systems, etc.</td>
</tr>
<tr>
<td>Ducts located in outdoor locations</td>
<td>Ducts located in exposed locations outdoors.</td>
</tr>
<tr>
<td>Verified low leakage ducts located entirely in conditioned space</td>
<td>Duct systems for which air leakage to outside is equal to or less than 25 cfm when measured in accordance with Reference Appendices, Residential Appendix RA3.1.</td>
</tr>
<tr>
<td>Ducts located in multiple places</td>
<td>Ducts with different supply and return duct locations.</td>
</tr>
</tbody>
</table>

### Table 2-11: Summary of Verified Air Distribution Systems

<table>
<thead>
<tr>
<th>Measure</th>
<th>Description</th>
<th>Procedures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verified Duct Sealing</td>
<td>Mandatory measures require that space conditioning ducts be sealed. Field verification and diagnostic testing is required to verify that approved duct system materials are utilized and that duct leakage meets the specified criteria.</td>
<td>RA3.1.4.3</td>
</tr>
<tr>
<td>Verified Duct Location, Reduced Surface Area and R-value</td>
<td>Compliance credit can be taken for improved supply duct location, reduced surface area and R-value. Field verification is required to verify that the duct system was installed according to the duct design, including location, size and length of ducts, duct insulation R-value and installation of buried ducts. For buried ducts measures Verified Insulation Construction Quality (QII) is required as well as duct sealing.</td>
<td>RA3.1.4.1, 3.1.4.1.1</td>
</tr>
<tr>
<td>Low Leakage Ducts in Conditioned Space</td>
<td>When the Standards specify use of the procedures in Section RA3.1.4.3.8 to determine if space conditioning system ducts are located entirely in directly conditioned space, the duct system location is verified by diagnostic testing. Compliance credit can be taken for verified duct systems with low air leakage to the outside when measured in accordance with Reference Appendices, Residential Appendix Section RA3.1.4.3.8. Field Verification for ducts in conditioned space is required. Duct sealing is required.</td>
<td>RA3.1.4.3.8</td>
</tr>
<tr>
<td>Measure</td>
<td>Description</td>
<td>Procedures</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>---------------</td>
</tr>
<tr>
<td>Low Leakage Air-handling Units</td>
<td>Compliance credit can be taken for installation of a factory sealed air handling unit tested by the manufacturer and certified to the Commission to have met the requirements for a Low Leakage Air-Handling Unit achieved. Field verification of the air handler’s model number is required. Duct Sealing is required.</td>
<td>RA3.1.4.3.9</td>
</tr>
<tr>
<td>Verified Return Duct Design</td>
<td>Verification to confirm that the return duct design conforms to the criteria given in Table 150.0-C or Table 150.0-D as an alternative to meeting 0.58 W/cfm fan efficacy of §150.0(m).</td>
<td>RA3.1.4.4</td>
</tr>
<tr>
<td>Verified Air Filter Device Design</td>
<td>Verification to confirm that the air filter devices conform to the requirements given in §150.0(m)12.</td>
<td>RA3.1.4.5</td>
</tr>
<tr>
<td>Verified Bypass Duct Condition</td>
<td>Verification to determine if system is zonally controlled, and confirm that bypass ducts condition modeled matches installation.</td>
<td>RA3.1.4.6</td>
</tr>
</tbody>
</table>

1. Compliance credit for increased duct insulation R-value (not buried ducts) may be taken without field verification if the R-value is the same throughout the building, and for supply ducts located in crawl spaces and garages where all supply registers are either in the floor or within 2 feet of the floor. These two credits may be taken subject only to enforcement agency inspection.

**STANDARD DESIGN**

The standard heating and cooling system for central systems is modeled with non-designed air distribution ducts located as described in Table 2-12, with verified tested duct leakage (see Table 2-15). The standard design duct insulation is determined by Package A as R-6 in climate zones 1-10, 12-13, and R-8 in climate zones 11 and 14-16. The standard design building is assumed to have the same number of stories as the proposed design for purposes of determining the duct efficiency.

**Table 2-12: Summary of Standard Design Duct Location**

<table>
<thead>
<tr>
<th>Configuration of the Proposed Design</th>
<th>Standard Design Duct Location</th>
<th>Detailed Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attic over the dwelling unit</td>
<td>Ducts and air handler located in the attic</td>
<td>Ducts sealed (mandatory requirement) No credit for verified R-value, location or duct design</td>
</tr>
<tr>
<td>No attic but crawl space or basement</td>
<td>Ducts and air handler located in the crawl space or basement</td>
<td></td>
</tr>
<tr>
<td>Multi-family buildings and buildings with no attic, crawl space or basement</td>
<td>Ducts and air handler located indoors</td>
<td></td>
</tr>
</tbody>
</table>

*This table is applicable only when the standard design system has air distribution ducts as determined in Table 2-10.*

**VERIFICATION AND REPORTING**

Distribution type, location, R-value, and whether tested and sealed will be shown on the CF1R. If there are no ducts, this is shown as a special feature on the CF1R. Any duct location other than attic (e.g., crawl space) is shown as a special feature on the CF1R. Ducts in crawl space or basement shall include a special feature note if supply registers are located within 2 feet of the floor. Measures that require HERS verification will be shown in the HERS Verification section of the CF1R.
2.4.6.2 Duct Location

Duct location determines the external temperature for duct conduction losses, the temperature for return leaks, and the thermal regain of duct losses.

**Proposed Design**

If any part of the supply or return duct system is located in an unconditioned attic, that entire duct system is modeled with an attic location. If no part of the supply or return duct system is located in the attic, but the duct system is not entirely in conditioned space, it is modeled in the unconditioned zone which contains the largest fraction of its surface area. If the supply or return duct system is located entirely in conditioned space, the duct system is modeled in conditioned space.

For ducted HVAC systems with some or all ducts in unconditioned space, the user specifies the R-value and surface area of supply and return ducts, and the duct location.

Duct location and areas other than the defaults shown in Table 2-13 may be used following the verification procedures in Reference Appendices, Residential Appendix RA3.1.4.1.

**Standard Design**

The standard design duct location is determined from the building conditions (see Table 2-12).

**Verification and Reporting**

Duct location is reported on the CF1R. Ducts located entirely in conditioned space and verified low leakage ducts entirely in conditioned space are reported in the HERS Required Verification listing on the CF1R.

Default duct locations are as shown in Table 2-13. The duct surface area for crawl space and basement applies only to buildings or zones with all ducts installed in the crawl space or basement. If the duct is installed in locations other than crawl space or basement, the default duct location is “Other.” For houses with 2 or more stories 35 percent of the default duct area may be assumed to be in conditioned space as shown in Table 2-13.

The surface area of ducts located in conditioned space is ignored in calculating conduction losses.

<table>
<thead>
<tr>
<th>Supply duct location</th>
<th>Location of Default Duct Surface Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>One story</td>
</tr>
<tr>
<td></td>
<td>Two or more story</td>
</tr>
<tr>
<td>All in Crawl space</td>
<td>100% crawl space</td>
</tr>
<tr>
<td></td>
<td>65% crawl space 35% conditioned space</td>
</tr>
<tr>
<td>All in Basement</td>
<td>100% Basement</td>
</tr>
<tr>
<td></td>
<td>65% basement 35% conditioned space</td>
</tr>
<tr>
<td>Other</td>
<td>100% attic</td>
</tr>
<tr>
<td></td>
<td>65% attic 35% conditioned space</td>
</tr>
</tbody>
</table>

2.4.6.3 Duct Surface Area

The supply-side and return-side duct surface areas are treated separately in distribution efficiency calculations. The duct surface area is determined using the following methods.
2.4.6.4 Default Return Duct Surface Area

Default return duct surface area is calculated using:

Equation 2-4 \[ A_{r,\text{out}} = K_r \times A_{\text{floor}} \]

Where \( K_r \) (return duct surface area coefficient) is 0.05 for one-story buildings and 0.1 for two or more stories.

2.4.6.5 Default Supply Duct Surface Area

**STANDARD DESIGN**

The standard design and default proposed design supply duct surface area is calculated using Equation 2-5.

Equation 2-5 \[ A_{s,\text{out}} = 0.27 \times A_{\text{floor}} \times K_s \]

Where \( K_s \) (supply duct surface area coefficient) is 1 for one-story buildings and 0.65 for two or more stories.

2.4.6.6 Supply Duct Surface Area for Less Than 12 feet of Duct In Unconditioned Space

**PROPOSED DESIGN**

For proposed design HVAC systems with air handlers located outside the conditioned space but with less than 12 linear feet of duct located outside the conditioned space including air handler and plenum, the supply duct surface area outside the conditioned space is calculated using Equation 2-6. The return duct area remains the default for this case.

Equation 2-6 \[ A_{s,\text{out}} = 0.027 \times A_{\text{floor}} \]

2.4.6.7 Diagnostic Duct Surface Area

Proposed designs may claim credit for reduced surface area using the procedures in Reference Appendices, Residential Appendix RA3.1.4.1.

The surface area of each duct system segment is calculated based on its inside dimensions and length. The total supply surface area in each unconditioned location (attic, attic with radiant barrier, crawl space, basement, other) is the sum of the area of all duct segments in that location. The surface area of ducts completely inside conditioned space need not be input in the compliance software and is not included in the calculation of duct system efficiency. The area of ducts in floor cavities or vertical chases that are surrounded by conditioned space and separated from unconditioned space with draft stops are also not included.
2.4.6.8  Bypass Duct

**PROPOSED DESIGN**
Software shall allow users to specify whether a bypass duct is or is not used for a zonally controlled forced air system.

**STANDARD DESIGN**
The standard design is based on a split system air conditioner meeting the requirements of §150.1(c) and Table 150.1-A. The system is not a zonally-controlled system.

**VERIFICATION AND REPORTING**
An HVAC system with zonal control, and whether the system is assumed to have a bypass duct or have no bypass duct, is reported in the HERS Required Verification listings on the CF1R.

2.4.6.9  Duct System Insulation
For the purposes of conduction calculations in both the standard and proposed designs, 85 percent of the supply and return duct surface is assumed to be duct material at its specified R-value and 15 percent is assumed to be air handler, plenum, connectors and other components at the mandatory minimum R-value.

The area weighted effective R-value is calculated by the compliance software using Equation 2-7 and including each segment of the duct system that has a different R-value.

\[
R_{\text{eff}} = \frac{(A_1 + A_2 + \ldots + A_N)}{\frac{A_1}{R_1} + \frac{A_2}{R_2} + \ldots + \frac{A_N}{R_N}}
\]

Where:

\[R_{\text{eff}} = \text{Area weighted effective R-value of duct system for use in calculating duct efficiency, (h-ft}^2\cdot{}^\circ\text{F/Btu)}\]

\[A_N = \text{Area of duct segment } n, \text{ square feet}\]

\[R_n = \text{R-value of duct segment } n \text{ including film resistance, (duct insulation rated } R + 0.7), (\text{h-ft}^2\cdot{}^\circ\text{F/Btu)}\]

**PROPOSED DESIGN**
The software user inputs the R-value of the proposed duct insulation. The default duct thermal resistance is R-6.0.

**STANDARD DESIGN**
Package A required duct insulation R-values are used in the standard design.

**VERIFICATION AND REPORTING**
Duct location, duct R-value, non-standard supply and return duct areas are reported on the CF1R. Credit for systems with mixed insulation levels or ducts buried in the attic require the compliance and diagnostic procedures in Reference Appendices, Residential Appendix RA3.1.4.1.

2.4.6.10 Buried Attic Ducts

Ducts partly or completely buried in blown attic insulation in dwelling units meeting the requirements for verified quality insulation installation may take credit for increased effective duct insulation.

The duct design shall identify the segments of the duct that meet the requirements for being buried, and these are separately input into the computer software. Ducts to be buried shall have a minimum of R-6.0 duct insulation prior to being buried. The user shall calculate the correct R-value based on the modeled attic insulation R-value, insulation type, and duct size for ducts installed on the ceiling, and whether the installation meets the requirements for deeply buried ducts for duct segments buried in lowered areas of ceiling.

The portion of duct runs directly on or within 3.5 inches of the ceiling gypsum board and surrounded with blown attic insulation of R-30 or greater may take credit for increased effective duct insulation as shown in Table 2-14. Credit is allowed for buried ducts on the ceiling only in areas where the ceiling is level and there is at least 6 inches of space between the outer jacket of the installed duct and the roof sheathing above.

Duct segments deeply buried in lowered areas of ceiling and covered by at least 3.5 inches of insulation above the top of the duct insulation jacket may claim effective insulation of R-25 for fiberglass insulation and R-31 for cellulose insulation.

**Proposed Design**

The software shall allow the user to specify the effective R-value of buried ducts. This feature must be combined with duct sealing and verified quality insulation installation. The default is no buried ducts.

**Standard Design**

The standard design has no buried ducts

**Verification and Reporting**

Buried duct credit is reported in the HERS Required Verification listing on the CF1R.
Table 2-14: Buried Duct Effective R-values

<table>
<thead>
<tr>
<th>Nominal Round Duct Diameter</th>
<th>Effective Duct Insulation R-value for Blown Fiberglass Insulation</th>
<th>Effective Duct Insulation R-value for Blown Cellulose Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R-30</td>
<td>R-38</td>
</tr>
<tr>
<td>Attic Insulation 4”</td>
<td>R-13</td>
<td>R-25</td>
</tr>
<tr>
<td></td>
<td>R-13</td>
<td>R-25</td>
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<tr>
<td></td>
<td>R-9</td>
<td>R-25</td>
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<td></td>
<td>R-4.2</td>
<td>R-25</td>
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<td>R-4.2</td>
<td>R-25</td>
</tr>
</tbody>
</table>

2.4.6.11 Duct/Air Handler Leakage

Duct/air handler average leakage factors shown in Table 2-15 are used in simulating the duct system. The supply duct leakage for each case is the table value times 1.17. The return leakage is the table value times 0.83.

**PROPOSED DESIGN**

For each ducted system the software user specifies one of the duct/air handler leakage cases shown in Table 2-15.

**STANDARD DESIGN**

For ducted systems the standard design is sealed and tested duct systems in existing dwelling units or new duct systems.

**VERIFICATION AND REPORTING**

Sealed and tested duct systems are listed in the HERS verification section of the CF1R.

2.4.6.12 Low Leakage Air Handlers

**PROPOSED DESIGN**

Credit can be taken for installation of a factory sealed air handling unit tested by the manufacturer and certified to the Energy Commission to meet the requirements for a Low Leakage Air-Handler. Field verification of the air handler’s model number is required.

**STANDARD DESIGN**

The standard design has a normal air handler.
VERIFICATION AND REPORTING

A Low Leakage Air Handler is reported on the compliance report and field verified in accordance with the procedures specified in Reference Appendices, Residential Appendix RA3.1.4.3.9.

2.4.6.13 Verified Low Leakage Ducts in Conditioned Space

PROPOSED DESIGN

For ducted systems the user may specify that all ducts are entirely in conditioned space and the software will model the duct system with no leakage and no conduction losses.

STANDARD DESIGN

The standard design has ducts in the default location.

VERIFICATION AND REPORTING

Systems that have all ducts entirely in conditioned space are reported on the compliance documents and this is verified by measurements showing duct leakage to outside conditions is equal to or less than 25 cfm when measured in accordance with Reference Appendices, Residential Appendix RA3.

Table 2-15: Duct/Air Handler Leakage Factors

<table>
<thead>
<tr>
<th>Case</th>
<th>Average of Supply and Return</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untested duct systems in homes built prior to June 1, 2001</td>
<td>0.86</td>
</tr>
<tr>
<td>Untested duct systems in homes built after June 1, 2001</td>
<td>0.89</td>
</tr>
<tr>
<td>Sealed and tested duct systems in existing dwelling units</td>
<td>0.915</td>
</tr>
<tr>
<td>Sealed and tested new duct systems</td>
<td>0.96</td>
</tr>
<tr>
<td>Verified low leakage ducts in conditioned space</td>
<td>1.00</td>
</tr>
<tr>
<td>Low leakage air handlers in combination with sealed and tested new duct systems</td>
<td>0.97 or as measured</td>
</tr>
</tbody>
</table>

2.4.7 Space Conditioning Fan Subsystems

Fan systems move air for air conditioning, heating and ventilation systems. The software allows the user to define fans to be used for space conditioning, indoor air quality and ventilation cooling. Indoor air quality and ventilation cooling are discussed in Sections 2.4.9 and 2.4.10.

PROPOSED DESIGN

For the space conditioning fan system, the user selects the type of equipment and enters basic information to model the energy use of the equipment. For ducted central air conditioning and heating systems the fan efficacy default is the mandatory minimum verified efficacy of 0.58 W/cfm (also assumed when there is no cooling system).

STANDARD DESIGN

The standard design fan shall meet the minimum §150.1(c) and Table 150.1-A requirements.
2.4.8 Space Conditioning Systems

This section describes the general procedures for heating and cooling systems in low-rise residential buildings. The system includes the cooling system, the heating system, distribution system, and mechanical fans.

If multiple systems serve a building, each system and the conditioned space it serves may be modeled in detail separately or the systems may be aggregated together and modeled as one large system. If the systems are aggregated together they must be the same type and all meet the same minimum specifications.

2.4.8.1 Multiple System Types Within Dwelling

PROPOSED DESIGN

For proposed designs using more than one heating system type, equipment type or fuel type, and the types do not serve the same floor area, the user shall zone the building by system type.

STANDARD DESIGN

The standard design shall have the same zoning and heating system types as the proposed design.

VERIFICATION AND REPORTING

The heating system type of each zone is shown on the CF1R

2.4.8.2 Multiple Systems Servings Same Area

If a space or a zone is served by more than one heating system, compliance is demonstrated with the most TDV energy-consuming system serving the space or the zone. For spaces or zones that are served by electric resistance heat in addition to other heating systems, the electric resistance heat is deemed to be the most TDV energy-consuming system unless the supplemental heating meets the Exception to §150.1(c)6. See eligibility criteria in Residential Compliance Manual Section 4.2.2 for conditions under which the supplemental heat may be ignored.

For floor areas served by more than one cooling system, equipment, or fuel type, the system, equipment, and fuel type that satisfies the cooling load is modeled.

2.4.8.3 No Cooling

PROPOSED DESIGN

When the proposed design has no cooling system, the proposed design is required to model the standard design cooling system defined in §150.1(c) and Table 150.1-A. Since the proposed design system is identical to the standard design system, there is no penalty or credit.
**STANDARD DESIGN**

The standard design system is the same as the proposed design.

**VERIFICATION AND REPORTING**

No cooling is reported as a special feature on the CF1R.

### 2.4.8.4 Zonal Control

With zonal control, the sleeping and living areas are modeled separately for heating, each with its own separate thermostat schedule and internal gain assumptions. Zonal control cannot be modeled with heat pump heating. The total non-closable opening area between zones cannot exceed 40 ft². Other eligibility criteria for this measure are presented in the Residential Compliance Manual, Chapter 4, Section 4.5.2.

**PROPOSED DESIGN**

The user selects zonal control as an HVAC system input.

**STANDARD DESIGN**

The standard design does not have zonal control.

**VERIFICATION AND REPORTING**

Zonal control is reported as a *Special Feature* on the CF1R.

### 2.4.9 Indoor Air Quality Ventilation

The standards require mechanical ventilation that complies with ASHRAE Standard 62.2 to provide acceptable indoor air quality for all newly constructed buildings and additions greater than 1,000 square feet. ASHRAE Standard 62.2 provides several ways to comply with the requirement for mechanical ventilation and these are described in the Residential Compliance Manual.

For the purposes of estimating the energy impact of this requirement in compliance software, the minimum ventilation rate is met either by a standalone IAQ fan system or a central air handler fan system that can introduce outdoor air. In many cases, this energy is substantially compliance neutral because the standard design is typically set equal to the proposed design.

The simplest IAQ fan system is an exhaust fan like a bathroom fan that meets the criteria in ASHRAE Standard 62.2 for air delivery and low noise. More advanced IAQ fan systems that have a supply or both supply and exhaust fans are also possible. To calculate the energy use of standalone IAQ fan systems, the systems are assumed to be on continuously.

To calculate the energy use of central fan integrated ventilation, the systems are assumed to be on for at least 20 minutes each hour as described below. The fan flow rate and fan power ratio may be different than the values used when the system is on to provide for heating or cooling depending on the design or controls on the IAQ ventilation portion of the system.
The minimum ventilation rate for continuous ventilation of each single family dwelling unit is given in Equation 2-8.

\[
Q_{\text{fan}} = 0.01A_{\text{floor}} + 7.5(N_{\text{br}} + 1)
\]

Where:

- \(Q_{\text{fan}}\) = fan flow rate in cubic feet per minute (cfm),
- \(A_{\text{floor}}\) = floor area in square feet (ft\(^2\)),
- \(N_{\text{br}}\) = number of bedrooms (not less than one).

The minimum ventilation rate for continuous ventilation of each multi-family dwelling unit is given in Equation 2-9.

\[
Q_{\text{fan}} = 0.03A_{\text{floor}} + 7.5(N_{\text{br}} + 1)
\]

Where:

- \(Q_{\text{fan}}\) = fan flow rate in cubic feet per minute (cfm),
- \(A_{\text{floor}}\) = floor area in square feet (ft\(^2\)),
- \(N_{\text{br}}\) = number of bedrooms (not less than one).

**Proposed Design**

The proposed design shall incorporate a mechanical ventilation system fan. This requirement is a mandatory measure. The compliance software allows the user to specify the IAQ ventilation type (see Table 2-16) and the cfm of outdoor ventilation air which must be equal to or greater than what is required by ASHRAE Standard 62.2. The default is a standalone exhaust system meeting standard 62.2.

**Standard Design**

The mechanical ventilation system in the standard design is the same as the proposed design. The airflow rate is equal to the proposed design. The apparent heat or enthalpy recovery efficiency is the same as the proposed design. For standalone IAQ fan systems, the fan power ratio is equal to the proposed design value or 1.2 W/cfm, whichever is smaller. For central air handler fans, the fan power ratio is 0.58 W/cfm of central system airflow in ventilation mode.

**Verification and Reporting**

The required ventilation rate to comply with ASHRAE Standard 62.2 and the means to achieve compliance are indicated on the CF1R. The IAQ system characteristics are reported in the HERS Required Verification listing on the CF1R. The diagnostic testing procedures are in RA3.7.
Table 2-16: IAQ Fans

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Inputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standalone IAQ Fan (exhaust, supply or balanced)</td>
<td>Dedicated fan system that provides indoor air quality ventilation to meet or exceed the requirements of ASHRAE Standard 62.2.</td>
<td>cfm, Watts/cfm, recovery effectiveness for balanced only</td>
</tr>
<tr>
<td>Central Fan Integrated (CFI) (variable or fixed speed)</td>
<td>Automatic operation of the normal furnace fan for IAQ ventilation purposes. Ventilation type uses a special damper to induce outdoor IAQ ventilation air and distribute it through the HVAC duct system. Mixing type distributes and mixes IAQ ventilation air supplied by a separate standalone IAQ fan system.</td>
<td>cfm, Watts/cfm</td>
</tr>
</tbody>
</table>

Table 2-17: CF1R Report – Indoor Air Quality

<table>
<thead>
<tr>
<th>IAQ System Name</th>
<th>IAQ System Type</th>
<th>Whole Building IAQ Airflow Rate (cfm)</th>
<th>Standalone IAQ Fan Power Ratio (W/cfm)</th>
</tr>
</thead>
</table>

2.4.10 Ventilation Cooling System

Ventilation cooling systems operate at the dwelling unit level using fans to bring in outside air to cool the house when this can reduce cooling loads and save cooling energy. Ventilation cooling systems such as whole house fans involve window operation and attic venting. Central fan ventilation cooling systems use the HVAC duct system to distribute ventilation air. Ventilation cooling systems operate according to the schedule and setpoints shown in Table 2-18. Ventilation cooling systems that exhaust air through the attic require a minimum of 1 ft² of free attic ventilation area per 375 cfm of rated capacity for relief (see §150.1(c)12 of the standards). Alternatively, the software user may select a ventilation rate of 1 ft² of free attic ventilation area per 750 cfm of rated capacity, which is reflected in a reduced effectiveness of the ventilation cooling system.

**Proposed Design**

Software allows the user to specify whether a ventilation cooling system will be used in conditioned and living zones (see Table 2-18). When cooling ventilation is modeled, the default fan size is 2 cfm/ft² of conditioned floor area and the default ventilation rate is 1 ft² for every 375 cfm of rated fan capacity. The default is none.

**Standard Design**

The standard design building for a newly constructed building or for an addition greater than 1,000 square feet has a whole house fan with 2 cfm/ft² conditioned floor area in climate zones 8 through 14 and no ventilation cooling in other climate zones (see §150.1(c) and Table 150.1-A).

**Verification and Reporting**

A ventilation cooling system is a special feature and the size and type is reported on the CF1R. A variable speed ventilation cooling system requires HERS verification of the make/model number and controls using the CF2R-MECH-30.
### Table 2-18: Ventilation Cooling Fans

<table>
<thead>
<tr>
<th>Measure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole House Fan</td>
<td>Traditional whole house fan mounted in the ceiling to exhaust air from the house to the attic, inducing outside air in through open windows. Whole house fans are assumed to operate between dawn and 11 PM only at 25% of rated cfm to reflect manual operation of fan and windows by occupant. Fans must be listed in the California Energy Commission’s Whole House Fan directory. If multiple fans are used, enter the total cfm.</td>
</tr>
<tr>
<td>Central Fan Ventilation Cooling</td>
<td>Central fan ventilation cooling system. Ventilation type uses a special damper to induce outdoor air and distribute it through the HVAC duct system.</td>
</tr>
<tr>
<td>Variable or fixed speed</td>
<td></td>
</tr>
</tbody>
</table>

### 2.5 Conditioned Zones

The software requires the user to enter the characteristics of one or more conditioned zones. Subdividing dwelling units into conditioned zones for input convenience or increased accuracy is optional.

#### 2.5.1 Zone Type

**Proposed Design**

The zone is defined as conditioned, living or sleeping.

**Standard Design**

The standard design is conditioned.

**Verification & Reporting**

When the zone type is living or sleeping, this is reported as a Special Feature on the CF1R.
2.5.2 Conditioned Floor Area

The total conditioned floor area (CFA) is the raised floor as well as the slab-on-grade floor area of the conditioned spaces measured from the exterior of exterior walls. Stairwell floor area is included in conditioned floor area as the horizontal area of the stairs and landings between two floors of each story of the house.

**PROPOSED DESIGN**

The compliance software requires the user to enter the total conditioned floor area of each conditioned zone.

**STANDARD DESIGN**

The standard design building has the same conditioned floor area and same conditioned zones as the proposed design.

**VERIFICATION AND REPORTING**

The conditioned floor area of each conditioned zone is reported on the CF1R.

2.5.3 Number of Stories

2.5.3.1 Number of Stories of the Zone

**PROPOSED DESIGN**

The number of stories of the zone.

**STANDARD DESIGN**

The standard design is the same as the proposed design.

2.5.3.2 Ceiling Height

**PROPOSED DESIGN**

The average ceiling height of the proposed design is the conditioned volume of air enclosed by the building envelope. The volume is determined from the total conditioned floor area and the average ceiling height.

**STANDARD DESIGN**

The volume of the standard design building is the same as the proposed design.

**VERIFICATION AND REPORTING**

The conditioned volume of each zone is reported on the CF1R.

2.5.3.3 Free Ventilation Area

Free ventilation area is the window area adjusted to account for bug screens, window framing and dividers, and other factors.
**PROPOSED DESIGN**

Free ventilation area for the proposed design is calculated as 5 percent of the fenestration area (rough opening), assuming all windows are operable.

**STANDARD DESIGN**

The standard design value for free ventilation area is the same as the proposed design.

**VERIFICATION AND REPORTING**

Free ventilation is not reported on the CF1R.

2.5.3.4  **Ventilation Height Difference**

Ventilation height difference is not a user input.

**PROPOSED DESIGN**

The default assumption for the proposed design is 2 feet for one-story buildings or one-story dwelling units and 8 feet for two or more stories (as derived from number of stories and other zone details).

**STANDARD DESIGN**

The standard design modeling assumption for the elevation difference between the inlet and the outlet is 2 feet for one-story dwelling unit and 8 feet for two or more stories.

2.5.3.5  **Zone Elevations**

The elevation of the top and bottom of each zone is required to set up the air flow network.

**PROPOSED DESIGN**

The user enters the height of the top surface the lowest floor of the zone relative to the ground outside as the “Bottom” of the zone. The user also enters the ceiling height (the floor to floor height (ceiling height plus the thickness of the intermediate floor structure) is calculated by the software).

**STANDARD DESIGN**

The standard design has the same vertical zone dimensions as the proposed design.

**VERIFICATION AND REPORTING**

Vertical zone dimensions are shown on the CF1R.

2.5.3.6  **Mechanical Systems**

**PROPOSED DESIGN**

The software requires the user to specify a previously defined HVAC system to provide heating and cooling for the zone and an indoor air quality (IAQ) ventilation system. The user may also specify a ventilation cooling system that applies to this and other conditioned zones.
**STANDARD DESIGN**

The software assigns standard design HVAC, IAQ ventilation and ventilation cooling systems based on §150.1(c) and Table 150.1-A for the applicable climate zone.

### 2.5.3.7 Natural Ventilation

Natural ventilation (from windows) is available during cooling mode when needed and available as shown in Table 2-19. The amount of natural ventilation used by computer software for natural cooling is the lesser of the maximum potential amount available and the amount needed to drive the interior zone temperature down to the natural cooling setpoint. When natural cooling is not needed or is unavailable no natural ventilation is used.

Computer software shall assume that natural cooling is needed when the building is in “cooling mode” and when the outside temperature is below the estimated zone temperature and the estimated zone temperature is above the natural cooling setpoint temperature. Only the amount of ventilation required to reduce the zone temperature down to the natural ventilation setpoint temperature is used and the natural ventilation setpoint temperature is constrained by the compliance software to be greater than the heating setpoint temperature.

**Table 2-19: Hourly Thermostat Set Points**

<table>
<thead>
<tr>
<th>Hour</th>
<th>Cooling</th>
<th>Venting</th>
<th>Standard Heating</th>
<th>Zonal Control Heating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Single Zone</td>
<td>Living</td>
</tr>
<tr>
<td>1</td>
<td>78</td>
<td>Off</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>2</td>
<td>78</td>
<td>Off</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>3</td>
<td>78</td>
<td>Off</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>4</td>
<td>78</td>
<td>Off</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>5</td>
<td>78</td>
<td>Off</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>6</td>
<td>78</td>
<td>68*</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>7</td>
<td>78</td>
<td>68</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>8</td>
<td>83</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>9</td>
<td>83</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>10</td>
<td>83</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>11</td>
<td>83</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>12</td>
<td>83</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>13</td>
<td>83</td>
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<td>68</td>
</tr>
<tr>
<td>14</td>
<td>82</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>15</td>
<td>81</td>
<td>68</td>
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</tr>
<tr>
<td>16</td>
<td>80</td>
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<td>68</td>
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</tr>
<tr>
<td>17</td>
<td>79</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>18</td>
<td>78</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>19</td>
<td>78</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>20</td>
<td>78</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>21</td>
<td>78</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>22</td>
<td>78</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>23</td>
<td>78</td>
<td>68</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>24</td>
<td>78</td>
<td>Off</td>
<td>65</td>
<td>65</td>
</tr>
</tbody>
</table>

*Venting starts in the hour the sun comes up.*
2.5.4 Conditioned Zone Assumptions

2.5.4.1 Internal Thermal mass

Internal mass objects are completely inside a zone so that they do not participate directly in heat flows to other zones or outside. They are connected to the zone radiantly and convectively and participate in the zone energy balance by passively storing and releasing heat as conditions change.

Table 2-20: Conditioned Zone Thermal Mass Objects

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Simulation Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior walls</td>
<td>The area of one side of the walls completely inside the conditioned zone is calculated as the conditioned floor area of the zone minus ½ of the area of interior walls adjacent to other conditioned zones. The interior wall is modeled as a construction with 25% 2x4 wood framing and sheetrock on both sides.</td>
<td>Wall exposed to the zone on both sides</td>
</tr>
<tr>
<td>Interior floors</td>
<td>The area of floors completely inside the conditioned zone is calculated as the difference between the CFA of the zone and the sum of the areas of zone exterior floors and interior floors over other zones. Interior floors are modeled as a surface inside the zone with a construction of carpet, wood decking, 2x12 framing at 16 in. o.c. with miscellaneous bridging, electrical and plumbing and a sheetrock ceiling below.</td>
<td>Floor/ceiling surface exposed to the zone on both sides</td>
</tr>
<tr>
<td>Furniture and heavy contents</td>
<td>Contents of the conditioned zone with significant heat storage capacity and delayed thermal response, for example heavy furniture, bottled drinks and canned goods, contents of dressers and enclosed cabinets. These are represented by a 2 in. thick slab of wood twice as large as the conditioned floor area, exposed to the room on both sides.</td>
<td>Horizontal wood slab exposed to the zone on both sides</td>
</tr>
<tr>
<td>Light and thin contents</td>
<td>Contents of the conditioned zone that have a large surface area compared to their weight, for example, clothing on hangers, curtains, pots and pans. These are assumed to be 2 BTU per square foot of conditioned floor area.</td>
<td>Air heat capacity (Cair) = CFA * 2</td>
</tr>
</tbody>
</table>

PROPOSED DESIGN

The proposed design has standard conditioned zone thermal mass objects which are not user editable and are not a compliance variable. If the proposed design includes specific interior thermal mass elements that are significantly different from what is included in typical wood frame production housing, such as masonry partition walls, the user may include them. See also 2.5.6.4.

STANDARD DESIGN

The standard design has standard conditioned zone thermal mass objects.
VERIFICATION AND REPORTING

Any user input interior thermal mass elements are fully documented on the building plans and noted in the Special Features on the CF1R.

2.5.4.2 Thermostats and Schedules

Thermostat settings are shown in Table 2-19. The values for cooling, venting, and standard heating apply to the standard design run and are the default for the proposed design run. See the explanation later in this section regarding the values for zonal control.

Systems with no setback required by §110.2(c) (gravity gas wall heaters, gravity floor heaters, gravity room heaters, non-central electric heaters, fireplaces or decorative gas appliances, wood stoves, room air conditioners, and room air-conditioner heat pumps) are assumed to have a constant heating set point of 68 degrees and the same value as in column 1 of Table 2-19 for the cooling set point in both the proposed design and standard design runs.

PROPOSED DESIGN

The proposed design assumes a mandatory setback thermostat meeting the requirements of §110.2(c). Systems exempt from the requirement for a setback thermostat are assumed to have no setback capabilities.

STANDARD DESIGN

The standard design has setback thermostat conditions based on the mandatory requirement for a setback thermostat. For equipment exempt from the setback thermostat requirement, the standard design has no setback thermostat capabilities.

VERIFICATION AND REPORTING

When the proposed equipment is exempt from setback thermostat requirements this is shown as a Special Feature on the CF1R.

2.5.4.3 Determining Heating Mode vs. Cooling Mode

When the building is in the heating mode, the heating setpoints for each hour are set to the “heating” values in Table 2-19, the cooling setpoint is a constant 78°F and the ventilation setpoint is set to a constant 77°F. When the building is in the cooling mode the heating setpoint is a constant 60°F, and the cooling and venting setpoints are set to the values in Table 2-19.

The mode is dependent upon the outdoor temperature averaged over hours 1 through 24 of day 8 through day 2 prior to the current day (e.g., if the current day is June 21, the mode is based on the average temperature for June 13 through 20). When this running average temperature is equal to or less than 60°F, the building is in a heating mode. When the running average is greater than 60°F, the building is in a cooling mode.

2.5.5 Internal Gains

Internal gains are consistent with the HERS Whole House specification:
except for modifications to include latent gains.

**Seasonal Adjustments**

Daily internal gain is modified each month according to the multipliers shown in Table 2-21. These multipliers are derived from the number of daylight hours for each month. Identical inputs are used for both the proposed design and the standard design.

<table>
<thead>
<tr>
<th>Month</th>
<th>Multiplier</th>
<th>Month</th>
<th>Multiplier</th>
<th>Month</th>
<th>Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>1.19</td>
<td>May</td>
<td>0.84</td>
<td>Sep</td>
<td>0.98</td>
</tr>
<tr>
<td>Feb</td>
<td>1.11</td>
<td>Jun</td>
<td>0.80</td>
<td>Oct</td>
<td>1.07</td>
</tr>
<tr>
<td>Mar</td>
<td>1.02</td>
<td>Jul</td>
<td>0.82</td>
<td>Nov</td>
<td>1.16</td>
</tr>
<tr>
<td>Apr</td>
<td>0.93</td>
<td>Aug</td>
<td>0.88</td>
<td>Dec</td>
<td>1.21</td>
</tr>
</tbody>
</table>

### 2.5.6 Exterior Surfaces

The user enters exterior surfaces to define the envelope of the proposed design. The areas, construction assemblies, orientations, and tilts modeled are consistent with the actual building design and shall equal the overall roof/ceiling area with conditioned space on the inside and unconditioned space on the other side.

#### 2.5.6.1 Ceilings below Attics

Ceilings below attics are horizontal surfaces between conditioned zones and attics. The area of the attic floor is determined by the total area of ceilings below attics defined in conditioned zones.

**PROPOSED DESIGN**

The software allows the user to define ceilings below attics and enter the area and select a construction assembly for each.

**STANDARD DESIGN**

The standard design has the same ceiling below attic area as the proposed design. The standard design ceiling is constructed with 2x4 framed trusses and insulated with the R-value specified in §150.1(c) and Table 150.1-A for the applicable climate zone.

**VERIFICATION AND REPORTING**

Ceiling below attic area and insulation are reported on the CF1R. Metal frame or SIP assemblies are reported as a special feature on the CF1R.
2.5.6.2 Non-Attic (Cathedral) Ceiling and Roof
Non-Attic Ceilings, also known as cathedral ceilings, are surfaces with roofing on the outside and finished ceiling on the inside but without an attic space.

**Proposed Design**
The software allows the user to define cathedral ceilings and enter the area and select a construction assembly for each. The user also enters the roof characteristics of the surface.

**Standard Design**
The non-attic ceiling/roof areas of the standard design building are equal to the non-attic ceiling/roof areas of the proposed design. The standard design roof and ceiling surfaces are assumed to be horizontal (no tilts). The standard design is modeled with the same construction assembly as the proposed design but with Package A insulation R-value. The aged reflectance and emittance of the standard design are determined by §150.1(c) and Table 150.1-A for the applicable climate zone.

**Verification and Reporting**
Non-attic ceiling/roof area and construction are reported on the CF1R. Metal frame or SIP assemblies are reported as a special feature on the CF1R.

2.5.6.3 Exterior Walls

**Proposed Design**
The software allows the user to define walls, enter the gross area and select a construction assembly for each. The user also enters the plan orientation (front, left, back or right) or plan azimuth (value relative to the front which is represented as 0 degrees) and tilt of the wall.

The wall areas modeled are consistent with the actual building design and the total wall area is equal to the gross wall area with conditioned space on the inside and unconditioned space or exterior conditions on the other side. Walls adjacent to unconditioned spaces with no solar gains (such as knee walls or garage walls) are entered as an interior wall with the zone on the other side as attic or garage and the compliance manager treats that wall as a demising wall. The unconditioned space is modeled as an unconditioned zone.

**Standard Design**
The gross exterior wall area in the standard design is equal to the gross exterior wall area of the proposed design. If the proposed wall area is framed wall, the gross exterior wall area of framed walls in the standard design (excluding knee walls) is equally divided between the four main compass points, north, east, south, and west. Window and door areas are subtracted from the gross wall area to determine the net wall area in each orientation. Walls adjacent to unconditioned space (garage walls) for all climate zones are wood framed, 2x4, 16-in. o.c., R-15 cavity insulation.

**Verification and Reporting**
Exterior wall area and construction details are reported on the CF1R. Metal frame or SIP assemblies are reported as a special feature on the CF1R.
2.5.6.4 **Exterior Thermal Mass**

Constructions for standard exterior mass is supported but not implemented beyond the assumptions for typical mass.

The performance approach assumes that both the proposed design and standard design building have a minimum mass as a function of the conditioned area of slab floor and non-slab floor (see Section 2.5.4.1).

Mass such as concrete slab floors, masonry walls, double gypsum board and other special mass elements can be modeled. When the proposed design has more than the typical assumptions for mass in a building then each element of heavy mass is modeled in the proposed design, otherwise, the proposed design is modeled with the same thermal mass as the standard design.

**PROPOSED DESIGN**

The proposed design may be modeled with the default 20 percent exposed mass/80 percent covered mass or with actual mass.

**STANDARD DESIGN**

The conditioned slab floor in the standard design is assumed to be 20 percent exposed slab and 80 percent slab covered by carpet or casework. Interior mass assumptions as described in Section 2.5.4.1 are also assumed. No other mass elements are modeled in the standard design. The standard design mass is modeled with the following characteristics.

- The conditioned slab floor area (slab area) shall have a thickness of 3.5 inches; a volumetric heat capacity of 28 Btu/ft³·°F; a conductivity of 0.98 Btu-in/hr-ft²·°F. The exposed portion shall have a surface conductance of 1.3 Btu/hr-ft²·°F (no thermal resistance on the surface) and the covered portion shall have a surface conductance of 2.0 Btu/hr-ft²·°F, typical of a carpet and pad.

- The “exposed” portion of the conditioned non-slab floor area shall have a thickness of 2.0 inches; a volumetric heat capacity of 28 Btu/ft³·°F; a conductivity of 0.98 Btu-in/hr-ft²·°F; and a surface conductance of 1.3 Btu/hr-ft²·°F (no added thermal resistance on the surface). These thermal mass properties apply to the “exposed” portion of non-slab floors for both the proposed design and standard design. The covered portion of non-slab floors is assumed to have no thermal mass.

**VERIFICATION AND REPORTING**

Exposed mass greater than 20 percent exposed slab on grade and any other mass modeled by the user shall be reported as a special feature on the CF1R.
2.5.6.5 Doors

**Proposed Design**

The compliance software shall allow users to enter doors specifying the U-factor, area, and orientation. Doors to the exterior or to unconditioned zones are modeled as part of the conditioned zone. For doors with less than 50 percent glass area, the U-factor shall come from JA4, Table 4.5.1 (default U-factor 0.50). The glass area of the door, calculated as the sum of all glass surfaces plus two inches on all sides of the glass (to account for a frame), is modeled under the rules for fenestrations; the opaque area of the door is considered the total door area minus this calculated glass area. Doors with 50 percent or more glass area are modeled under the rules for fenestrations using the total area of the door.

When modeling a garage zone, large garage doors (metal roll-up or wood) are modeled with a 1.0 U-factor.

**Standard Design**

The standard design has the same door area for each dwelling unit as the proposed design. The standard design door area is distributed equally between the four main compass points—north, east, south and west. All doors are assumed to have a U-factor of 0.50. The net opaque wall area is reduced by the door area in the standard design.

**Verification and Reporting**

Door area and construction are reported on the CF1R.

2.5.6.6 Fenestration

Fenestration is modeled with a U-factor and solar heat gain coefficient (SHGC). Acceptable sources of these values are National Fenestration Rating Council (NFRC), default tables from §110.6 of the standards, and Reference Appendix NA6.

In limited cases for certain site-built fenestration that is field fabricated the performance factors (U-factor, SHGC) may come from Nonresidential Reference Appendix NA6 as described in exception 4 to §150.1(c)3A.

There is no detailed model of chromogenic fenestration available at this time. As allowed by exception 3 to §150.1(c)3A, the lower rated labeled U-factor and SHGC may be used only when installed with automatic controls as noted in the exception. Chromogenic fenestration cannot be averaged with non-chromogenic fenestration.

**Proposed Design**

The compliance software allows users to enter individual fenestration or window types, the U-factor, SHGC, area, orientation, and tilt. Performance data (U-factors and SHGC) are either NFRC values or are taken from the Energy Commission default tables from §110.6 of the standards. In spaces other than sunspaces, solar gains from windows or skylights use the CSE default solar gain targeting.
Skylights are a fenestration with a slope of 60 degrees or more. Skylights are modeled as part of a roof.

**STANDARD DESIGN**

If the proposed design fenestration area is less than 20 percent of the conditioned floor area, the standard design fenestration area is set equal to the proposed design fenestration area. Otherwise, the standard design fenestration area is set equal to 20 percent of the conditioned floor area. The standard design fenestration area is distributed equally between the four main compass points—north, east, south and west.

The standard design has no skylights.

The net wall area on each orientation is reduced by the fenestration area (and door area) on each facade. The U-factor and SHGC performance factors for the standard design are taken from the §150.1(c) and Table 150.1-A (Package A). Where Package A has no requirement, the SHGC is set to 0.50.

**VERIFICATION AND REPORTING**

Fenestration area, U-factor, SHGC, orientation, and tilt are reported on the CF1R.

### 2.5.6.7 Overhangs and Sidefins

**PROPOSED DESIGN**

Software users enter a set of basic parameters for a description of an overhang and sidefin for each individual fenestration or window area entry. The basic parameters include *fenestration height*, *overhang/sidefin length*, and *overhang/sidefin height*. Compliance software user entries for overhangs may also include *fenestration width*, *Overhang left extension* and *overhang right extension*. Compliance software user entries for sidefins may also include *fin left extension* and *fin right extension* for both left and right fins. Walls at right angles to windows may be modeled as sidefins.
**STANDARD DESIGN**

The standard design does not have overhangs or side fins.

**VERIFICATION AND REPORTING**

Overhang and fin dimensions are reported on the CF1R.

2.5.6.8 Interior Shading Devices

For both the proposed and standard design, all windows are assumed to have draperies and skylights are assumed to have no interior shading. Window medium drapes are closed at night and half open in the daytime hours. Interior shading is not a compliance variable and is not user editable.
2.5.6.9  Exterior Shading

For both the proposed and standard design, all windows are assumed to have bug screens and skylights are assumed to have no exterior shading. Exterior shading is modeled as an additional glazing system layer using the ASHWAT calculation.

**PROPOSED DESIGN**

The compliance software shall require the user to accept the default exterior shading devices, which are bug screens for windows and none for skylights. Credit for shading devices that are allowable for prescriptive compliance are not allowable in performance compliance.

**STANDARD DESIGN**

The standard design shall assume bug screens. The standard design does not have skylights.

2.5.6.10  Walls and Floors Between Zones

The user must model unconditioned attached zones such as garages, crawl spaces, and basements.

**PROPOSED DESIGN**

The user inputs the area and construction of walls and floors between zones.

**STANDARD DESIGN**

The standard design shall have the same wall and floor areas and the constructions meet §150.1(c) and Table 150.1-A.

**VERIFICATION AND REPORTING**

Areas and construction of interzone surfaces is reported on the CF1R.

2.5.6.11  Slab on grade floors

**PROPOSED DESIGN**

The software allows users to enter areas and exterior perimeter of slabs that are heated or unheated, covered or exposed slab, and with or without with slab edge insulation. Perimeter is the length of wall between conditioned space and the exterior, but does not include edges that cannot be insulated, such as between the house and the garage. The default condition for the proposed design is that 80 percent of each slab area is carpeted or covered by walls and cabinets, and 20 percent is exposed. Inputs other than the default condition require that carpet and exposed slab conditions are documented on the construction plans.

When the proposed heating distribution is radiant floor heating (heated slab), the software user will identify that the slab is heated and model the proposed slab edge insulation. The mandatory minimum requirement is R-5 insulation in climate zones 1-15 and R-10 in climate zone 16 (§110.8(g), Table 110.8-A).
**STANDARD DESIGN**

The standard design perimeter lengths and slab on grade areas are the same as the proposed design. Eighty percent of standard design slab area is carpeted and 20 percent is exposed. For the standard design, an unheated slab edge has no insulation with the exception of climate zone 16, which assumes R-7 to a depth of 16 inches. The standard design for a heated slab is a heated slab with the mandatory slab edge insulation of R-5 in climate zones 1-15 and R-10 in climate zone 16.

**VERIFICATION AND REPORTING**

Slab areas, perimeter lengths and inputs of other than the default condition are reported on the CF1R.

2.5.6.12 Raised Floors

**PROPOSED DESIGN**

The software allows the user to input floor areas and constructions for raised floors over a crawl space, over exterior (garage or unconditioned), over a controlled ventilation crawl space, and raised concrete floors. The proposed floor area is consistent with the actual building design.

**STANDARD DESIGN**

The standard design is the area and construction as the proposed design, except the thermal characteristics meet §150.1(c) and Table 150.1-A.

**VERIFICATION AND REPORTING**

Raised floor areas and constructions are reported on the CF1R.

### 2.6 Attics

The compliance software models attics as a separate thermal zone and includes the interaction with the air distribution ducts, infiltration exchange between the attic and the house, the solar gains on the roof deck and other factors. These interactions are illustrated in Figure 2-11.
2.6.1 Attic Components

2.6.1.1 Roof Rise
This is the ratio of rise to run (or pitch), and refers to the number of feet the roof rises every 12 feet. For roofs with multiple pitches the roof rise that makes up the largest roof area is used.

2.6.1.2 Vent Area
This value is the vent area as a fraction of attic floor area. This value is not a compliance variable and is assumed to be a value equal to attic floor area/300.

2.6.1.3 Fraction High
The fraction of the vent area that is high due to the presence of ridge, roof or gable end mounted vents. Soffit vents are considered low ventilation. Default value is 0 for attics with standard ventilation. Attics with radiant barriers are required to have a vent high fraction of at least 0.3.

2.6.1.4 Roof Deck/Surface Construction
Typical roof construction types are concrete or clay tile, metal tile or wood shakes, or other high or low sloped roofing types.

2.6.1.5 Solar Reflectance
This input is a fraction that specifies the certified aged reflectance of the roofing material or 0.1 default value for uncertified materials. The installed value must be equal to or higher than the value specified here. Roof construction with a roof membrane mass of at least 25 lb/ft$^3$ or a roof area that has integrated solar collectors is assumed to meet the minimum solar reflectance.

2.6.1.6 Emittance
The certified aged emittance (or emissivity) of the roofing material, or a default value. The installed value must be equal to or greater than the value modeled here. Default value is 0.85 if certified aged
thermal emittance value is not available from the Cool Roof Rating Council (www.coolroofs.org). Roof construction with a roof membrane mass of at least 25 lb/ft³ or roof area incorporated integrated solar collectors are assumed to met the minimal emittance.

**PROPOSED DESIGN**

The conditioning is either ventilated or conditioned. Each characteristic of the roof is modeled to reflect the proposed construction. Values for solar reflectance and emittance shall be default or from the Cool Roof Rating Council.

Roofs with PV systems or with thermal mass over the roof membrane with a weight of at least 25 lb/ft² may model the Package A values for solar reflectance and emittance.

**STANDARD DESIGN**

The standard design depends on the variables of the climate zone and roof slope. Low-sloped roofs (with a roof rise of 2 feet in 12 or less) in climate zones 13 and 15 will have a standard design aged solar reflectance of 0.63 and a thermal emittance of 0.85.

Steep-sloped roofs in climate zones 10 through 15 will have a standard design roof with an aged solar reflectance of 0.20 and a minimum thermal emittance of 0.85.

Roofs with PV systems or with thermal mass over the roof membrane with a weight of at least 25 lb/ft² are assumed to meet the standard design values for solar reflectance and thermal emittance.

**VERIFICATION AND REPORTING**

Each input of Section 2.3.2 Attics modeled for the proposed design is reported on the CF1R for verification. A reflectance of 0.20 or higher is reported as a cool roof, a value higher than the default but less than 0.20 is reported as a non-standard roof reflectance value.

### 2.6.2 Ceiling Below Attic

**PROPOSED DESIGN**

For each conditioned zone, the user enters the area and construction of each ceiling surface that is below an attic space. The compliance software shall allow a user to enter multiple ceiling constructions. Surfaces that tilt 60 degrees or more are treated as knee walls and are not included as ceilings. The sum of areas shall equal the overall ceiling area with conditioned space on the inside and unconditioned attic space on the other side.

The compliance software creates an attic zone whose floor area is equal to the sum of the areas of all of the user input ceilings below an attic in the building. The user specifies the framing and spacing, the materials of the frame path and the R-value of the insulation path for each ceiling construction.

The user inputs the proposed insulation R-value rounded to the nearest whole R. For simulation, all ceiling below attic insulation is assumed to have nominal properties of 2.6 R/inch, a density of 0.5 lb/ft³ and a specific heat of 0.2 Btu/lb.
**STANDARD DESIGN**

The standard design shall have the same area of ceiling below attic as the proposed design. The ceiling/framing construction is based on the Package A prescriptive requirement and standard framing is assumed to be 2x4 wood trusses at 24 inches on center.

**VERIFICATION AND REPORTING**

The area, insulation R-value, and layer of each construction is reported on the CF1R.

### 2.6.3 Attic Roof Surface and Pitch

**PROPOSED DESIGN**

The roof pitch is the ratio of run to rise, e.g., 4:12 or 5:12. If the proposed design has more than one roof pitch, the pitch of the largest area is used.

The compliance software creates an attic zone roof. The roof area is calculated as the ceiling below attic area divided by the cosine of the roof slope where the roof slope is angle in degrees from the horizontal. The roof area is then divided into four equal sections with each section sloping in one of the cardinal directions (north, east, south and west). Gable walls, dormers or other exterior vertical surfaces that enclose the attic are ignored.

If the user specifies a roof with a pitch less than 2:12, the compliance software creates an attic with a flat roof that is 30 in. above the ceiling.

**STANDARD DESIGN**

The standard design shall have the same roof pitch, roof surface area and orientations as the proposed design.

**VERIFICATION AND REPORTING**

The roof pitch is reported on the CF1R.

### 2.6.4 Attic Conditioning

**PROPOSED DESIGN**

When spray foam insulation is applied to a roof that will not be vented, it is modeled as a “conditioned” attic and the volume of the attic is included in the conditioned space. A conventional attic is assumed to be “vented.”

**STANDARD DESIGN**

Attic ventilation is not a compliance variable and is the same for both proposed and standard design.

**VERIFICATION AND REPORTING**

The attic conditioning (ventilated, conditioned) is reported on the CF1R.
2.6.5 Attic Edge

With a standard roof truss (Figure 2-12), the depth of the ceiling insulation is restricted to the space left between the roof deck and the wall top plate for the insulation path and the space between the bottom and top chord of the truss in the framing path. If the modeled insulation completely fills this space, there is no attic air space at the edge of the roof. Heat flow through the ceiling in this attic edge area is directly to the outside both horizontally and vertically, instead of to the attic space. Measures that depend on an attic air space, such as radiant barriers or ventilation, do not affect the heat flows in the attic edge area.

Figure 2-12: Section at Attic Edge with Standard Truss
A raised heel truss (Figure 2-13) provides additional height at the attic edge that, depending on the height \( Y \) and the ceiling insulation \( R \), can either reduce or eliminate the attic edge area and its thermal impact.

**Figure 2-13: Section at Attic Edge with a Raised Heel Truss**

For cases where the depth of insulation (including below deck insulation depth) is greater than the available height at the attic edge, the compliance software automatically creates cathedral ceiling surfaces to represent the attic edge area and adjusts the dimensions of the attic air space using the algorithms contained in the document *2013 Residential Alternative Calculation Method Algorithms*. If above deck insulation is modeled, it is included in the attic edge cathedral ceiling constructions, but radiant barriers below the roof deck are not.

**Proposed Design**
The compliance software shall allow the user to specify that a raised heel truss will be used (as supported by construction drawings), with the default being a standard truss as shown in Figure 2-12. If the user selects a raised heel truss, the compliance software will require the user to specify the vertical distance between the wall top plate and the bottom of the roof deck (\( Y \) in Figure 2-13).

**Standard Design**
The standard design shall have a standard truss with the default vertical distance of 3.5 in. between wall top plate and roof deck as shown in Figure 2-12.
**VERIFICATION AND REPORTING**

A raised heel truss is a special feature and its vertical height above the top plate will be included on the CF1R.

### 2.6.6 The Roof Deck

The roof deck is the construction at the top of the attic and includes the solar optic properties of the exterior surface, the roofing type, the framing, insulation, air gaps and other features. These are illustrated in Figure 2-14, which shows a detailed section through the roof deck.

![Figure 2-14: Components of the Attic through Roof Deck](image)

**2.6.6.1 Radiant Barrier**

Radiant barriers are used to reduce heat flow at the bottom of the roof deck in the attic. A 0.05 emittance is modeled at the bottom surface of the roof deck if radiant barriers are used. If no radiant barrier is used, the value modeled is 0.9. If radiant barrier is installed over existing skip sheathing in a reroofing application, 0.5 is modeled.

**PROPOSED DESIGN**

The user shall specify whether or not the proposed design has a:

- Continuous Radiant Barrier
- Radiant Barrier over Discontinuous Sheathing
- No Radiant Barrier

**STANDARD DESIGN**

The standard design shall have a radiant barrier if required by the prescriptive standards (§150.1(c) and Table 150.1-A) for the applicable climate zone.

**VERIFICATION AND REPORTING**

Radiant barriers are reported as a *Special Feature* on the CF1R.
2.6.6.2 **Below Deck Insulation**

Below deck insulation is insulation that will be installed below the roof deck between the roof trusses or rafters.

**PROPOSED DESIGN**

The compliance software shall allow the user to specify the R-value of insulation that will be installed below the roof deck between the roof trusses or rafters. The default is no below deck roof insulation.

**STANDARD DESIGN**

The standard design has below deck insulation.

**VERIFICATION AND REPORTING**

The R-value of any below deck insulation is reported as a *Special Feature* on the CF1R.

2.6.6.3 **Roof Deck and Framing**

The roof deck is the structural surface which supports the roofing. The compliance software assumes a standard wood deck and this is not a compliance variable. The size, spacing and material of the roof deck framing are compliance variables.

**PROPOSED DESIGN**

The roof deck is wood siding/sheathing/decking. The compliance software shall default the roof deck framing to 2x4 trusses at 24 in. o. c. The compliance software shall allow the user to specify alternative framing size, material and framing spacing.

**STANDARD DESIGN**

The standard design is 2x4 trusses at 24 in. o. c.

**VERIFICATION AND REPORTING**

Non-standard roof deck framing or spacing is reported as a *Special Feature* on the CF1R.

2.6.6.4 **Above Deck Insulation**

Above deck insulation represents the insulation value of the air gap in “concrete or clay tile” or “metal tile or wood shakes.” The R-value of any user modeled insulation layers between the roof deck and the roofing is added to the air gap value.

**PROPOSED DESIGN**

This input defaults to R= 0.85 for “concrete or clay tile” or for “metal tile or wood shakes” to represent the benefit of the air gap, but no additional insulation. The compliance software shall allow the user to specify the R-value of additional above deck insulation in any roof deck construction assembly.
The standard design accounts for the air gap based on roofing type, but has no additional above deck insulation.

Above deck insulation R-value is reported as a Special Feature on the CF1R.

The choice of roofing type determines the air gap characteristics between the roofing material and the deck, and establishes whether other inputs are needed, as described below. The choices for roof type are shown below.

- **Concrete or clay tile.** These have significant thermal mass and an air gap between the deck and the tiles.
- **Metal tile or wood shakes.** These are lightweight, but have an air gap between the tiles or shakes and the deck. Note that tapered cedar shingles do not qualify and are treated as a conventional roof surface.
- **Other high slope roofing types.** This includes asphalt and composite shingles and tapered cedar shingles. These products have no air gap between the shingles and the structural roof deck.
- **Low slope membranes.** These are basically flat roofs with a slope of 2:12 or less.

Above deck mass. The above deck mass depends on the roofing type. The mass is 10 lb/ft² for concrete and clay tile and 5 lb/ft² for metal tile, wood shakes or other high slope roofing types. For low slope roofs the additional thermal mass is assumed to be gravel or stone and the user chooses one of the following inputs that is less than or equal to the weight of the material being installed above the roof deck:

- No mass
- 5 lb/ft²
- 10 lb/ft²
- 15 lb/ft²
- 25 lb/ft²

The roof type and slope shall match the proposed design.

The roof type is reported on the CF1R.
2.6.6.6 Solar Reflectance and Thermal Emittance

**Proposed Design**

The compliance software shall allow the user to default the solar reflectance and thermal emittance of the roofing. The solar reflectance default is 0.10 for all roof types. The thermal emittance default is 0.85.

The compliance software shall allow the user to input aged solar reflectance and thermal emittance of roofing material that are rated by the Cool Roof Rating Council (CRRC). The installed value must be equal to or higher than the value specified here. Roof construction with a roof membrane mass of at least 25 lb/ft³ or roof area incorporated integrated solar collectors are assumed to meet the minimal solar reflectance.

**Standard Design**

The solar reflectance and thermal emittance of the standard design roofing are as specified in the prescriptive Standards.

**Verification and Reporting**

Thermal emittance and solar reflectance shall be reported on the CF1R. A reflectance of 0.20 or higher is reported as a cool roof, a value higher than the default but less than 0.20 is reported as a non-standard roof reflectance value.

### 2.7 Crawl Spaces

The crawl space type is either a (1) normal vented crawl space (has a conditioned space above with raised floor insulation), (2) insulated with reduced ventilation [as used in the Building Code], or (3) sealed and mechanically ventilated crawl space (also called a controlled ventilation crawl space or CVC).

**Proposed Design**

The software user will model the crawl space as a separate unconditioned zone, selecting the appropriate crawl space type, with the perimeter of the crawlspace (in linear feet) and the height of the crawl space.

**Standard Design**

The standard design has a typical vented crawlspace when a crawl space is shown. Otherwise the raised floor is assumed to be over exterior or unconditioned space.

**Verification and Reporting**

The crawl space zone type and characteristics shall be reported on the CF1R. A controlled ventilation crawl space shall be reported as a special feature on the CF1R.
2.8 Basements

Not yet implemented.

2.9 Garage/Storage

An attached unconditioned space is modeled as a separate unconditioned zone. While the features of this space have no effect on compliance, it is modeled to accurately represent the building. The walls and door that separate the conditioned zone from the garage are modeled as part of the conditioned zone.

**PROPOSED DESIGN**

The software user will model the area and type for the floor, exterior walls (ignore windows), large metal roll-up or wood doors (assume a 1.0 U-factor), and roof/ceiling (typically an attic or the same as the conditioned zone).

**STANDARD DESIGN**

The standard design building has the same features as the proposed design.

**VERIFICATION AND REPORTING**

The presence of an attached garage or unconditioned space is reported as general information on the CF1R. The general characteristics of the unconditioned zone are reported on the CF1R.

2.10 Domestic Hot Water (DHW)

Water heating energy use is based on the number of dwelling units, fuel type, distribution system, water heater type, and conditioned floor area (up to 2500 ft²).

**PROPOSED DESIGN**

The water heating system is defined by the tank type, heater element type, distribution type, multi-family central water heating distribution, efficiency (either energy factor or recovery efficiency with the standby loss), tank volume, exterior insulation R-value (only for indirect) and rated input.

Tank types include:

- Small storage: <= 75,000 Btu gas/propane, <=105,000 Btu/hr oil, <= 12 kW electric, or <= 24 amps heat pump.
- Small tankless: gas or propane with an input of 200,000 Btu per hour or less, oil with an input of 210,000 Btu per hour or less, or electric with an input of 12 kW or less. Tankless...
water heater is a water heater with an input rating of \( \geq 4,000 \text{ Btu per hour per gallon of stored water} \). Rated with an energy factor.

- Large storage: \( > 75,000 \text{ Btu gas/propane}, >105,000 \text{ Btu/hr oil}, \) or \( > 12 \text{ kW electric} \). Rated with thermal efficiency and standby loss.

- Large tankless: gas or propane with an input of \( > 200,000 \text{ Btu per hour} \), oil with an input of \( > 210,000 \text{ Btu per hour} \), or electric with an input of \( > 12 \text{ kW} \). Tankless water heater is a water heater with an input rating of \( \geq 4,000 \text{ Btu per hour per gallon of stored water} \). Rated with thermal efficiency.

- Mini tank: a temperature buffering electric heater sometimes used with gas tankless to mitigate fluctuations between draws (units not listed in the appliance database use a standby loss (in Watts) of 100).

- Indirect: a tank with no heating element or combustion device used in combination with a boiler or other device serving as the heating element.

- Boiler: a water boiler that supplies hot water. Rated with Thermal Efficiency or AFUE.

Heater element type includes:

- Electric resistance
- Natural gas/oil
- Propane, or
- Heat pump.

For water heating systems serving a single dwelling unit, a dwelling unit distribution type must be specified. Dwelling unit distribution system types for systems serving individual dwelling units include:

- Standard (the full length of the line from the water heater to the kitchen fixtures and all piping of nominal ¾” or larger diameter insulated with 1 inch of insulation
- Pipe insulation, all lines
- Central parallel piping
- Recirculation with non-demand control (continuous pumping)
- Recirculation with demand control push button
- Recirculation with demand control occupancy/motion sensor
- HERS required pipe insulation, all lines
- HERS required central parallel piping
- HERS required recirculation, demand control push button
- HERS required recirculation, demand control occupancy/motion sensor
- HERS required point of use
- HERS required compact distribution system
When a multi-family building has central water heating, both a dwelling unit and a central system distribution type must be specified. Dwelling unit distribution types for this case include:

- Standard (the full length of the line from the water heater to the kitchen fixtures and all piping of nominal ¾” or larger diameter insulated with 1 inch of insulation
- Pipe insulation, all lines
- HERS required pipe insulation, all lines

Multi-family central hot water heating central system distribution types include:

- No loops or recirculation pump
- No control
- Recirculation with demand control (standard design for new construction)
- Recirculation with temperature modulation control
- Recirculation with temperature modulation and monitoring

Some distribution systems have an option to increase the amount of credit received if the option for HERS verification is selected. See Appendix E for the amount of credit and Reference Appendices, Residential Appendix Table RA2-1 for a summary of inspection requirements.

**STANDARD DESIGN**

**Individual dwelling units:** The standard design is based on §150.1(c)8. For single-family dwellings or dwelling units served by a dedicated water heating system, each dwelling unit has one small storage (< 75000 Btu), 50-gallon gas storage water heater, meeting minimum federal Energy Factor standard (0.575 in 2014, 0.60 in 2015). If natural gas is not available, the fuel type is the same as the proposed fuel type, meeting the minimum federal Energy Factor standard for propane (0.575 in 2014, 0.60 in 2015) or electric (0.904 in 2014, 0.945 in 2015). When the proposed fuel type is electric resistance, a solar water heating system with a minimum solar savings fraction of 0.50 is included. The distribution type for gas or propane is either standard or, if a recirculating system is shown in the proposed design, a recirculating system with manual controls. The distribution type for electric resistance is no recirculating system.

**Multiple dwelling units:** If the proposed design is a central water heating system the standard design is the same type of water heater equipment (natural gas, if available or electric meeting minimum appliance efficiency standard) as the proposed design meeting the minimum appliance efficiency requirements. The system includes a recirculation system with controls that regulate pump operation based on measurement of hot water demand and hot water return temperature, is capable of turning off the system (§110.3(c)2), has one recirculation loop (if serving more than eight dwelling units or if the proposed design for a system serving eight or fewer dwelling units includes a recirculation system) with efficiency based on Nonresidential Appendix NA6, and incorporates provisions of §110.3(c)5:

1) Air release valve or vertical pump installation,
2) Recirculation loop backflow prevention,
3) Equipment for pump priming,
4) Pump isolation valves,

| Does the proposed water heating system have a storage tank? | Yes | Is the input rating of each water heater in the proposed design less than or equal to 75,000 Btu/h or if electric, less than or equal to 12 kW? | Yes | Standard design is one or more NAEC gas or propane water heater. If natural gas is available at the site, the standard design is a gas water heater, otherwise it is electric. If the total storage volume of the proposed design is less than 100 gallons, then the standard design is single water heater with a storage volume equal to the total storage volume of the proposed design. If the total storage volume of the proposed design is larger than 100 gallons, then the standard design shall have multiple water heaters. The number of water heaters is equal to the total storage capacity of the proposed design divided by 100 and rounded up. The EF of each 100 gallon water heater shall be based on the compliance year as:
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<td>Does the proposed water heating system have a storage tank?</td>
<td>Yes</td>
<td>Is the input rating of each water heater in the proposed design less than or equal to 75,000 Btu/h or if electric, less than or equal to 12 kW?</td>
<td>Yes</td>
<td>Standard design is composed of the same number of large storage gas or propane water heaters as in the proposed design with a storage volumes the same as the storage volumes of the proposed design. If natural gas is available at the site, the standard design is a gas water heater, otherwise it is electric. The thermal efficiency is 0.80 and stand-by losses are as specified in the Appliance Efficiency Regulations. See specification of distribution system below.</td>
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| No | No | Standard design is the same number of natural gas or propane instantaneous water heaters as in the proposed design with input ratings equal to those in the proposed design. If natural gas is available at the site, the standard design is a gas water heater, otherwise it is electric. Efficiency of the instantaneous water heaters shall be:
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Table 2-22: Standard Design for Systems Serving Multiple Dwelling Units

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See specification of distribution system below.
5) Cold water supply and recirculation loop connection to hot water storage tank, and
6) Cold water supply backflow prevention.

A central water heating system standard design also includes a solar fraction of 0.20 in climate zones 1 through 9, and 0.35 in climate zones 10 through 16.

**VERIFICATION AND REPORTING**

All modeled features and the number of devices modeled for the water heating system are reported on the CF1R. Where distribution systems specify HERS verification, those features are listed in the HERS Required Verification listings on the CF1R.

**2.10.1 Solar Water Heating Credit**

When a water heating system has a solar system to provide part of the water heating, the Solar Fraction (SF) is determined using an F-chart program, OG-100 or OG-300 calculation method (see www.gosolarcalifornia.org). The calculation method requires that the user specify the climate zone and conditioned floor area, in addition to published data for the solar water heating system.

**2.11 Additions/Alterations**

Addition and alteration compliance is based on standards §150.2. Alterations must model the entire dwelling unit. Additionally, if there is no addition the standards require at least two components of the residence are altered (see 150.2(b)2). Additions may be modeled as an entirely new building (whole building), addition alone, or as “existing+addition+alteration”.

**2.11.1 Whole Building**

The entire proposed building, including all additions and/or alterations, is modeled the same as a newly constructed building. The building complies if the proposed design uses equal or less energy than the standard design. This is a difficult standard to meet as the existing building usually does not meet current standards and must be substantively upgraded.

**2.11.2 Addition Alone Approach**

The proposed addition alone is modeled the same as a newly constructed building except that the internal gains are prorated to the size of the dwelling and any surfaces such as walls or ceilings that are between the existing building and the addition are modeled not included in the calculations. The addition complies if the proposed design uses equal or less space heating and space cooling TDV energy than the standard design.

The Addition Alone Approach shall not be used when alterations to the existing building are proposed. Modifications to any surfaces between the existing building and the addition are part of the addition and are not considered alterations.
PROPOSED DESIGN

The user shall indicate that an addition alone is being modeled and enter the conditioned floor area of the addition. Any surfaces that are between the existing building and the addition are not modeled or treated as an adiabatic surfaces. All other features of the addition shall be modeled as for a newly constructed building.

When an existing HVAC system is extended to serve the addition, the proposed design shall assume the same efficiency for the HVAC equipment as the standard design (or Package A, see Sections 2.4.1 and 2.4.5). When a dual-glazed greenhouse or garden window is installed in an addition or alteration, the proposed design U-factor can be assumed to be 0.32.

STANDARD DESIGN

The addition alone is modeled the same as newly constructed building.

2.11.3 Existing + Addition + Alteration Approach

Standards §150.2(a)2 and (b)2 contain the provisions for additions and alterations to be modeled by including the existing building in the calculations. This is called the “Existing + Addition + Alteration” (or “E+A+A”) performance approach.

The proposed design is modeled by identifying each energy feature as part of the existing building, the addition, or an alteration. The compliance software uses this information to create an E+A+A standard design in accordance with the rules in the standards that take into account whether altered components meet or exceed the threshold at which point they receive a compliance credit and whether any measures are triggered by altering a given component. For example, when replacing or adding an air handler, outdoor condensing unit of a split system, or cooling or heating coil, the prescriptive requirements include duct leakage testing to 15%.

For building surfaces and systems designated below, all compliance software must provide an input field with labels for the proposed design which define how the standard design requirements are established, based on the option selected by the software user:

• **Existing:** remains unchanged within the proposed design.

• **Altered:** the surface or system is being altered in the proposed design. No verification of existing conditions is performed.

• **Verified and Altered:** the surface or system is being altered in the proposed design and the original condition is verified by a HERS rater.

• **New:** a new surface or system is added in the proposed design (typically part of the addition, but may be in the existing building).

Features being removed are not included in the proposed design.
When the standard design requirements for existing, altered and new are identical for a particular input, this section uses the term “all”.

The compliance software user shall indicate that an existing + addition + alteration is being modeled and select the correct tag for each surface or system. Features to be altered must be paired with an existing feature. The compliance documentation shall clearly indicate each tag.

The user chooses whether the project is run “Without” or “With Third Party Verification” of an existing condition (see §150.2, Table 150.2-B):

- **Without Third Party Verification of Existing Conditions** (the default selection). This compliance path does not require an on-site inspection of existing conditions prior to the start of construction. The software ignores the specific attributes of the existing condition, and automatically sets the standard design based solely on the type of surface or system being altered and the climate zone. Energy compliance credit is a function of the difference between the value for that specific feature allowed in Table 150.2-B and the modeled/installed efficiency of the feature. This path is the default user selection.

  The existing condition for altered features may be left undefined since the software uses Table 150.1-B to set the standard design.

  Example: an existing 2x4 wood frame exterior wall with no insulation is upgraded to include R-15 cavity insulation. The standard design is based on R-13 cavity insulation (U=0.102), the mandatory minimum insulation requirement, and the proposed R-15 in the walls receives an energy credit for the difference between R-13 and R-15.

- **With Third Party Verification of Existing Conditions**. This compliance path requires that a HERS Rater perform an on-site inspection of pre-alteration conditions prior to registration of the performance Certificate of Compliance by the HERS Provider Data Registry. If an altered component or system meets or exceeds the prescriptive alteration requirements, the compliance software uses the existing condition as the standard design value. Energy compliance credit is then based on the difference between the verified existing condition for that altered feature and the modeled/installed efficiency of the proposed design.

  The HERS Rater verifies only those existing features that are being altered for compliance credit and used to set the standard design. A summary of the existing measures to be verified are listed on a special Verification of Existing Conditions form (CF3R-20-H) which can be downloaded by the HERS Rater from the HERS Provider website.

  In this approach, the existing condition for altered features must be defined by the user since that is used to set the standard design.

  Using the same example as above, the standard design is the existing uninsulated wall, and
the energy compliance credit is based on the difference between the R-0 wall and the proposed R-15 wall.

Details on the verification of existing conditions are contained in the Residential Compliance Manual, Appendix G.

This subsection presents a summary of standard design modeling assumptions based on proposed design inputs, including whether a proposed feature is new, altered or existing to remain unchanged.

2.11.3.1 Roof/Ceilings

**STANDARD DESIGN**

The standard design roof/ceiling construction assembly is based on the proposed design assembly type as shown in Table 2-23.

<table>
<thead>
<tr>
<th>Proposed Design Roof/Ceiling Types</th>
<th>Standard Design Based on Proposed Roof/Ceiling Status (Tag)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ADDITION Addition or New Construction</td>
<td>ALTERED ALTERED With 3rd Party Verification</td>
</tr>
<tr>
<td>Ceilings Below Attics</td>
<td>CZ1 &amp; 11-16: R-38 between 2x wood framing, 24” o.c.</td>
<td>R-30 between 2x wood framing, 24” o.c.</td>
</tr>
<tr>
<td></td>
<td>CZ2-10: R-30 between 2x wood framing, 24” o.c.</td>
<td></td>
</tr>
<tr>
<td>Non-Attic (Cathedral) Ceilings and Roofs</td>
<td>CZ1 &amp; 11-16: R-38 between 2x wood framing, 24” o.c.</td>
<td>R-30 between 2x wood framing, 24” o.c.</td>
</tr>
<tr>
<td></td>
<td>CZ2-10: R-30 between 2x wood framing, 24” o.c.</td>
<td></td>
</tr>
<tr>
<td>Radiant Barrier</td>
<td>CZ2-15: Radiant Barrier</td>
<td>Existing radiant barrier condition</td>
</tr>
<tr>
<td></td>
<td>CZ1&amp;16: No Radiant Barrier</td>
<td></td>
</tr>
<tr>
<td>Roofing Surface (Cool Roof)</td>
<td>Low Sloped (&lt; 2:12), CZ13&amp;15: Reflectance=0.63 &amp; Emittance=0.85 or SRI=75 Steep Sloped (&gt; 2:12), CZ10-15: Reflectance=0.20 &amp; Emittance=0.85; or SRI=16</td>
<td>Same as Addition.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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2.11.3.2 Exterior Walls

PROPOSED DESIGN

Existing structures being converted to conditioned space using an E+A+A approach are allowed to show compliance using R-11 wall insulation, without having to upgrade to R-13 mandatory insulation requirements. The walls are modeled as an assembly with R-11 insulation.

STANDARD DESIGN

The areas, orientation and tilt of existing, new and altered net exterior wall areas (with windows and doors subtracted) are the same in the existing and addition portions of standard design as the proposed design.

If the proposed wall area is framed, the gross exterior wall area (excluding knee walls) is equally divided between the four building orientations: front, left, back and right. The gross exterior wall area of any unframed walls is also equally divided between the four orientations in the standard design.

The standard design exterior wall construction assembly is based on the proposed design assembly type as shown in Table 2-24.
# Table 2-24: Standard Design for Exterior Walls

<table>
<thead>
<tr>
<th>Proposed Design Exterior Wall Assembly Type</th>
<th>Standard Design Values Based on Proposed Wall Status (Tag)</th>
<th>ADDITION Addition or New Construction</th>
<th>ALTERED Without 3rd Party Verification</th>
<th>VERIFIED ALTERED With 3rd Party Verification</th>
<th>EXISTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above Grade, Any Framed Wall</td>
<td></td>
<td>R-15 cavity insulation in 2x4 16” o.c. wood frame + R-4 exterior continuous insulation</td>
<td>R-13 cavity insulation in 2x4 16” o.c. wood frame</td>
<td>If proposed U-factor is &lt;= Altered, standard design = existing wall. If proposed U-factor is &gt; Altered, standard design = Altered</td>
<td>Existing Wall</td>
</tr>
<tr>
<td>Above &amp; Below Grade, Mass Wall, Interior Insulation</td>
<td></td>
<td>CZ1-15: R-13 cavity insulation in 2x4 16” o.c. wood frame inside 8” CMU heavy weight solid grout CZ16: R-13 cavity insulation in 2x4 16” o.c. wood frame + R-4 continuous insulation inside 8” CMU heavy weight solid grout</td>
<td>If proposed U-factor is &lt;= Addition, standard design = existing wall. If proposed U-factor is &gt; Addition, standard design = Addition</td>
<td>Pre-alteration Existing Wall</td>
<td>Existing Wall</td>
</tr>
<tr>
<td>Above Grade, Mass Wall, Exterior Insulation</td>
<td></td>
<td>CZ1-15: R-8 continuous insulation outside of 8” CMU heavy weight solid grout CZ16: R-13 cavity insulation in 2x4 16” o.c. wood frame outside of 8” CMU heavy weight solid grout</td>
<td>If proposed U-factor is &lt;= Addition, standard design = existing wall. If proposed U-factor is &gt; Addition, standard design = Addition</td>
<td>Pre-alteration Existing Wall</td>
<td>Existing Wall</td>
</tr>
<tr>
<td>Below Grade, Mass Wall, Exterior Insulation</td>
<td></td>
<td>CZ1-13: R-5 continuous insulation outside of 8” CMU heavy weight solid grout CZ14-15: R-10 continuous insulation outside of 8” CMU heavy weight solid grout CZ16: R-19 cavity insulation in 2x6 16”o.c. frame outside of 8” CMU heavy weight solid grout</td>
<td>If proposed U-factor is &lt;= Addition, standard design = existing wall. If proposed U-factor is &gt; Addition, standard design = Addition</td>
<td>Pre-alteration Existing Wall</td>
<td>Existing Wall</td>
</tr>
<tr>
<td>Framed Wall Adjacent to Unconditioned (Garage Wall)</td>
<td></td>
<td>R-15 cavity insulation in 2x4 16” o.c. wood frame</td>
<td>R-13 cavity insulation in 2x4 16”o.c. wood frame</td>
<td>Pre-alteration Existing Wall</td>
<td>Existing Wall</td>
</tr>
</tbody>
</table>
### 2.11.3.3 Fenestration

Table 2-25: Standard Design for Fenestration (in Walls and Roofs)

<table>
<thead>
<tr>
<th>Proposed Design Fenestration Type</th>
<th>Standard Design Based on Proposed Fenestration Status (Tag)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ADDITION</td>
</tr>
<tr>
<td></td>
<td>Addition or New Construction</td>
</tr>
<tr>
<td><strong>Vertical Glazing:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Area and Orientation</strong></td>
<td></td>
</tr>
<tr>
<td><strong>See full description below.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>See full description below.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Vertical Glazing:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>U-Factor</strong></td>
<td>U=0.32</td>
</tr>
<tr>
<td><strong>If proposed U-factor is &lt;= Altered, standard design = Altered</strong></td>
<td></td>
</tr>
<tr>
<td><strong>If proposed U-factor &gt; Altered, standard design = Altered</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Vertical Glazing:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>SHGC</strong></td>
<td>CZ2, 4, 6-16: SHGC=0.25</td>
</tr>
<tr>
<td><strong>CZ1,3 &amp; 5: SHGC=0.66</strong></td>
<td>CZ1,3 &amp; 5: SHGC = 0.66</td>
</tr>
<tr>
<td><strong>Skylight:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Area and Orientation</strong></td>
<td></td>
</tr>
<tr>
<td><strong>No skylight area in the standard design</strong></td>
<td></td>
</tr>
<tr>
<td><strong>See full description below, “E+A+A standard design Fenestration Areas and Orientation”</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Skylight:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>U-Factor</strong></td>
<td>U=0.32</td>
</tr>
<tr>
<td><strong>If proposed U-factor is &lt;= Altered, standard design = Altered</strong></td>
<td></td>
</tr>
<tr>
<td><strong>If proposed U-factor &gt; Altered, standard design = Altered</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Skylight:</strong></td>
<td></td>
</tr>
<tr>
<td><strong>SHGC</strong></td>
<td>CZ2, 4, 6-16: SHGC=0.25</td>
</tr>
<tr>
<td><strong>CZ1,3 &amp; 5: SHGC=0.66</strong></td>
<td>CZ1,3 &amp; 5: SHGC = 0.66</td>
</tr>
</tbody>
</table>

**PROPOSED DESIGN**

Fenestration areas are modeled in the addition as new. In the existing building they may be existing, altered or new. Altered (replacement) fenestration is defined in §150.2(b)1.B as “existing fenestration area in an existing wall or roof [which is] replaced with a new manufactured fenestration product...Up to the total fenestration area removed in the existing wall or roof....” Added fenestration area in an existing wall or roof is modeled as new.

**Example:** A 5'-0” x 6’-8” (33.33 ft²) single pane metal frame sliding door is replaced with a 6’-0” x 6’-8” (40.0 ft²) dual vinyl low-e sliding door. Since the new glass sliding door replaces the full area of the existing glass sliding door, an altered glass door is modeled with an area of 33.33 ft², and a new glass door is modeled with an area of (40.0 - 33.33) = 16.67 ft².

**STANDARD DESIGN**

Standard design fenestration U-factor and SHGC are based on the proposed design fenestration as shown in Table 2-25. Vertical glazing includes all fenestration in exterior walls such as...
windows, clerestories and glazed doors. Skylights include all glazed openings in roofs and ceilings.

The standard design is set for fenestration areas and orientations as:

1. **Proposed design \(< 20\%\) total fenestration area:**

   In the existing building, the standard design uses the same area and orientation of each existing or altered fenestration area (in its respective existing or altered wall or roof.)

   In the addition, new fenestration is divided equally between the four project compass points similar to new gross wall areas in the addition described above.

2. **Proposed design \(> 20\%\) total fenestration area:**

   The standard design first calculates the allowed total fenestration area as follows total existing and altered fenestration area in existing or altered walls and roofs + 20\% of the addition conditioned floor area.

   Example: An existing 2,000 sf house is undergoing alterations and a 400-ft\(^2\) addition. The existing portion of the house has a total of 560 ft\(^2\) (28\%) of windows, glazed doors and skylights that are existing (unchanged) or altered (replaced) within the exterior walls and roofs to remain. Therefore:

   \[
   \text{Standard design} = 560 + (0.20 \times 400) = 560 + 80 = 640 \text{ ft}^2
   \]

   The standard design is based on 640 ft\(^2\) of glazing divided among the 4 building surfaces.

2.11.3.4 **Overhangs, Sidefins and Other Exterior Shading**

**STANDARD DESIGN**

The standard design for a proposed building with overhangs, sidefins and/or other exterior shades is shown in Table 2-26. Treated differently than fixed overhangs and sidefins, exterior shading includes such features as exterior woven or louvered sunscreen, or roll-down awnings or slats as explained in Section 2.5.6.9.
Table 2-26: Standard Design for Overhangs, Sidefins and Other Exterior Shading

<table>
<thead>
<tr>
<th>Proposed Design Shading Type</th>
<th>ADDITION Addition or New Construction</th>
<th>ALTERED Without 3rd Party Verification</th>
<th>VERIFIED ALTERED With 3rd Party Verification</th>
<th>EXISTING Overhangs and Sidefins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhangs and Sidefins</td>
<td>No overhangs or sidefins on new fenestration in the standard design.</td>
<td>Standard design uses whatever overhangs and sidefins are defined with the altered fenestration.</td>
<td>Same as Altered.</td>
<td>Existing overhangs and sidefins</td>
</tr>
<tr>
<td>Exterior Shading</td>
<td>No exterior shading except default (standard) bug screens.</td>
<td>Standard design uses whatever exterior shading is defined as part of the altered fenestration.</td>
<td></td>
<td>Existing exterior shading</td>
</tr>
<tr>
<td>Window Film</td>
<td>No exterior shading except default (standard) bug screens.</td>
<td>Standard design uses whatever exterior shading is defined as part of the altered fenestration.</td>
<td></td>
<td>Existing exterior shading</td>
</tr>
</tbody>
</table>

2.11.3.5 Window Film

**PROPOSED DESIGN**

A window film is treated as a window replacement for the SHGC value. To determine the SHGC value, use Table 2-27 to calculate the adjusted SHGC value for the program input. If a window film does not have a 10-year warranty, multiply column 3 by column 4 (ignore column 5) and enter the adjusted SHGC value into the software for the window’s altered SHGC value. If a window film has a 10-year warranty, the multiplier in Column 4 is used with the NFRC value in column 5 (ignore column 3) and enter the adjusted SHGC value into the software for the window’s altered SHGC value. It shall be treated as a window replacement.

Table 2-27: Window Film Calculated SHGC

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator Type</td>
<td>Default Glazing Reference</td>
<td>Default SHGC Value Table 110.6-B</td>
<td>SHGC Ratio</td>
<td>NFRC Window Film SHGC</td>
<td>New Adjusted Total Value</td>
</tr>
<tr>
<td>Fixed</td>
<td>3 mm (1/8in.) clear (Single Pane)</td>
<td>0.83</td>
<td>1.1528</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Fixed</td>
<td>3 mm (1/8in.) clear (Double Pane - Clear)</td>
<td>0.73</td>
<td>1.1406</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Window Wall</td>
<td>6 mm (1/4in.) clear (Single Pane - Clear)</td>
<td>0.83</td>
<td>1.1370</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Window Wall</td>
<td>6 mm (1/4in.) grey (Single Pane - Tinted)</td>
<td>0.68</td>
<td>1.3077</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Window Wall</td>
<td>6 mm (1/4in.) clear (Double Pane - Clear)</td>
<td>0.73</td>
<td>1.1587</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Window Wall</td>
<td>6 mm (1/4in.) grey 6 mm (1/4in.) clear (Double Pane - Tinted)</td>
<td>0.60</td>
<td>1.4634</td>
<td>x</td>
<td>=</td>
</tr>
</tbody>
</table>
2.11.3.6 Floors

**STANDARD DESIGN**

The standard design for floors is shown in Table 2-28.

<table>
<thead>
<tr>
<th>Proposed Design Floor Type</th>
<th>Standard Design Based on Proposed Floor Status (Tag)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ADDITION</strong> Addition or New Construction</td>
<td><strong>ALTERED</strong> Without 3rd Party Verification</td>
</tr>
<tr>
<td>Raised Floor Over Crawl Space or Over Exterior</td>
<td>R-19 cavity insulation in 2x6 16” o.c. raised floor</td>
</tr>
<tr>
<td>Slab-on-Grade: Unheated</td>
<td>CZ1-15: Un-insulated slab edge</td>
</tr>
<tr>
<td>Slab-on-Grade: Heated, Vertical Insulation</td>
<td>CZ1-15: R-5 16” vertical slab edge insulation CZ16: R-10 16” vertical slab edge insulation</td>
</tr>
<tr>
<td>Raised Concrete Slab</td>
<td>CZ1,2,11,13,14,16: R-8 CZ3-10: Un-insulated CZ12,15: R-4</td>
</tr>
</tbody>
</table>

2.11.3.7 Thermal Mass

**STANDARD DESIGN**

The standard design for thermal mass in Existing + Addition + Alteration calculations is the same as for all newly constructed buildings as explained in Section 2.5.4.1.

2.11.3.8 Air Leakage and Infiltration

**STANDARD DESIGN AIR LEAKAGE AND INFILTRATION**

The standard design for space conditioning systems is shown in Table 2-29.

<table>
<thead>
<tr>
<th>Proposed Air Leakage and Infiltration</th>
<th>Standard Design Air Leakage Based on Building Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ADDITION</strong> Addition or New Construction</td>
<td><strong>ALTERED</strong> Without 3rd Party Verification</td>
</tr>
<tr>
<td>Single Family Buildings</td>
<td>5 ACH50</td>
</tr>
<tr>
<td>Multi-Family Buildings</td>
<td>7 ACH50</td>
</tr>
</tbody>
</table>
### 2.11.3.9 Space Conditioning System

**STANDARD DESIGN**

The standard design for space conditioning systems is shown in Table 2-30.

<table>
<thead>
<tr>
<th>Proposed Design</th>
<th>Proposed Space Conditioning System Type</th>
<th>Standard Design Based on Proposed Space Conditioning Status (Tag)</th>
<th>ADDITION</th>
<th>ALTERED</th>
<th>VERIFIED ALTERED</th>
<th>EXISTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating System</td>
<td>Compliance 2014</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing heating fuel type, equipment type/efficiency.</td>
<td></td>
</tr>
<tr>
<td>Heating System</td>
<td>Compliance 2015</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing heating fuel type and equipment type/efficiency.</td>
<td></td>
</tr>
<tr>
<td>Cooling System</td>
<td>Compliance 2014</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing cooling equipment type/efficiency.</td>
<td></td>
</tr>
<tr>
<td>Cooling System</td>
<td>Compliance 2015</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing cooling equipment type/efficiency.</td>
<td></td>
</tr>
<tr>
<td>Whole House Fan</td>
<td>WHF applies only if addition &gt; 1,000 ft²</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing condition. To count as Existing the WHF must be &gt;= 2.0 cfm/sf and be CEC-rated</td>
<td></td>
</tr>
</tbody>
</table>

### 2.11.3.10 Duct System

**STANDARD DESIGN**

<table>
<thead>
<tr>
<th>Proposed Design</th>
<th>Proposed Duct System Type</th>
<th>Standard Design Based on Proposed Duct System Status (Tag)</th>
<th>ADDITION</th>
<th>ALTERED</th>
<th>VERIFIED ALTERED</th>
<th>EXISTING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating System</td>
<td>Compliance 2014</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing heating fuel type, equipment type/efficiency.</td>
<td></td>
</tr>
<tr>
<td>Heating System</td>
<td>Compliance 2015</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing heating fuel type and equipment type/efficiency.</td>
<td></td>
</tr>
<tr>
<td>Cooling System</td>
<td>Compliance 2014</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing cooling equipment type/efficiency.</td>
<td></td>
</tr>
<tr>
<td>Cooling System</td>
<td>Compliance 2015</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing cooling equipment type/efficiency.</td>
<td></td>
</tr>
<tr>
<td>Whole House Fan</td>
<td>WHF applies only if addition &gt; 1,000 ft²</td>
<td>Same as Addition.</td>
<td>No</td>
<td>Same as</td>
<td>Existing condition. To count as Existing the WHF must be &gt;= 2.0 cfm/sf and be CEC-rated</td>
<td></td>
</tr>
</tbody>
</table>

Note 1: Refer to section 150.2(b)1Diia for definition of an “Entirely New or Complete Replacement Duct System”.

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2.11.3.11 Water Heating System

**STANDARD DESIGN**

Table 2-32: Standard Design for Water Heater Systems

<table>
<thead>
<tr>
<th>Proposed Design Water Heating System Type</th>
<th>Standard Design Based on Proposed Water Heating Status (Tag)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ADDITION</td>
</tr>
<tr>
<td>Single Family</td>
<td>Package A water heating system (see Section 2.10)</td>
</tr>
<tr>
<td>Multi-family: Individual Water Heater for Each Dwelling Unit</td>
<td>Package A water heating system for each dwelling unit (see Section 2.10).</td>
</tr>
<tr>
<td>Multi-family: Central Water Heating System</td>
<td>Central water heating system per Section 2.10.</td>
</tr>
</tbody>
</table>

2.12 Documentation

The software shall be capable of displaying and printing an output of the energy use summary and a text file of the building’s features. These are the same features as shown on the CFIR when generated using the Report Manager.

See CBECC user manual or vendor software guide for detailed modeling guidelines.
APPENDIX A – CERTIFICATION TESTS

The purpose of ACM testing is to demonstrate that candidate software submitted for approval successfully integrates Compliance Manager into the candidate software. This includes testing a variety of both inputs and reporting to ensure that buildings are being accurately modeled under the rules established by the Energy Commission.

A test data set with specific description and details of the tests, inputs, and a spreadsheet of compliance results is available from the Energy Commission to assist vendors in preparing the certification tests. The tests are based on the Energy Commission 2100 ft², 2700 ft² and 6960 ft² new construction prototypes and a 1665 ft² addition/alteration prototype generally described in Section A5.

A1. Test Data Set

The test data set is maintained by the Energy Commission and made available to vendors. This data consists of:

1. The reference program input files (currently .ribd files) for all runs that describe all inputs for each run.

2. The test data set spreadsheet that describes each test and compares the current reference results to the candidate results to determine if it passes the numeric results test. The results for the reference software will be imported using the AnalysisResults.csv file generated by CBECC-Res reference software. Results for the candidate software may be imported or manually entered.

3. Additional intermediate results and reports for a small subset of runs that is used to demonstrate that the candidate software is capable of completing the entire compliance process of input, run, and reporting. These results will be verified either by visual review or with the use of a file comparison utility program.

A2. Software Vendor Requirements

Candidate software needs to:

1. Secure the latest copy of the test data set from the Energy Commission.

2. Create input files in the candidate software’s user interface to match those in the test data set.

3. Run the test data set and load the results into the spreadsheet to verify that the results match.
4. Compare the intermediate results and reports to verify that the results match, as described in the test data set spreadsheet

A3. **Submittals for Approval**

Submittals to the Energy Commission requesting approval shall include:

1. Access to the candidate software in a manner that allows the Energy Commission to use the software.

2. All files necessary to compare results to the test data set, including the input files, the results spreadsheet and the specified intermediate results and reports.


The Energy Commission will review the test data set results to verify that the software works and that the documentation meets ACM requirements.

A4. **Compliance Manager Updates**

When new versions of Compliance Manager or its components become available, the Energy Commission will run the test data set to verify that the results match. If the results do not match, but it is determined that the new results are the correct results, the test data set will be updated to substitute the results of the new version as the test data set.

A5. **Prototype Buildings**

One-Story Prototype

Figure A-1: One-Story Prototype Front View
Figure A-2: One-Story Prototype Back View
Figure A-3 through Figure A-3 and Table A-1 define the 2100 ft² prototype.

Note that the glass area and distribution provided on these drawings is only to show a realistic image of the home. Glass area and orientation for impact and cost effectiveness is set using a glass distribution typical of California homes. Glass area, distribution and other details for the ACM tests are specified in the test data set.
Figure A-3: One-Story Prototype Floor Plan
Table A-1: One-Story Prototype Description

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling height</td>
<td>9 ft</td>
</tr>
<tr>
<td>Conditioned floor area</td>
<td>2100 ft²</td>
</tr>
<tr>
<td><strong>Gross areas</strong></td>
<td></td>
</tr>
<tr>
<td>Slab</td>
<td>2100 ft²</td>
</tr>
<tr>
<td>Slab perimeter, outside</td>
<td>162 ft</td>
</tr>
<tr>
<td>Slab Garage</td>
<td>440 ft²</td>
</tr>
<tr>
<td>Slab perimeter, garage</td>
<td>54 ft from garage to outside</td>
</tr>
<tr>
<td>Ceiling</td>
<td>2100 ft², vented attic</td>
</tr>
<tr>
<td>Front wall</td>
<td>270 ft²</td>
</tr>
<tr>
<td>Front garage wall</td>
<td>180 ft²</td>
</tr>
<tr>
<td>Left wall</td>
<td>324 ft²</td>
</tr>
<tr>
<td>Left garage wall</td>
<td>90 ft²</td>
</tr>
<tr>
<td>Back wall</td>
<td>450 ft²</td>
</tr>
<tr>
<td>Right wall</td>
<td>414 ft²</td>
</tr>
<tr>
<td>Garage front wall</td>
<td>180 ft² from garage to outside</td>
</tr>
<tr>
<td>Garage left wall</td>
<td>198 ft² from garage to outside</td>
</tr>
<tr>
<td>Garage right wall</td>
<td>108 ft² from garage to outside</td>
</tr>
<tr>
<td><strong>Doors</strong></td>
<td></td>
</tr>
<tr>
<td>Front door</td>
<td>20 ft²</td>
</tr>
<tr>
<td>Garage door</td>
<td>20 ft²</td>
</tr>
<tr>
<td>Garage car door</td>
<td>128 ft²</td>
</tr>
<tr>
<td>Overhangs</td>
<td>1 ft (when modeled)</td>
</tr>
</tbody>
</table>

**Two-Story Prototype**

Figure A-4 through Figure A-7 and Table A-2 define the 2700 ft² prototype.

Note that the glass area and distribution provided on these drawings is only to show a realistic image of the home. Glass area and orientation for impact and cost effectiveness is set using a glass distribution typical of California homes. Glass area, distribution and other details for the ACM tests are specified in the test data set.
Figure A-4: Two-Story Prototype Front View

Figure A-5: Two-Story Prototype Back View
Figure A-7: Two-Story Prototype Floor Plan – 2nd Floor
## Table A-2: Two-Story Prototype Description

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling height</td>
<td>9 ft with 1 ft between floors</td>
</tr>
<tr>
<td>Conditioned floor area</td>
<td>2700 ft²</td>
</tr>
<tr>
<td><strong>Gross areas</strong></td>
<td></td>
</tr>
<tr>
<td>Slab</td>
<td>1250 ft²</td>
</tr>
<tr>
<td>Slab perimeter, outside</td>
<td>128 ft</td>
</tr>
<tr>
<td>Slab, garage</td>
<td>440 ft²</td>
</tr>
<tr>
<td>Slab perimeter, garage</td>
<td>54 ft from garage to outside</td>
</tr>
<tr>
<td>Ceiling</td>
<td>1450 ft², vented attic</td>
</tr>
<tr>
<td>Floor over garage</td>
<td>200 ft²</td>
</tr>
<tr>
<td>Front wall</td>
<td>728 ft²</td>
</tr>
<tr>
<td>Front garage wall</td>
<td>180 ft²</td>
</tr>
<tr>
<td>Front garage kneewall</td>
<td>42 ft²</td>
</tr>
<tr>
<td>Left wall</td>
<td>551 ft²</td>
</tr>
<tr>
<td>Back wall</td>
<td>950 ft²</td>
</tr>
<tr>
<td>Right wall</td>
<td>461 ft²</td>
</tr>
<tr>
<td>Right garage wall</td>
<td>90 ft²</td>
</tr>
<tr>
<td>Garage front wall</td>
<td>180 ft² from garage to outside</td>
</tr>
<tr>
<td>Garage left wall</td>
<td>108 ft² from garage to outside</td>
</tr>
<tr>
<td>Garage right wall</td>
<td>198 ft² from garage to outside</td>
</tr>
<tr>
<td><strong>Doors</strong></td>
<td></td>
</tr>
<tr>
<td>Front door</td>
<td>20 ft²</td>
</tr>
<tr>
<td>Garage door</td>
<td>20 ft²</td>
</tr>
<tr>
<td>Garage car door</td>
<td>128 ft²</td>
</tr>
<tr>
<td>Overhangs</td>
<td>1 ft (when modeled)</td>
</tr>
</tbody>
</table>

### Multifamily Prototype

The multifamily prototype is a 6960 ft² eight-unit two-story apartment building consisting of four 780 ft² (26 ft wide by 30 ft deep) one-bedroom apartments and four 960 ft² (32 ft wide by 30 ft deep) two-bedroom apartments. The units share common walls and either common floors or ceilings. Multiples of this layout may be combined to represent other typical multifamily configurations.

Figure A-8 through Figure A-11 and Table A-3 define the 6960 ft² prototype.

Note that the glass area and distribution provided on these drawings is only to show a realistic image of the home. Glass area and orientation for impact and cost effectiveness is set using a glass
distribution typical of California construction. Glass area, distribution and other details for the ACM tests are specified in the test data set.

**Figure A-8: Multifamily Prototype Front View**

![Multifamily Prototype Front View](image1)

**Figure A-9: Multifamily Prototype Back View**

![Multifamily Prototype Back View](image2)

**Figure A-10: Multifamily Prototype Floor Plan – 1st Floor**

![Multifamily Prototype Floor Plan – 1st Floor](image3)
Figure A-11: Multifamily Prototype Floor Plan – 2nd Floor

Table A-3: Multifamily Prototype Description

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling height</td>
<td>8 ft with 1 ft between floors</td>
</tr>
<tr>
<td>Conditioned floor area</td>
<td>6960 ft²</td>
</tr>
<tr>
<td>Dwelling units</td>
<td>8</td>
</tr>
<tr>
<td>Gross areas</td>
<td></td>
</tr>
<tr>
<td>Slab</td>
<td>3480 ft²</td>
</tr>
<tr>
<td>Slab perimeter, outside</td>
<td>292 ft</td>
</tr>
<tr>
<td>Ceiling</td>
<td>3480 ft², vented attic</td>
</tr>
<tr>
<td>Front wall</td>
<td>1972 ft²</td>
</tr>
<tr>
<td>Left wall</td>
<td>510 ft²</td>
</tr>
<tr>
<td>Back wall</td>
<td>1972 ft²</td>
</tr>
<tr>
<td>Right wall</td>
<td>510 ft²</td>
</tr>
<tr>
<td>Doors</td>
<td></td>
</tr>
<tr>
<td>Front door</td>
<td>160 ft²</td>
</tr>
<tr>
<td>Overhangs</td>
<td>1 ft (when modeled)</td>
</tr>
</tbody>
</table>

Addition/Alteration Prototype

Figure A-12 through Figure A-14 define the addition/alteration 1665 ft² prototype without the addition. Figure A-15 through Figure A-16 and Table A-4 define the addition/alteration with the addition.
Figure A-12: Addition/Alteration Prototype Front View without Addition

Figure A-13: Addition/Alteration Prototype Back View without Addition
Figure A-14: Addition/Alteration Prototype Floor Plan without Addition

Existing
1440 sq ft
Figure A-15: Addition/Alteration Prototype Back View with Addition
Figure A-16: Addition/Alteration Prototype Floor Plan with Addition

Addition
225 sq ft

Existing
1440 sq ft
Table A-4: Addition/Alteration Prototype Description

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling height</td>
<td>8 ft</td>
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<tr>
<td>Existing floor area</td>
<td>1440 ft²</td>
</tr>
<tr>
<td>Addition floor area</td>
<td>225 ft²</td>
</tr>
<tr>
<td>Gross areas</td>
<td></td>
</tr>
<tr>
<td>Existing Slab</td>
<td>1440 ft²</td>
</tr>
<tr>
<td>Addition Slab</td>
<td>225 ft²</td>
</tr>
<tr>
<td>Existing Slab perimeter</td>
<td>137 ft</td>
</tr>
<tr>
<td>Addition Slab perimeter</td>
<td>45 ft</td>
</tr>
<tr>
<td>Existing Ceiling</td>
<td>1440 ft², vented attic</td>
</tr>
<tr>
<td>Addition Ceiling</td>
<td>225 ft², vented attic</td>
</tr>
<tr>
<td>Existing Front wall</td>
<td>320 ft²</td>
</tr>
<tr>
<td>Existing Left wall</td>
<td>288 ft²</td>
</tr>
<tr>
<td>Addition Left wall</td>
<td>120 ft²</td>
</tr>
<tr>
<td>Existing Back wall</td>
<td>320 ft²</td>
</tr>
<tr>
<td>Addition Back wall</td>
<td>120 ft²</td>
</tr>
<tr>
<td>Existing Right wall</td>
<td>288 ft²</td>
</tr>
<tr>
<td>Addition Right wall</td>
<td>120 ft²</td>
</tr>
<tr>
<td>Windows</td>
<td></td>
</tr>
<tr>
<td>Existing Front Window 1</td>
<td>24 ft²</td>
</tr>
<tr>
<td>Existing Front Window 2</td>
<td>32 ft²</td>
</tr>
<tr>
<td>Existing Left Window 1</td>
<td>24 ft²</td>
</tr>
<tr>
<td>Existing Left Window 2</td>
<td>24 ft²</td>
</tr>
<tr>
<td>Addition Left Window</td>
<td>16 ft²</td>
</tr>
<tr>
<td>Existing Back Window 1</td>
<td>30 ft²</td>
</tr>
<tr>
<td>Existing Back Window 2</td>
<td>6 ft²</td>
</tr>
<tr>
<td>Addition Back Window</td>
<td>16 ft²</td>
</tr>
<tr>
<td>Existing Right Window 1</td>
<td>6 ft²</td>
</tr>
<tr>
<td>Existing Right Window 2</td>
<td>24 ft²</td>
</tr>
<tr>
<td>Addition Right Window</td>
<td>16 ft²</td>
</tr>
<tr>
<td>Doors</td>
<td></td>
</tr>
<tr>
<td>Existing Front door</td>
<td>20 ft²</td>
</tr>
<tr>
<td>Existing Back door</td>
<td>20 ft²</td>
</tr>
</tbody>
</table>
## APPENDIX C – SPECIAL FEATURES

<table>
<thead>
<tr>
<th>Measure</th>
<th>CF1R Documentation Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GENERAL</strong></td>
<td></td>
</tr>
<tr>
<td>Controlled-Ventilation Crawlspace (CVC)</td>
<td>Not yet implemented</td>
</tr>
<tr>
<td>Photovoltaic (PV) system credit</td>
<td>Special feature</td>
</tr>
<tr>
<td>Zonal heating controls</td>
<td>Special feature</td>
</tr>
<tr>
<td><strong>ENVELOPE</strong></td>
<td></td>
</tr>
<tr>
<td>Above deck insulation</td>
<td>Special feature</td>
</tr>
<tr>
<td>Advanced wall framing</td>
<td>Special feature</td>
</tr>
<tr>
<td>Below deck insulation</td>
<td>Special feature</td>
</tr>
<tr>
<td>Building air leakage / reduced infiltration</td>
<td>HERS verification of reported ACH50 value</td>
</tr>
<tr>
<td>Cool roof</td>
<td>Special feature</td>
</tr>
<tr>
<td>Dynamic glazing</td>
<td>Not yet implemented</td>
</tr>
<tr>
<td>Exterior shading device</td>
<td>Not yet implemented</td>
</tr>
<tr>
<td>Exposed slab area greater than 20%</td>
<td>Special feature</td>
</tr>
<tr>
<td>High quality insulation installation (QII)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Metal-framed assembly</td>
<td>Special feature</td>
</tr>
<tr>
<td>Non-default spray foam insulation R-values</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Overhangs and sidefins</td>
<td>Special feature</td>
</tr>
<tr>
<td>Raised heel truss (height above top plate)</td>
<td>Special feature</td>
</tr>
<tr>
<td>Spray foam insulation, closed cell &gt;R-5.8/inch</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Spray foam insulation, open cell &gt;R-3.6/inch</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Structurally insulated panel (SIP) assembly</td>
<td>Special feature</td>
</tr>
<tr>
<td><strong>MECHANICAL</strong></td>
<td></td>
</tr>
<tr>
<td>Air handling unit fan efficacy</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Airflow or System Airflow (cfm)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Central fan ventilation cooling, fixed speed</td>
<td>Special feature</td>
</tr>
<tr>
<td>Feature</td>
<td>Details</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>Central fan ventilation cooling, variable speed</td>
<td>Special feature</td>
</tr>
<tr>
<td>Energy Efficiency Ratio (EER)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Evaporatively-cooled condenser</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Evaporative cooling, indirect, indirect/direct</td>
<td>Not yet implemented.</td>
</tr>
<tr>
<td>Fan efficacy</td>
<td>HERS verification</td>
</tr>
<tr>
<td>High Seasonal Energy Efficiency Ratio (SEER)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Indoor air quality ventilation</td>
<td>HERS verification</td>
</tr>
<tr>
<td>No cooling</td>
<td>Special feature</td>
</tr>
<tr>
<td>Refrigerant charge or charge indicator display (CID)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Ventilation cooling system, central fan</td>
<td>special feature</td>
</tr>
<tr>
<td>Whole-building mechanical ventilation airflow</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Whole house fan</td>
<td>Special feature</td>
</tr>
<tr>
<td><strong>DUCTS</strong></td>
<td></td>
</tr>
<tr>
<td>Buried duct</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Bypass duct conditions in a zonal system</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Deeply buried duct</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Duct leakage testing</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Ducts in conditioned space</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Ducts in conditioned space</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Ducts in crawl space</td>
<td>Special feature</td>
</tr>
<tr>
<td>High R-value ducts</td>
<td>Special feature</td>
</tr>
<tr>
<td>Low leakage air handler</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Low leakage ducts in conditioned space</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Non-standard duct leakage target</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Non-standard duct location (any location other than attic)</td>
<td>Special feature</td>
</tr>
<tr>
<td>Return duct design</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Supply duct location, surface area, R-value</td>
<td>HERS verification</td>
</tr>
<tr>
<td><strong>WATER HEATING</strong></td>
<td></td>
</tr>
<tr>
<td>Compact distribution system (HERS verified)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Feature</td>
<td>Description</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>Central parallel piping</td>
<td>Special feature</td>
</tr>
<tr>
<td>Central parallel piping (HERS verified)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Multi-family: Central water heating recirculating dual loop design</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Multi-family: Demand recirculating</td>
<td>Special feature</td>
</tr>
<tr>
<td>Multi-family: Pipe insulation, central water heating (HERS verified)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Multi-family: Pipe insulation, central water heating</td>
<td>Special feature</td>
</tr>
<tr>
<td>Multi-family: Recirculating with continuous monitoring</td>
<td>Special feature</td>
</tr>
<tr>
<td>Multi-family: Recirculating with temperature modulation</td>
<td>Special feature</td>
</tr>
<tr>
<td>Multi-family: Solar water heating credit</td>
<td>Special feature and additional documentation</td>
</tr>
<tr>
<td>Pipe insulation, all lines</td>
<td>Special feature</td>
</tr>
<tr>
<td>Pipe insulation, all lines (HERS verified)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Point of use (HERS verified)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Recirculation with demand control, occupancy/motion sensor</td>
<td>Special feature</td>
</tr>
<tr>
<td>Recirculation with demand control, occupancy/motion sensor (HERS verified)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Recirculation with demand control, push button</td>
<td>Special feature</td>
</tr>
<tr>
<td>Recirculation with demand control, push button (HERS verified)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Recirculation with non-demand control (continuous pumping)</td>
<td>Special feature</td>
</tr>
<tr>
<td>Recirculation with non-demand control (HERS verified)</td>
<td>HERS verification</td>
</tr>
<tr>
<td>Solar water heating credit, single family building</td>
<td>Special feature and additional documentation</td>
</tr>
</tbody>
</table>

**ADDITIONS/ALTERATIONS**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verified existing conditions</td>
<td>HERS verification</td>
</tr>
</tbody>
</table>
APPENDIX E – WATER HEATING CALCULATION METHOD

E1. Purpose and Scope

ACM Reference Manual Appendix B documents the methods and assumptions used for calculating the hourly energy use for residential water heating systems for both the proposed design and the standard design. The hourly fuel and electricity energy use for water heating will be combined with hourly space heating and cooling energy use to come up with the hourly total fuel and electricity energy use to be factored by the hourly TDV energy multiplier. The calculation procedure applies to low-rise single family, low-rise multi-family, and high-rise residential.

When buildings have multiple water heaters, the hourly total water heating energy use is the hourly water heating energy use summed over all water heating systems, all water heaters, and all dwelling units being modeled.

The following diagrams illustrate the domestic hot water (DHW) system types that shall be recognized by the compliance software.

1. One distribution system with one or multiple water heaters serving a single dwelling unit. The system might include recirculation loops within the dwelling unit.
2. Two water heaters with independent distribution systems serving a single dwelling unit. One or more of the distribution systems may include a recirculation loop within the dwelling unit.
3. One distribution system without recirculation loop and with one or multiple water heaters serving multiple dwelling units.
4. One distribution system with one or multiple recirculation loops and with one or multiple water heaters serving multiple units.
E2. Water Heating Systems

Water heating distribution systems may serve more than one dwelling unit and may have more than one water heating appliance. The energy used by a water heating system is calculated as the sum of the energy used by each individual water heater in the system. Energy used for the whole building is calculated as the sum of the energy used by each of the water heating systems. To delineate different water heating elements several indices are used.

- i Used to describe an individual dwelling unit. For instance CFAi would be the conditioned floor area of the ith dwelling unit. N is the total number of dwelling units.
- j Used to refer to the number of water heaters in a system. M is the total number of water heaters.
- k Used to refer to a water heating system or distribution system. A building can have more than one system and each system can have more than one water heater.
- l Used to refer to the lth unfired- or indirectly-fired storage tank in the kth system. L is the total number of unfired- or indirectly-fired storage tanks in the kth system. Temperature buffering tanks with electric heating shall not to be treated as unfired or indirectly-fired storage tanks.

E3. Hourly Adjusted Recovery Load

The hourly adjusted recovery load (HARL) can be calculated by Equation 1 through Equation 6.

Equation 1  
\[ HARL_k = HSEU_k \times DLM_k - HSEU_k \times SSF_k + HRDL_k + \sum_l HJL_l \]

Where,
- \( HARL_k \) = Hourly adjusted recovery load (Btu).
- \( HSEU_k \) = Hourly standard end use at all use points (Btu). See Equation 2
- \( DLM_k \) = Distribution loss multiplier (unitless). See Equation 4
- \( SSF_k \) = Solar savings fraction (unitless) for the kth water heating system, which is the fraction of the total water heating load that is provided by solar hot water heating. Annual average value for SSFk is provided from the results generated by the CEC approved calculations approaches for the OG-100 and OG-300 test procedure. A CEC approved method shall be used to convert the annual average value for SSFk to hourly values to be used in Equation 1. For hours when SSFk > DLMk, set SSFk = DLMk.
- \( HRDL_k \) = Hourly recirculation distribution loss (Btu) See Equation 10.
- \( HJL_l \) = The tank surface losses of the lth unfired tank of the kth system (Btu) See Equation 41.

Equation 1 calculates the hourly adjusted recovery load (HARL) which is the heat content of the water delivered at the fixture. HRDL only occurs for multi-family central water heating systems and is zero for single family dwellings.

Equation 2  
\[ HSEU_k = 8.345 \times GPH_k \times \Delta T \]
Where,

\( HSEU_k = \) Hourly standard end use (Btu).

\( GPH_k = \) Hourly hot water consumption (gallons)

\( \Delta T = \) Temperature difference (ºF) See Equation 3

Equation 2 calculates the hourly standard end use (HSEU). The heat content of the water delivered at the fixture is the draw volume in gallons (GPH) times the temperature rise \( \Delta T \) (difference between the cold water inlet temperature and the hot water supply temperature) times the heat required to elevate a gallon of water 1ºF (the 8.345 constant).

**Equation 3**

\[ \Delta T = T_s - T_{inlet} \]

Where,

\( \Delta T = \) Temperature difference between the cold water inlet and the hot water supply (ºF)

\( T_s = \) Hot water supply temperature of (ºF). For DHW system type 1, 2, and 3, use 124 ºF. For DHW system type 4, use 130 ºF.

\( T_{inlet} = \) The cold water inlet temperature (ºF) is defined in Section E3.3.

Equation 3 calculates the temperature difference (ºF) between cold water inlet temperature \( T_{inlet} \) and the hot water supply temperature \( T_s \).

**Equation 4**

\[ DLM_k = 1 + (SDLM_k - 1) \times DSM_k \]

Where,

\( DLM_k = \) Distribution loss multiplier (unitless)

\( SDLM_k = \) Standard distribution loss multiplier (unitless). See Equation 5

\( DSM_k = \) Distribution system multiplier (unitless) Equation 4 calculates the distribution loss multiplier (DLM) which combines two terms: the standard distribution loss multiplier (SDLM), which depends on the floor area of the dwelling unit and the distribution system multiplier (DSM) listed in Table E-2.

**Equation 5**

\[ SDLM_k = 1.004 + 0.000202 \times CFA_k - 0.0000000231 \times CFA_k \times CFA_k \]

Where,

\( SDLM_k = \) Standard distribution loss multiplier (unitless).

\( CFA_k = \) Conditioned floor area (ft²) capped at 2500 ft² for all single and multi-family units.

Equation 5 calculates the standard distribution loss multiplier (SDLM) for all dwelling units with three stories or less. For situations with one or more water heaters serving a single dwelling unit (System Types 1 or 2), \( CFA_k \) is calculated as the total dwelling unit CFA divided by the number of water heaters. For multi-family configurations where multiple dwelling units are served by a central water heating system, either with or without recirculation distribution loops (System Types 3 or 4),
CFA\(_k\) is defined as the average CFA for all dwelling units covered by the system \(k\). For all residential building types, CFA\(_k\) is capped at 2500 ft\(^2\) in Equation 5. When a water heating system has more than one water heater, the total system load is assumed to be shared equally by each water heater. The HARL for the \(j^\text{th}\) water heater is shown in Equation 6.

\[
\text{Equation 6} \quad \text{HARL}_j = \frac{\text{HARL}_k + \sum_{l=1}^{L} \text{HJL}_l}{\text{NmbrWH}_k}
\]

Where,

- \(\text{HARL}_j\) = Hourly adjusted recovery load for the \(j^\text{th}\) water heater of the \(k^\text{th}\) system (Btu).
- \(\text{HARL}_k\) = Hourly adjusted total recovery load for the \(k^\text{th}\) system (Btu)
- \(\text{HJL}_l\) = The tank surface losses of the \(l^\text{th}\) unfired tank of the \(k^\text{th}\) system (Btu)
- \(L\) = The total number of unfired tanks in the \(k^\text{th}\) system
- \(\text{NmbrWH}_k\) = The number of water heaters in the \(k^\text{th}\) system.

### 3.1 Hourly Hot Water Consumption (GPH)

The average daily hot water consumed (not including hot water waste) at use points GPD for a dwelling unit is equal to 21.4 gallons/day plus an additional 6.79 gallons per day for each 1000 ft\(^2\) of conditioned floor area. Consumption is equal to 26.2 gallons/day for a 700 ft\(^2\) apartment and 38.4 gallons/day for a 2500 ft\(^2\) dwelling unit. The equation for daily hot water consumption can be expressed as follows:

\[
\text{Equation 7} \quad \text{GPD}_i = 21.4 + 0.00679 \times \text{CFA}_i
\]

Where,

- \(\text{GPD}_i\) = Average daily hot water consumption (gallons) of the \(i^\text{th}\) dwelling unit.
- \(\text{CFA}_i\) = Conditioned floor area (ft\(^2\)) of the \(i^\text{th}\) dwelling unit. When actual conditioned floor area is greater than 2500 ft\(^2\), 2500 should be used in Equation 7.

The hourly water consumption GPH of the \(k^\text{th}\) system is calculated using the average daily hot water consumption and the hourly water consumption schedule for all dwelling units served by the system.

\[
\text{Equation 8} \quad \text{GPH}_k = \left( \sum_i \text{GPD}_i \right) \times \text{WF}_m \times \text{SCH}_m
\]

Where,

- \(\text{GPH}_k\) = Hourly hot water consumption (gallons) of the \(k^\text{th}\) system.
- \(\text{WF}_m\) = Hot Water Waste Factor. For system type 1, 2, and 3, \(\text{WF}_m = 1.0\) for non-recirculating systems, 0.90 for recirculating systems. For system type 4, \(\text{WF}_m = 1.0\).
- \(\text{SCH}_m\) = Fractional daily load for hour \(m\) from Table E-1.
m = Hour of the day.

There are significant variations between hot water usage on weekdays and weekends, and separate schedules are used. The hourly schedules shown in Table E-1 shall be used for calculating the hourly hot water consumption. These data are used for dwelling units of all types.

<table>
<thead>
<tr>
<th>Hour</th>
<th>Weekday</th>
<th>Weekend</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.014</td>
<td>0.018</td>
</tr>
<tr>
<td>2</td>
<td>0.008</td>
<td>0.010</td>
</tr>
<tr>
<td>3</td>
<td>0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>4</td>
<td>0.011</td>
<td>0.008</td>
</tr>
<tr>
<td>5</td>
<td>0.020</td>
<td>0.015</td>
</tr>
<tr>
<td>6</td>
<td>0.044</td>
<td>0.023</td>
</tr>
<tr>
<td>7</td>
<td>0.089</td>
<td>0.026</td>
</tr>
<tr>
<td>8</td>
<td>0.107</td>
<td>0.047</td>
</tr>
<tr>
<td>9</td>
<td>0.089</td>
<td>0.077</td>
</tr>
<tr>
<td>10</td>
<td>0.066</td>
<td>0.083</td>
</tr>
<tr>
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<td>0.038</td>
<td>0.061</td>
</tr>
<tr>
<td>13</td>
<td>0.036</td>
<td>0.051</td>
</tr>
<tr>
<td>14</td>
<td>0.033</td>
<td>0.043</td>
</tr>
<tr>
<td>15</td>
<td>0.032</td>
<td>0.039</td>
</tr>
<tr>
<td>16</td>
<td>0.026</td>
<td>0.039</td>
</tr>
<tr>
<td>17</td>
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<td>19</td>
<td>0.052</td>
<td>0.056</td>
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<tr>
<td>20</td>
<td>0.047</td>
<td>0.052</td>
</tr>
<tr>
<td>21</td>
<td>0.042</td>
<td>0.047</td>
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<tr>
<td>22</td>
<td>0.039</td>
<td>0.044</td>
</tr>
<tr>
<td>23</td>
<td>0.036</td>
<td>0.040</td>
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<tr>
<td>24</td>
<td>0.022</td>
<td>0.028</td>
</tr>
<tr>
<td>Sum</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

3.2 Distribution System Multiplier (DSM) within the Dwelling Unit

The distribution system multiplier (unitless) is an adjustment for alternative water heating distribution systems within the dwelling unit. A value of 1.00 for “standard” distribution systems, defined as a non-recirculating system with the following mandatory requirements:

The full length of the line from the water heater to the kitchen fixtures insulated in accordance to Section 120.3.

All piping of nominal ¾” or larger diameter insulated in accordance to Section 120.3.

For all four system types, values for alternative distribution systems are given in Table E-2. Improved DSM values are available for cases where voluntary HERS inspections are completed, as per the eligibility criteria shown in Reference Residential Appendix RA4.4. Detailed descriptions of all of the distribution system measures is found in Residential Appendix RA 4.4.
Table E-2. Distribution System Multipliers within a Dwelling Unit with One or More Water Heaters

<table>
<thead>
<tr>
<th>Distribution System Types</th>
<th>Assigned Distribution System Multiplier</th>
<th>System Type 1 and 2</th>
<th>System Type 3 and 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No HERS Inspection Required</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk and Branch -Standard (STD)</td>
<td>1.0</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Pipe Insulation (PIC)</td>
<td>0.9</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Parallel Piping (PP)</td>
<td>1.05</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Recirculation: Non-Demand Control Options (R-ND)</td>
<td>9.0*</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Recirculation with Manual Demand Control (R-DRmc)</td>
<td>1.6*</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Recirculation with Motion Sensor Demand Control (R-DRsc)</td>
<td>2.4*</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td><strong>Optional Cases: HERS Inspection Required</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe Insulation (PIC-H)</td>
<td>0.8</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Parallel Piping with 5’ maximum length (PP-H)</td>
<td>0.95</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Compact Design (CHWDS-H)</td>
<td>0.7</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Point of Use (POU-H)</td>
<td>0.3</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Recirculation with Manual Demand Control (R-DRmc-H)</td>
<td>1.45*</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Recirculation with Motion Sensor Demand Control (RDRsc-H)</td>
<td>2.2*</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Non-Compliant Installation Distribution Multiplier</td>
<td>1.2</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*Recirculation DSMs reflect impact of reduced hot water consumption associated with recirculation systems.

3.3 Cold Water Inlet Temperature

The water heater inlet temperature is assumed to vary on a daily basis with the following relationship defined by the data included in the climate zone weather files. For each day of the year, $T_{inlet}$ will be calculated as follows:

$$Equation\ 9\quad T_{inlet} = T_{ground} \times 0.65 + T_{avg31} \times 0.35$$

Where,

- $T_{avg31}$ is the dry-bulb temperature averaged over the previous 31 days (note for January days, weather data from December will be used), and
- $T_{ground}$ is calculated by the following:

For each day (THETA = 1 TO 365)
T_{ground}(\Theta) = TyrAve - 0.5 \times (TyrMax-TyrMin) \times \cos(2\pi \times (\Theta/PB)-PO-PHI) \times GM

Where,

- TyrAve = average annual temperature, degrees F
- TyrMin is the lowest average monthly temperature, degrees F
- TyrMax is the highest average monthly temperature, degrees F
- pi = 3.1416
- PB = 365
- PO = 0.6
- DIF = 0.025
- BETA = SQR(PI/(DIF*PB))*10
- XB = EXP(-BETA)
- CB = COS(BETA)
- SB = SIN(BETA)
- GM = SQR((XB*XB - 2.*XB*CB + 1)/(2.*BETA*BETA))
- PHI = ATN((1.-XB*(CB+SB)) / (1.-XB*(CB-SB)))

E4. **Hourly Recirculation Distribution Loss for Central Water Heating Systems**

This section is applicable to the DHW system type 3 and 4, as defined in E1 Purpose and Scope. The distribution losses accounted for in the distribution loss multiplier (DLM), Equation 4, reflect distribution heat loss within each individual dwelling unit. Additional distribution losses occur outside dwelling units and they include losses from recirculation loop pipes and branch piping feeding individual dwelling units. The hourly values of these losses, HRDL, shall be calculated according to Equation 10. Compliance software shall provide input for specifying recirculation system designs and controls according to the following algorithms.

**Equation 10**

\[ HRDL_k = NLoop_k \times HRLL_k + HRBL_k \]

Where,

- HRDL_k = Hourly recirculation loop and branch pipe distribution loss for kth system (Btu).
- HRLL_k = Hourly recirculation loop pipe heat loss (Btu). This component is only applicable to system type 4. See Equation 11
- HRBL_k = Hourly recirculation branch pipe heat loss (Btu). See Equation 19
- NLoop_k = Number of recirculation loops in water heating system k.
  This component is only applicable to system type 4. See section 4.3
A recirculation loop usually includes multiple pipe sections with different pipe diameters, which are exposed to different ambient conditions. The compliance software shall provide input entries for up to six pipe sections with three sections for supply piping and three sections for return piping for users to describe the configurations of the recirculation loop. For each of the six pipe sections, input entries shall include pipe diameter (inch), pipe length (ft), and ambient conditions. Ambient condition input shall include three options: outside air, underground, conditioned or semi-conditioned air. Modeling rules for dealing with recirculation loop designs are provided in Section 4.3.

Outside air includes crawl spaces, unconditioned garages, unconditioned equipment rooms, as well as actual outside air. Solar radiation gains are not included in the calculation because the impact of radiation gains is relatively minimal compared to other effects. Additionally, the differences in solar gains for the various conditions (e.g., extra insulation vs. minimum insulation) are relatively even less significant.

The ground condition includes any portion of the distribution piping that is underground, including that in or under a slab. Insulation in contact with the ground must meet all the requirements of Section 150.0(j), Part 6, of Title 24.

The losses to conditioned or semi-conditioned air include losses from any distribution system piping that is in an attic space, within walls (interior, exterior or between conditioned and unconditioned spaces), within chases on the interior of the building, or within horizontal spaces between or above conditioned spaces. It does not include the pipes within the residence. The distribution piping stops at the point where it first meets the boundaries of the dwelling unit.

### 4.1 Hourly Recirculation Loop Pipe Heat Loss Calculation

Hourly recirculation loop pipe heat loss (HRLLk) is the hourly heat loss from all six pipe sections. There are two pipe heat loss modes, pipe heat loss with non-zero water flow (PLWF) and pipe heat loss without hot water flow (PLCD). The latter happens when the recirculation pump is turned off by a control system and there is no hot water draw flows, such as in recirculation return pipes. Pipe heat loss modes are determined by recirculation control schedules and hot water draw schedules. For each pipe section, hourly pipe heat loss is the sum of heat loss from the two heat loss modes. Hourly heat loss for the whole recirculation loop (HRLLk) is the heat loss from all six pipe sections, according to the following equation:

\[
HRLLk = \sum_n [PLWF_n \cdot (1 - f_{no\text{flow}, n}) + PLCD_n \cdot f_{no\text{flow}, n}]
\]

Where,

- \(PLWF_n\) = Hourly pipe heat loss with non-zero water flow (Btu/hr). See Equation 12
- \(PLCD_n\) = Hourly pipe heat loss without water flow (Btu/hr). See Equation 17
- \(f_{no\text{flow}, n}\) = Fraction of the hour for pipe section \(n\) to have zero water flow. See Equation 13
- \(n\) = Recirculation pipe section index, 1-6.
APPENDIX E - Water Heating Calculation Method

Equation 12  \[ PLWF_{n} = (\text{Flow}_{\text{Draw},n} + \text{Flow}_{\text{Recirc}}) \cdot \rho \cdot C_{p} \cdot (T_{\text{IN},n} - T_{\text{OUT},n}) \]

Where,

- \( \text{Flow}_{\text{Draw},n} \) = Average hourly hot water draw flow (gallon). For supply sections, \( n=1, 2, \) or 3, \( \text{Flow}_{\text{Draw},n} = \text{GPH}_k/N\text{Loop} \). For return pipes, \( n=4, 5, \) and 6, \( \text{Flow}_{\text{Draw},n} = 0 \).

- \( \text{Flow}_{\text{Recirc}} \) = Hourly recirculation flow (gallon). It is assumed to be 360 gallons based on the assumption that the recirculation flow rate is 6 GPM.

- \( \rho \) = Density of water, 8.3 (lb/gallon).

- \( C_{p} \) = Heat Capacity of water, 1 (Btu/lb/^oF).

- \( T_{\text{IN},n} \) = Input temperature of section \( n (^{o}\text{F}) \). For the first section \((n=1)\), \( T_{\text{IN},1} \) shall be determined based on Table E-3. The control schedule of the proposed design shall be based on user input. The standard design is demand control. For other sections, input temperature is the same as the output temperature the proceeding pipe section, \( T_{\text{IN},n} = T_{\text{OUT},n-1} \). A proposed design may not provide input for all pipe sections, the compliance software shall treat all sections with input as connected in sequence.

- \( T_{\text{OUT},n} \) = Output temperature of section \( n (^{o}\text{F}) \). See Equation 14

Equation 13  \[ f_{\text{flow, } n} = (1 - \text{SCH}_{k,m}) \cdot \text{NoDraw}_n \]

Where,

- \( \text{NoDraw}_n \) = Fraction of the hour for pipe section \( n \) to have no hot water draw flows. \( \text{NoDraw}_1 = 20\% \), \( \text{NoDraw}_2 = 40\% \), \( \text{NoDraw}_3 = 60\% \), \( \text{NoDraw}_4 = \text{NoDraw}_5 = \text{NoDraw}_6 = 100\% \).

- \( \text{SCH}_{k,m} \) = Recirculation pump operation schedule, representing the fraction of the hour that the recirculation pump is turned off, see Table E-3. \( \text{SCH}_{k,m} \) for the proposed design shall be based on proposed recirculation system controls. Recirculation system control for the standard design is demand control.

Equation 14  \[
T_{\text{OUT},n} = T_{\text{Amb},n} + \left( T_{\text{IN},n} - T_{\text{Amb},n} \right) \cdot e^{-\frac{U_{A_n} T_{\text{OUT},n}}{\rho C_{p} \cdot \text{Flow}_{n}}} \]

Where,

- \( T_{\text{Amb},n} \) = Ambient temperature of section \( n (^{o}\text{F}) \), which can be outside air, underground, conditioned or semi-conditioned air. Outside air temperatures shall be the dry-bulb temperature from the weather file. Underground temperatures shall be obtained from Equation 9. Hourly conditioned air temperatures shall be the same as conditioned space temperature. For the proposed design, \( T_{\text{Amb},n} \) options shall be based on user input. The standard design assumes all pipes are in conditioned air.

- \( U_{A_n} \) = Heat loss rate of section \( n \) (Btu/hr-^{o}\text{F}). See Equation 15 and Equation 16
Equation 15 is for standard design with extra 0.5 inch of insulation and Equation 16 is for minimum pipe insulation.

Equation 15
\[ U_{An} = \frac{2\pi Len_n \cdot \text{cond}}{12 \ln \left( \frac{\text{Dian} + \frac{1}{2}(\text{Thick} + 0.5)}{\text{Dian}} \right)} \cdot f_{UA} \cdot f_{Area} \]

Equation 16
\[ U_{An} = \frac{2\pi Len_n \cdot \text{cond}}{12 \ln \left( \frac{\text{Dian} + 2 \cdot \text{Thick}}{\text{Dian}} \right)} \cdot f_{UA} \cdot f_{Area} \]

Where,
\( \pi = 3.1416 \)
\( \text{Dian} = \) Section n pipe diameter (inch). It is divided by 12 in the above equation to convert the unit from inch to foot. For the proposed design, use user input; for the standard design, see Equation 27.
\( \text{Len}_n = \) Section n pipe length (foot). For the proposed design, use user input; for the standard design, see Equation 26.
\( \text{Thick} = \) Pipe insulation minimum thickness (inch) as defined in the Title 24 Section 120.3, TABLE 120.3-A for service hot water system.
\( \text{cond} = \) Insulation conductivity shall be assumed 0.26 (Btu inch/h∙sf∙F)
\( f_{UA} = \) Correction factor to reflect imperfect insulation, insulation material degradation over time, and additional heat transfer through connected branch pipes that is not reflected in branch loss calculation. It is assumed to be 2.0.
\( f_{area} = \) The multiplier to adjust proposed design based on pipe surface area validation. See Equation 28.

Pipe heat loss without water flow shall be calculated according to the following equations:

Equation 17
\[ PLCD_n = Vol_n \cdot \rho \cdot C_p \cdot (T_{\text{Start},n} - T_{\text{End},n}) \]

Where,
\( \text{Vol}_n = \) Volume of section n (gallons). It is calculated as \( 7.48 \cdot \pi \cdot \left( \frac{\text{Dias} + 0.125}{24} \right)^2 \cdot \text{Len}_n \), where 0.125 inch is added to reflect thermal mass of the pipe and 7.48 is the volumetric unit conversion factor from cubic feet to gallons.
\( T_{\text{Start},n} = \) Average pipe temperature (°F) of pipe section n at the beginning of the hour. It is the average of \( T_{\text{In},n} \) and \( T_{\text{Out},n} \) calculated according to Equation 14.
\( T_{\text{End},n} = \) Average pipe temperature (°F) of pipe section n at the end of pipe cool down. See Equation 18.
Equation 18

\[
T_{End,n} = T_{Amb,n} + (T_{Start,n} - T_{Amb,n}) \cdot e^{-\frac{UA_n}{V_{vol,p} \cdot C_p \cdot f_{n} \cdot f_{n,flow, n}}}
\]

Calculates average pipe temperature after one hour of cooling down, so the pipe heat loss calculated by Equation 17 is for pipe with zero flow for one hour. Recirculation pumps are usually turned off for less than an hour and there could hot water draw flows in the pipe. As a result, recirculation pipes usually cool down for less than an hour. The factor \(f_{n,flow, n}\) calculated according Equation 13 is used to reflect this effect, when it is used in Equation 11.

Compliance software shall provide four options of recirculation system controls listed in Table E-3. A proposed design shall select a control type from one of the four options. Standard design shall use demand control.

4.2 Hourly Recirculation Branch Pipe Heat Loss Calculation

The proposed design and standard design shall use the same branch pipe heat loss assumptions. Branch pipe heat loss is made up of two components. First, pipe heat losses occur when hot water is in use (HBUL). Second, there could be losses associated with hot water waste (HBWL) when hot water was used to displace cold water in branch pipes and hot water is left in pipe to cool down after hot water draws, and must be dumped down the drain. The Total Hourly Branch Losses (HRBL\(k\)) shall include both components and be calculated as:

\[
Equation 19 \quad HRBL_k = N_{branch_k}(HBUL + HBWL)
\]

Where,

\(HBUL = \) Hourly pipe loss for one branch when water is in use (Btu/hr). See Equation 20
\(HBWL = \) Hourly pipe loss for one branch due to hot water waste (Btu/hr). See Equation 23
\(N_{branch_k} = \) Number of branches in water heating system k. See Equation 30

The hourly branch pipe loss while water is calculated in the same way as recirculation pipe heat loss with non-zero water flow (PLWF) using the following equations:

\[
Equation 20 \quad HBUL = \left(\frac{GPH_k}{N_{branch_k}}\right) \cdot \rho \cdot C_p \cdot (T_{IN,b} - T_{OUT,b})
\]

Where,

\(T_{IN,b} = \) Average branch input temperature (\(^\circ\)F). It is assumed to be equal to the output temperature of the first recirculation loop section, \(T_{OUT,1}\).
\(T_{OUT,b} = \) Average branch output temperature (\(^\circ\)F). See Equation 21
Equation 21

\[ T_{OUT,b} = T_{Amb,b} + (T_{IN,b} - T_{Amb,b}) \times e^{-\frac{U_{Ab}}{\text{Flow}_b}} \]

Where,

- \( T_{Amb,b} \) = Branch pipe ambient temperature (°F) Branch pipes are assumed to be located in the conditioned or semi-conditioned air.
- \( U_{Ab} \) = Branch pipe heat loss rate (Btu/hr-°F). See Equation 22.
- \( \text{Flow}_b \) = Average branch hot water flow rate (Gal/hr). It is assumed to be 2 GPM or 120 Gal/hr.

### Table E-3. Recirculation Loop Supply Temperature and Pump Operation Schedule

<table>
<thead>
<tr>
<th>Hour</th>
<th>No Control</th>
<th>Demand Control</th>
<th>Temperature Modulation</th>
<th>Temperature Modulation with Continuous Monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( T_{IN,1} ) (°F)</td>
<td>SCH(_{k,m})</td>
<td>( T_{IN,1} ) (°F)</td>
<td>SCH(_{k,m})</td>
</tr>
<tr>
<td>1</td>
<td>130</td>
<td>1</td>
<td>130</td>
<td>0.2</td>
</tr>
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<td>2</td>
<td>130</td>
<td>1</td>
<td>130</td>
<td>0.2</td>
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<td>3</td>
<td>130</td>
<td>1</td>
<td>130</td>
<td>0.2</td>
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<td>4</td>
<td>130</td>
<td>1</td>
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<td>130</td>
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<td>130</td>
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<tr>
<td>23</td>
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<td>1</td>
<td>130</td>
<td>0.2</td>
</tr>
<tr>
<td>24</td>
<td>130</td>
<td>1</td>
<td>130</td>
<td>0.2</td>
</tr>
</tbody>
</table>
Equation 22
\[ UA_b = \frac{2\pi Len_b \cdot \text{cond}}{12 \cdot \ln\left(\frac{Diab + 2 \cdot \text{Thick}_b}{Diab}\right)} \]

Where,
\[ \pi = 3.1416 \]
\[ Diab = \text{Branch pipe diameter (inch). It is divided by 12 in the above equation to convert the unit from inch to foot. See Equation 31.} \]
\[ Len_b = \text{Branch pipe length (foot). See Equation 32.} \]
\[ \text{Thick}_b = \text{Branch pipe insulation thickness (inch). Since not all branch piping is required to be insulated, it shall be assumed to be 0.5 inch.} \]
\[ \text{Cond} = \text{Insulation conductivity, (assumed 0.26 Btu inch/h∙sf∙F)} \]

Equation 23
\[ HBWL = (N_{\text{waste}} \cdot SCH_{\text{waste,m}}) \cdot \left( f_{\text{vol}} \cdot 7.48 \cdot \pi \cdot \left(\frac{\text{Dia}_b}{24}\right)^2 \cdot Len_b \right) \cdot \rho \cdot C_p \cdot \left( T_{\text{IN,b}} - T_{\text{inlet}} \right) \]

Equation 24
\[ N_{\text{waste}} = 19.84 \cdot e^{(-0.544 \cdot N_{\text{unit,b}})} \]

Where,
\[ N_{\text{waste}} = \text{Number of times in a day for which water is dumped before use. It depends on the number of dwelling units served by a branch. Statistically, the less times of water waste is inversely proportional to the number of units a branch serves. See Equation 24.} \]
\[ SCH_{\text{waste,m}} = \text{Hourly schedule of water waste. See Table E-4 Branch Water Waste Schedule.} \]
\[ f_{\text{vol}} = \text{The volume of hot water waste is more than just the volume of branch pipes, due to branch pipe heating, imperfect mixing, and user behaviors. This multiplier is applied to include these effects and is assumed to be 1.4.} \]
\[ T_{\text{IN,b}} = \text{Average branch input temperature (°F). It is assumed to equal to the output temperature of the first recirculation loop section, } T_{\text{OUT,1}}. \]
\[ T_{\text{inlet}} = \text{The cold water inlet temperature (°F) according to Section 3.3 Cold Water Inlet Temperature.} \]
Table E-4. Branch Water Waste Schedule

<table>
<thead>
<tr>
<th>Hour</th>
<th>SCH\textsubscript{waste,m}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
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<tr>
<td>2</td>
<td>0.02</td>
</tr>
<tr>
<td>3</td>
<td>0.05</td>
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<tr>
<td>4</td>
<td>0.22</td>
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<td>0.01</td>
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<tr>
<td>11</td>
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<td>23</td>
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<tr>
<td>24</td>
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</tr>
</tbody>
</table>

4.3 Recirculation System Plumbing Designs

A recirculation system can have one or multiple recirculation loops. Each recirculation loop consists of many pipe sections, which are connected in sequence to form a loop. Each pipe section could have different pipe diameter, length, and location. The compliance software shall use six pipe sections, with three supply pipe sections and three return pipe sections, to represent a recirculation loop. When multiple recirculation loops exist, all recirculation loops are assumed to be identical. The compliance software shall provide default and standard recirculation system designs based on building geometry according to the procedures described in the following sections. The default design reflects typical recirculation loop design practices. The standards design represents an improved design with two recirculation loops and is used to set recirculation loop heat loss budget.

Compliance software shall provide users with the option either to provide a user-input recirculation system design or to use the default design as the proposed design. The option of using the default
design as the proposed design helps users to reduce compliance documentation efforts. However, this option leads to a higher recirculation pipe heat loss than the standard design, since the default design is less efficient than the standard design. User-input recirculation designs shall be validated according the process described in Equation 28.

The first step of establishing recirculation system designs is to determine the number of recirculation loops, Nloop, in water heating system k. The default design has one recirculation loop, Nloop =1, while the standard design has two recirculation loops, Nloop =2. Proposed designs are allowed to specify more than one loop only if the recirculation loop designs are verified by a HERS rater. Otherwise, the proposed design can only be specified to have one recirculation loop.

The standard and default recirculation loop designs are based on characteristics of the proposed building. There could be many possibilities of building shapes and dwelling unit configurations, which would determine recirculation loop pipe routings. Without requiring users to provide detailed dwelling unit configuration information, the compliance software shall assume the proposed buildings to have same dwelling units on each floor and each floor to have a corridor with dwelling units on both sides. Recirculation loops start from the mechanical room (located on the top floor), go vertically down to the middle floor, loop horizontally in the corridor ceiling to reach the dwelling units on both ends of the building, then go vertically up back to the mechanical room. At each dwelling unit on the middle floor, a vertical branch pipe, connected to the recirculation loop supply pipe, is used to provide hot water connection to dwelling units on other floors. For the default design, the mechanical room is assumed to be located at one end of the top floor, so that the recirculation pipes on the middle floor loop around the whole floor in one loop. For the standard design, the mechanical room is assumed to be located in the middle of the top floor, so that the supply pipe splits into two to form two loops, with each serving half of the building.

Both the standard and default recirculation loop designs are assumed to have equal length of supply sections and return sections. The first section is from the mechanical room to the middle floor. The second section serves first half branches connected to the loop and the third section serves the rest branches. The first and second sections have the same pipe diameter. Pipe size for the third section is reduced since less dwelling units are served. Return sections match with the corresponding supply pipes in pipe length and location. All return sections have the same diameter. For both the standard and default designs, mechanical room is optimally located so that only vertical piping is needed between the mechanical room and the recirculation pipes located on the middle floor. Pipe sizes are determined based on the number of dwelling units served by the loop, following the 2009 Uniform Plumbing Code (UPC) pipe sizing guidelines. The detailed recirculation loop configurations are calculated as following.

<table>
<thead>
<tr>
<th>Description</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe Length in the mechanical room (foot)</td>
<td>( L_{mech} = 8 )</td>
</tr>
<tr>
<td>Height of each floor (foot)</td>
<td>( H_{floor} = 10 )</td>
</tr>
<tr>
<td>Length of each dwelling unit (foot)</td>
<td>( L_{unit} = \sqrt{CF_A_i} )</td>
</tr>
<tr>
<td>Length of recirculation pipe sections (foot)</td>
<td></td>
</tr>
</tbody>
</table>
Equation 25    Default Design

\[
\text{Len}_1 = L_{\text{mech}} + H_{\text{floor}} \cdot \frac{N_{\text{floor}}}{2}
\]

\[
\text{Len}_2 = L_{\text{unit}} \cdot \frac{N_{\text{unit}}}{4 \cdot N_k \cdot N_{\text{floor}}}
\]

\[\text{Len}_3 = \text{Len}_2\]

\[\text{Len}_4 = \text{Len}_3\]

\[\text{Len}_5 = \text{Len}_2\]

\[\text{Len}_6 = \text{Len}_1\]

Equation 26    Standard Design

\[
\text{Len}_1 = L_{\text{mech}} + H_{\text{floor}} \cdot \frac{N_{\text{floor}}}{2}
\]

\[
\text{Len}_2 = L_{\text{unit}} \cdot \frac{N_{\text{unit}}}{8 \cdot N_k \cdot N_{\text{floor}}}
\]

\[\text{Len}_3 = \text{Len}_2\]

\[\text{Len}_4 = \text{Len}_3\]

\[\text{Len}_5 = \text{Len}_2\]

\[\text{Len}_6 = \text{Len}_1\]

Pipe diameters (inch) for supply sections depends on the number of dwelling units being served. They shall be calculated using Equation 27, which is based on 2009 UPC pipe sizing specifications.

Equation 27

\[
\text{Dia}_1 = \text{INT}((-7.525 \times 10^{-9} \cdot N_{\text{unit,1}} \cdot 4 + 2.82 \times 10^{-6} \cdot N_{\text{unit,1}} \cdot 3 - 4.207 \times 10^{-4} \cdot N_{\text{unit,1}} \cdot 2 + 0.04378 \cdot N_{\text{unit,1}} + 1.232)/0.5 + 1) \cdot 0.5
\]

\[
\text{Dia}_2 = \text{Dia}_3
\]

\[
\text{Dia}_3 = \text{INT}((-7.525 \times 10^{-9} \cdot N_{\text{unit,3}} \cdot 4 + 2.82 \times 10^{-6} \cdot N_{\text{unit,3}} \cdot 3 - 4.207 \times 10^{-4} \cdot N_{\text{unit,3}} \cdot 2 + 0.04378 \cdot N_{\text{unit,3}} + 1.232)/0.5 + 1) \cdot 0.5
\]

\[\text{Dia}_4 = \text{Dia}_5 = \text{Dia}_6 = 0.75\]

\[\text{Dia}_4 = \text{Dia}_5 = \text{Dia}_6\]

\[\text{Dia}_4 = \text{Dia}_5 = \text{Dia}_6\]

for low-rise multi-family building and hotel/motel less than four stories

\[\text{Dia}_4 = \text{Dia}_5 = \text{Dia}_6\]

for high-rise multi-family and hotel/motel more than three stories

where

\[N_{\text{unit}} = \text{Number of dwelling unit in the building.}\]

\[N_{\text{floor}} = \text{Number of floors of the building.}\]
Nk = Number of water heating system in the building.

\[ N_{\text{unit},1} = \frac{N_{\text{unit}}}{Nk \cdot N_{\text{floor}} \cdot N_{\text{loop}}} \]

N\text{unit,}1= Number of dwelling unit served by the section 1.

\[ N_{\text{unit},3} = \frac{N_{\text{unit},1}}{2} \]

number of dwelling unit served by the section 3,

The compliance software shall validate the proposed recirculation system design to generate a validation correction factor, \( f_{\text{area}} \), based on comparison of total recirculation loop pipe surface area, according to Equation 28. When the proposed design has more than one loop and is HERS verified, the correction factor, \( f_{\text{area}} \), is set to be one, since the proposed design meets the prescriptive requirement.

\[ f_{\text{area}} = \begin{cases} 
1 & \text{for } \frac{SF_{\text{Default}}}{SF_{\text{Proposed}}} < 1.0 \\
\frac{SF_{\text{Default}}}{SF_{\text{Proposed}}} & \text{for } \frac{SF_{\text{Default}}}{SF_{\text{Proposed}}} \geq 1.0
\end{cases} \]

Equation 28

Where,

\[ SF_{\text{Proposed}} = \text{Proposed design recirculation loop surface area (sqft), based on proposed design inputs.} \]

\[ SF_{\text{Default}} = \text{Default design recirculation loop surface area (sqft), based on default design loop configurations.} \]

Branch design parameters include number of branches, branch length, and branch diameter. The standard design assumes that the dwelling units are evenly distributed on each floor and one branch is needed for each dwelling unit on a floor. Therefore, the number of branches in water heating system \( k \) is calculated as:

\[ N_{\text{unit,}b} = N_{\text{floor}} \]

Equation 29

\[ N_{\text{branch}} = \text{INT}\left(\frac{N_{\text{unit}}}{N_{\text{unit,}b} \cdot N_K} + 0.5\right) \]

Equation 30

Where,

\[ N_{\text{unit,}b}= \text{Number of dwelling unit served by each branch} \]

\[ N_{\text{branch}}= \text{Number of branch in water heating system} \]

The branch pipe diameter shall be calculated using Table E-5 according to the number of dwelling unit served by the branch, or using the formula below. Both methods are based on 2009 UPC pipe sizing specifications.
Equation 31

The branch length includes the vertical rise based on the number of floors in the building plus four feet of pipe to connect the branch to the recirculation loop.

Equation 32

Proposed designs shall use the same branch configurations as those in the standard design. Therefore, compliance software does not need to collect branch design information.

Table E-5. Pipe Sizing Schedule

<table>
<thead>
<tr>
<th>Number of Dwelling Units</th>
<th>Pipe Diameter (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;8</td>
<td>1.5</td>
</tr>
<tr>
<td>8 – 20</td>
<td>2</td>
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<tr>
<td>21 – 42</td>
<td>2.5</td>
</tr>
<tr>
<td>43 – 67</td>
<td>3</td>
</tr>
<tr>
<td>68 – 100</td>
<td>3.5</td>
</tr>
<tr>
<td>101 – 144</td>
<td>4</td>
</tr>
</tbody>
</table>

E5. High Rise Residential Buildings, Hotels and Motels

Simulations for high rise residential buildings, hotels and motels shall follow all the rules for central or individual water heating with the following exceptions.

For central systems which do not use recirculation but use electric trace heaters the program shall assume equivalency between the recirculation system and the electric trace heaters.

For individual water heater systems which use electric trace heating instead of gas, the program shall assume equivalency.

E6. Energy Use of Individual Water Heaters

Once the hourly adjusted recovery load is determined for each water heater, the energy use for each water heater is calculated as described below.
6.1  Small\(^1\) Gas, Oil, or Electric Storage\(^2\) and Heat Pump Water Heaters

The hourly energy use of storage gas, storage electric and heat pump water heaters is given by the following equation.

\[
WHEU_j = \left[ \frac{HARL_j \times HPAF_j}{LDEF_j} \right]
\]

where

- \(WHEU_j\) = Hourly energy use of the water heater (Btu for fuel or kWh for electric), adjusted for tank insulation. The above equation provides a value in unit of Btu. For electric water heaters, the calculation result needs to be converted to the unit of kWh by dividing 3413 Btu/kWh.
- \(HARL_j\) = Hourly adjusted recovery load (Btu).
- \(HPAF_j\) = Heat pump adjustment factor from the table below based on climate zone. This value is one for storage gas, storage oil and storage electric water heaters.

---

\(^1\) “Small water heater” means a water heater that is a gas storage water heater with an input of 75,000 Btu per hour or less, an oil storage water heater with an input of 105,000 Btu per hour or less, an electric storage water heater with an input of 12 kW or less, or a heat pump water heater rated at 24 amps or less.

\(^2\) “Small storage water heater” means a water heater that is a gas storage water heater with an input of 75,000 Btu per hour or less, an oil storage water heater with an input of 105,000 Btu per hour or less, or an electric storage water heater with an input of 12 kW. A small water heater includes a heat pump water heater rated at 24 amps or less.
### Table E-6. Heat Pump Adjustment Factors

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Heat Pump Adjustment Factor</th>
<th>Climate Zone</th>
<th>Heat Pump Adjustment Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>9</td>
<td>0.920</td>
</tr>
<tr>
<td>2</td>
<td>0.990</td>
<td>10</td>
<td>0.920</td>
</tr>
<tr>
<td>3</td>
<td>0.990</td>
<td>11</td>
<td>0.920</td>
</tr>
<tr>
<td>4</td>
<td>1.070</td>
<td>12</td>
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<td>5</td>
<td>1.070</td>
<td>13</td>
<td>0.920</td>
</tr>
<tr>
<td>6</td>
<td>0.920</td>
<td>14</td>
<td>1.040</td>
</tr>
<tr>
<td>7</td>
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</tr>
<tr>
<td>8</td>
<td>0.920</td>
<td>16</td>
<td>1.500</td>
</tr>
</tbody>
</table>

The annual load dependent energy factor (LDEF) is given by the following equation. This equation adjusts the nominal EF rating for storage water heaters for different load conditions.

**Equation 34**

\[
LDEF_j = \min \left[ LDEF_{\text{max}}, \max \left( LDEF_{\text{min}}, \ln \left( \frac{AAHARL_j \times 24}{1000} \right) \left( a \times EF_j + b \right) + \left( c \times EF_j + d \right) \right) \right]
\]

where

\[a, b, c, d, e = \text{Coefficients from the table below based on the water heater type.}\]

### Table E-7. LDEF Coefficients

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Storage Gas</th>
<th>Storage Electric</th>
<th>Heat Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>-0.098311</td>
<td>-0.91263</td>
<td>0.44189</td>
</tr>
<tr>
<td>b</td>
<td>0.240182</td>
<td>0.94278</td>
<td>-0.28361</td>
</tr>
<tr>
<td>c</td>
<td>1.356491</td>
<td>4.31687</td>
<td>-0.71673</td>
</tr>
<tr>
<td>d</td>
<td>-0.872446</td>
<td>-3.42732</td>
<td>1.13480</td>
</tr>
<tr>
<td>e</td>
<td>0.946</td>
<td>0.976</td>
<td>0.947</td>
</tr>
</tbody>
</table>

**AAHARL_j** = Annual average hourly adjusted load (Btu) = \( \frac{1}{8760} \sum_{i=1}^{8760} HARL_j \). Note that calculation of AAHARL_j requires a preliminary annual simulation that sums HARL_j values for each hour.

**EF_j** = Energy factor of the water heater (unitless). This is based on the DOE test procedure. EF for storage gas water heaters under 20 gallons must be assumed to be 0.58 unless the manufacturer has voluntarily reported an actual EF to the California Energy Commission.
6.2 Small Gas or Oil Instantaneous

The hourly energy use for instantaneous gas or oil water heaters is given by Equation 35, where the nominal rating is factored by 0.92 to reflect the impacts of heat exchanger cycling under real-world load patterns.

\[
WHEU_j = \left( \frac{HARL_j}{EF_j \times 0.92} \right)
\]

Where,

- \(WHEU_j\) = Hourly fuel energy use of the water heater (Btu).
- \(HARL_j\) = Hourly adjusted recovery load.
- \(EF_j\) = Energy factor from the DOE test procedure (unitless). This is taken from manufacturers’ literature or from the CEC Appliance Database.
- 0.92 = Efficiency adjustment factor

6.3 Small Electric Instantaneous

The hourly energy use for instantaneous electric water heaters is given by the following equation.

\[
WHEU_{j,electric} = \frac{HARL_j}{EF_j \times 0.92 \times 3413}
\]

Where,

- \(WHEU_{j,electric}\) = Hourly electric energy use of the water heater (kWh).
- \(HARL_j\) = Hourly adjusted recovery load (Btu).
- \(EF_j\) = Energy factor from DOE test procedure (unitless).
- 0.92 = Adjustment factor to adjust for overall performance.
- 3413 = Unit conversion factor (Btu/kWh).

6.4 Mini-Tank Electric Water Heaters

(Note: Not used in the current calculation)

---

3 “Instantaneous water heater” means a water heater that has an input rating of at least 4,000 Btu per hour per gallon of stored water. Small instantaneous water heaters include: gas instantaneous water heaters with an input of 200,000 Btu per hour or less, oil instantaneous water heaters with an input of 210,000 Btu per hour or less, and electric instantaneous water heaters with an input of 12 kW or less.
Mini-tank electric heaters are occasionally used with gas tankless water heaters to mitigate hot water delivery problems related to temperature fluctuations that may occur between draws. If mini-tank electric heaters are installed, the installed units must be listed in the CEC Appliance Database and their reported standby loss (in Watts) will be modeled to occur each hour of the year. (If the unit is not listed in the CEC Appliance Database, a standby power consumption of 100 W should be assumed.)

\[
MTEU = \left( \sum_{j} MTSBL_j \right) / 1000
\]

Where,

- \( MTEU \) = Hourly standby energy use of mini-tank electric water heaters (Watts)
- \( MTSBL_j \) = Mini-tank standby Watts for tank \( j \) (if not listed in CEC Appliance directory, assume 100 W)

### 6.5 Large Gas or Oil Storage

Energy use for large storage gas is determined by the following equations. Note: large storage gas water heaters are defined as any gas storage water heater with a minimum input rate of 75,000 Btu/h.

\[
WHEU_j = \left[ \frac{HARL_j}{EFF_j} + SBL \right]
\]

Where,

- \( WHEU_j \) = Hourly fuel energy use of the water heater (Btu), adjusted for tank insulation.
- \( HARL_j \) = Hourly adjusted recovery load. For independent hot water storage tank(s) substitute \( HARL_j \) from Section E3.
- \( SBL \) = Total Standby Loss (Btu/hr). Obtain from CEC Appliance Database or from AHRI certification database. This value includes tank losses and pilot energy. If standby rating is not available from either of the two databases, it shall be calculated as per Table F-2 of the 2015 Appliance Efficiency Regulations, as follows:

\[
SBL = Q/800 + 110 (V)^{1/2}, \text{where } Q \text{ is the input rating in Btu/hour, and } V \text{ is the tank volume in gallons.}
\]

- \( EFF_j \) = Efficiency (fraction, not %). Obtained from CEC Appliance Database or from manufacturer’s literature. These products may be rated as a recovery efficiency, thermal efficiency or AFUE.

---

4 "Large water heater" means a water heater that is not a small water heater.
6.6 Large Instantaneous, Indirect Gas and Hot Water Supply Boilers

Energy use for these types of water heaters is given by the following equation.

\[
WHEU_j = \left[ \frac{HARL_j}{EFF_j \times 0.92} + PILOT_j \right]
\]

Where,

- \(WHEU_j\) = Hourly fuel energy use of the water heater (Btu), adjusted for tank insulation.
- \(HARL_j\) = Hourly adjusted recovery load. For independent hot water storage tank(s) substitute \(HARL_j\) from Section E3.
- \(EFF_j\) = Efficiency (fraction, not %). To be taken from CEC Appliance Database or from manufacturers literature. These products may be rated as a recovery efficiency, thermal efficiency or AFUE.
- \(PILOT_j\) = Pilot light energy (Btu/h) for large instantaneous. For large instantaneous water heaters, and hot water supply boilers with efficiency less than 89 percent assume the default is 750 Btu/hr if no information is provided in manufacturer’s literature or CEC Appliance Database.
- 0.92 = Adjustment factor used when system is not supplying a storage system.

6.7 Large Electric Storage

Energy use for large storage electric water heaters is given by the following equation.

\[
WHEU_{j,\text{elec}} = \left[ \frac{HARL_j}{3413 \cdot EFF_j} \right] + SBL
\]

Where,

- \(WHEU_{j,\text{elec}}\) = Hourly electric energy use of the water heater (kWh).
- \(EFF_j\) = Efficiency (fraction, not %). To be taken from CEC Appliance Database or from manufacturers literature. These products may be rated as a recovery efficiency, thermal efficiency or AFUE.
- \(HARL_j\) = Hourly adjusted recovery load (Btu).
- \(SBL\) = Total Standby Loss (kWh). Obtain from CEC Appliance Database or from AHRI certification database. If the standby loss is reported in unit of Btu/hr, it needs to be

---

\(^5\) “Hot water supply boiler” means an appliance for supplying hot water for purposes other than space heating or pool heating.
converted to kWh by dividing by 3413 Btu/kWh. If standby loss is reported as a percent, SBL shall be determined based on the definition in Title 20 2012 Appliance Efficiency Regulations, Table F-2, as follows:

\[
SBL = (\text{standby loss percent} \times 8.25 \text{ Btu/gallon-}^\circ\text{F} \times \text{measured water heater tank volume (gallons)} \times 70^\circ\text{F}) / 3413 \text{ (Btu per kWh)}.
\]

### 6.8 Jacket Loss

The hourly jacket loss for the \(l^{th}\) unfired tank or indirectly fired storage tank in the \(k^{th}\) system is calculated as

\[
HJL_l = \frac{TSA_l \times \Delta TS}{RTI_l + REI_l} + FTL_l
\]

Where,

- \(HJL_l\) = The tank surface losses of the \(l^{th}\) unfired tank of the \(k^{th}\) system
- \(TSA_l\) = Tank surface area (ft\(^2\)).
- \(\Delta TS\) = Temperature difference between ambient surrounding water heater and hot water supply temperature (\(^\circ\)F). Hot water supply temperature shall be 124\(^\circ\)F. For water heaters located inside conditioned space use 75\(^\circ\)F for the ambient temperature. For water heaters located in outside conditions use hourly dry bulb temperature ambient.
- \(FTL_l\) = Fitting losses. This is a constant 61.4 Btu/h.
- \(REI_l\) = R-value of exterior insulating wrap. No less than R-12 is required.
- \(RTI_l\) = R-value of insulation internal to water heater. Assume 0 without documentation.

### 6.9 Tank Surface Area

Tank surface area (TSA) is used to calculate the hourly jacket loss (HJL) for large storage gas, indirect gas water heaters, and large storage electric water heaters. TSA is given in the following equation as a function of the tank volume.

\[
\text{TSA}_l = e \times \left[ f \times \text{VOL}_l^{0.33} + g \right]^2
\]

Where,

- \(\text{VOL}_l\) = Tank capacity (gallons).
- \(e, f, g\) = Coefficients given in Table E-8.
Table E-8. Coefficients for Calculating Tank Surface Areas

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Storage Gas</th>
<th>Large Storage Gas and Indirect Gas</th>
<th>Storage Electric and Heat Pumps</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>0.00793</td>
<td>0.01130</td>
<td>0.01010</td>
</tr>
<tr>
<td>F</td>
<td>15.67</td>
<td>11.8</td>
<td>11.8</td>
</tr>
<tr>
<td>G</td>
<td>1.9</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

6.10 Electricity Use for Circulation Pumping

For single-family recirculation systems, hourly pumping energy is fixed as shown in Table E-9.
Table E-9. Single Family Recirculation Energy Use (kWh) by Hour of Day

<table>
<thead>
<tr>
<th>Hour</th>
<th>Non-Demand Controlled Recirculation</th>
<th>Demand Recirculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.040</td>
<td>0.0010</td>
</tr>
<tr>
<td>2</td>
<td>0.040</td>
<td>0.0005</td>
</tr>
<tr>
<td>3</td>
<td>0.040</td>
<td>0.0006</td>
</tr>
<tr>
<td>4</td>
<td>0.040</td>
<td>0.0006</td>
</tr>
<tr>
<td>5</td>
<td>0.040</td>
<td>0.0012</td>
</tr>
<tr>
<td>6</td>
<td>0.040</td>
<td>0.0024</td>
</tr>
<tr>
<td>7</td>
<td>0.040</td>
<td>0.0045</td>
</tr>
<tr>
<td>8</td>
<td>0.040</td>
<td>0.0057</td>
</tr>
<tr>
<td>9</td>
<td>0.040</td>
<td>0.0054</td>
</tr>
<tr>
<td>10</td>
<td>0.040</td>
<td>0.0045</td>
</tr>
<tr>
<td>11</td>
<td>0.040</td>
<td>0.0037</td>
</tr>
<tr>
<td>12</td>
<td>0.040</td>
<td>0.0028</td>
</tr>
<tr>
<td>13</td>
<td>0.040</td>
<td>0.0025</td>
</tr>
<tr>
<td>14</td>
<td>0.040</td>
<td>0.0023</td>
</tr>
<tr>
<td>15</td>
<td>0.040</td>
<td>0.0021</td>
</tr>
<tr>
<td>16</td>
<td>0.040</td>
<td>0.0019</td>
</tr>
<tr>
<td>17</td>
<td>0.040</td>
<td>0.0028</td>
</tr>
<tr>
<td>18</td>
<td>0.040</td>
<td>0.0032</td>
</tr>
<tr>
<td>19</td>
<td>0.040</td>
<td>0.0033</td>
</tr>
<tr>
<td>20</td>
<td>0.040</td>
<td>0.0031</td>
</tr>
<tr>
<td>21</td>
<td>0.040</td>
<td>0.0027</td>
</tr>
<tr>
<td>22</td>
<td>0.040</td>
<td>0.0025</td>
</tr>
<tr>
<td>23</td>
<td>0.040</td>
<td>0.0023</td>
</tr>
<tr>
<td>24</td>
<td>0.040</td>
<td>0.0015</td>
</tr>
<tr>
<td>Annual Total</td>
<td>350</td>
<td>23</td>
</tr>
</tbody>
</table>

Multi-family recirculation systems typically have larger pump sizes, and therefore electrical energy use is calculated based on the installed pump size. The hourly recirculation pump electricity use (HEUP) is calculated by the hourly pumping schedule and the power of the pump motor as in the following equation.

\[
HEUP_k = \frac{0.746 \times PUMP_k \times SCH_{k,m}}{\eta_k}
\]

Where,

- \(HEUP_k\) = Hourly electricity use for the circulation pump (kWh).
- \(PUMP_k\) = Pump brake horsepower (bhp).
- \(\eta_k\) = Pump motor efficiency.
SCH_{k,m} = \text{Operating schedule of the circulation pump, see Table E-4 Table E-3. The operating schedule for the proposed design shall be based on user input. The standard design operation schedule is demand control.}

6.10 Prorating Energy Use in Multi-Family Buildings

For central water heating systems, the energy use is calculated at the system level, not at the dwelling unit level. When it is necessary to allocate energy use to individual dwelling units for home energy ratings or other purposes, the procedure in this section may be used.

The fraction of the energy that is allocated to an individual dwelling unit is the ratio of the gallons-per-day load for that dwelling unit to the gallons-per-day estimate for the whole building. This fraction is shown in Equation 44.

\[
\text{Equation 44} \quad \text{Fraction}_i = \frac{\text{GPD}_i}{\sum_{1}^{\text{NmbrDU}} \text{GPD}_i}
\]

Where,

- Fraction\textsubscript{i} = Fraction of water heating energy allocated to the \textit{i}th dwelling unit.
- GPD\textsubscript{i} = Gallons per day of consumption for the \textit{i}th dwelling unit. See Equation 8.
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1 Introduction

[To be written]
2 California Simulation Engine (CSE)

2.1 Overview

The building modeled can have multiple conditioned and unconditioned zones. Each conditioned zone has an air handler associated with it, and each air handler can have supply and/or return ducts in an unconditioned zone (nominally the attic), and in the conditioned zone itself. Air handlers can operate independently in either a heating, cooling, or off mode. See Figure 1.

Every time step (nominally two minutes), the zone model updates the heat transfers to and from the zones and the zone mass temperatures. Each zone’s conditions are updated in succession and independently, based on the conditions in the adjacent zones in the last time step.

The conditioned zone thermostat algorithms determine whether an air handler should be in a heating or cooling mode, or floating, and if heating or cooling, the magnitude of the load that must be met by the air handler to keep the conditioned zone at its current setpoint. If the setpoints cannot be satisfied, the conditioned zone floats with heating, cooling, or ventilation, at full capacity. In the off mode case the zones are modeled during the time step without duct or air handler effects.
The duct system model determines duct losses, their effect on the conditions of the unconditioned and conditioned zones, and their effect on the heating or cooling delivery of the air handler system.

The duct system model allows unequal return and supply duct areas, with optional insulation thicknesses. The ducts can have unequal supply and return leakages, and the influence of unbalanced duct leakage on the unconditioned and conditioned zones infiltration and ventilation is taken into account. Every time step it updates the air handler and duct system heat transfers, and HVAC energy inputs, outputs, and efficiency.

For each window, the ASHWAT window algorithm calculates the window instantaneous shortwave, longwave, and convective heat transfers to the zones.

The AIRNET infiltration and ventilation algorithm calculates the instantaneous air flow throughout the building based on the air temperatures in the zones, and on the outside wind and air temperature. AIRNET also handles fan induced flows.

In the update processes, a zones mass-node temperatures are updated using a forward-difference (Euler) finite difference solution, whereby the temperatures are updated using the
driving conditions from the last time step. For accuracy, this forward-difference approach necessitates a small time-step.

The small time-step facilitates the no-iterations approach we have used to model many of the interactions between the zones, and allows the zones to be updated independently.

For example, when the zone energy balance is performed for the conditioned zone, if ventilation is called for, the ventilation capacity, which depends on the zone temperatures (as well as maximum possible ventilation openings and fan flows), is determined from the instantaneous balance done by AIRNET. To avoid iteration, the ventilation flows, and the accompanying heat transfers are based on the most recently available zone temperatures.

To avoid iteration, a similar use of the last time-step data is necessary is dealing with inter-zone wall heat transfer. For example, heat transfer through the ceiling depends on the conditions in both zones, but these conditions are not known simultaneously. Thus, ceiling masses are treated as belonging to the attic zone, and updated at the same time as other attic masses, partly based on the heat transfer from the conditioned zone to the ceiling from the last time step. In turn, when the conditioned zone is updated it determines the ceiling heat transfer based on the ceiling temperature determined two-minutes ago when the attic balance was done.

Similarly, when the conditioned zone energy balance is performed, if for example heating is called for, then the output capacity of the heating system needs to be known, which requires knowing the duct system efficiency. But the efficiency is only known after the air handler simulation is run. To avoid iteration between the conditioned zone and attic zones, the most recent duct efficiency is used to determine the capacity in the conditioned zones thermostat calculations. When the attic simulation is next performed, if the conditioned zone was last running at capacity, and if the efficiency now calculated turns out to be higher than was assumed by the thermostat calculations, then the load will have exceeded the limiting capacity by a small amount depending on the assumed vs. actual efficiency. In cases like this, to avoid iteration, the limiting capacity is allowed to exceed the actual limit by a small amount, so that the correct energy demand is determined for the conditioned zone load allowed.

2.1.1 Schematic of Zone Thermal Network

Figure 2 shows a schematic of the zone model network. It models a single zone whose envelope consists of any number of walls, ceilings, floors, slabs, and windows, and can be adjacent to other conditioned or unconditioned zones. The envelope constructions can be made of any number of layers of different materials of arbitrary thermal conductivity and heat capacity. Each layer is modeled with one or more “T” networks in series. Each T has the layer heat capacitance, \( \text{cap}_{ij} \), centered between by two thermal conductances, where the first subscript corresponds to the wall construction number and the second to the layer number. Framed constructions are treated as two separate surface areas, the surface area of the part between framing, and the surface area of the part containing the framing itself; the heat flow is assumed to follow independent and parallel paths through these two surfaces.
The room air, represented by the mass node $T_a$, is assumed to be well-mixed and have heat capacitance $C_{air}$ (Btu/F). The air is shown in Figure 2 to interact with all of the building interior construction surfaces via convection coefficients $h_i l c_i$ for surface $i$. The overall conductance through the window between $T_a$ and an effective outdoor temperature $T_{eo}$ is $ccw_j$ for window surface $j$. The conductances $ccw_j$ and the corresponding radiant value $crw_j$ are outputs of the ASHWAT windows algorithm applied to window $j$ each time step.

A mean radiant temperature node, $T_r$, acts as a clearinghouse for radiant exchange between surfaces. With conductances similar to those of the air node: $hr I c_i$ and $crw_j$.

Depending on the size of the zone and the humidity of the air, the air is assumed to absorb a fraction of the long-wave radiation and is represented by the conductance $C_{xair}$.

The internal gains, $Q_{int}$, can be specified in the input as partly convective (fraction $fintC$), partly long wave ($fintLW$), and partly shortwave (fintSW). The heating or cooling heat transfers are shown as $Q_{hc}$ (+ for heating, - for cooling). If $Q_{hc}$ is heating, a fraction ($frConv$) can be convective with the rest long-wave. The convective parts of $Q_{int}$ and $Q_{hc}$ are shown as added to the air node. The long wave fraction of $Q_{int}$ and $Q_{hc}$ are shown added to the $T_r$ node.

Additional outputs of the ASHWAT algorithm are $FP_j$ the fraction of insolation $I_j$ incident on window $j$ that ultimately arrives at the air node via convection, and $FM_j$, the fraction that arrives at the radiant node as long-wave radiation.

The term $Qs_i$ is the total solar radiation absorbed by each construction surface $i$, as determined by the solar distribution algorithm. The short wave part of the internal gains, $Qint *$
fintSW, is distributed diffusely, with the same diffuse targeting as the diffusely distributed solar gains.

Solar gains absorbed at the outside surface of constructions are represented by $Q_{s_i}$ in Figure 2.

The slab is connected to the $T_a$ and $T_r$ in a similar fashion as the wall surfaces, although the slab/earth layering procedure is different than for walls.

### 2.1.2 Schematic of Reduced Thermal Network

Before a zone energy balance is formulated it is convenient to dissolve all the massless nodes from the network of Figure 2 (represented by the black dots), except for the mean radiant temperature node $Tr$. Figure 3 shows the resulting reduced network. A massless node is eliminated by first removing the short-wave gains from the node by using the current splitting principle (based on superposition), to put their equivalent gains directly onto adjacent mass nodes and other nodes that have fixed temperatures during a time step. Then the massless node can be dissolved by using Y-$\Delta$ transformations of the circuit.

**Figure 3: Network after Dissolving Massless Nodes**

For example, to eliminate the massless surface node of layered mass in Figure 2, the gain $Q_{s_i}$ absorbed by the surface node is split into three parts: $Q_{s_i}''$ to the $T_{i,1}$ node, $Q_{s_i}'''$ to the $T_a$ node and $Q_{s_i}''''$ to the $Tr$ node. For example, by current splitting,

$$Q_{s_i}'' = Q_{s_i} \frac{U h_{i,1}}{h c l_{c_i} + h r l_{c_i} + U h_{i,1}}$$

*Equation 1*
2.1 Overview

A Y-Δ transformation of the remaining Y circuit gives the \( ccc_i \) and \( crc_i \) conductances, as well as an additional cross conductance \( CXC_i \) that is added to \( CXair \). For example,

\[
ccc_i = \frac{hclc_i * U_{h_{i,1}}}{hclc_i + hrlc_i + U_{h_{i,1}}}
\]

Equation 2

2.1.3 Zone Balance Calculation Sequence

The temperatures in the zone are determined using a thermal balance method. The following procedure is followed each time step.

At the start of the simulation, say time \( t \), assume all temps \( Ta(t), Tr(t), T_{i,1}(t), T_{i,2}(t) \), etc. are known along with all the solar gains, internal gains, etc.

1. First, the layered mass temperatures are updated using the explicit Euler routine (see Section 2.2), giving \( T_{i,1}(t+dt), T_{i,2}(t+dt) \), etc. The Euler method determines each of these mass temperatures assuming that all the boundary conditions (temperatures and heat sources) that cause the change in the mass temperatures, are conditions at time \( t \). Thus the mass node temperatures can be in any order, independently of each other.

2. Next, a steady-state instantaneous energy balance at the Ta and Tr nodes is made at time \( t+dt \). This balance involves the mass temperatures determined for time \( t+dt \) in Step-1, as well other heating or cooling sources at time \( t+dt \). The balance in this step involves querying the HVAC control algorithm which allows heating, cooling and ventilation (forced or natural) in response to scheduled setpoints. The idealized control system is assumed to keep the zone at exactly the scheduled setpoint unless \( Ta \) is in the deadband or if the HVAC capacity is exceeded, whereupon the system runs at maximum capacity, and \( Ta \) floats above or below the relevant setpoint. While the heating, cooling and forced ventilation system capacities are scheduled inputs, the natural ventilation capacity is dependent on the current zone and environment conditions.

Thus, the energy balance at the Ta and Tr nodes returns either the heating, the cooling or the ventilation required to meet the setpoint, or else returns the floating \( Ta \) that results at the capacity limits or when \( Ta \) is in the deadband.

At this stage the conditions have been predicted for the end of the time step, and steps 1 and 2 and repeated. The various boundary conditions and temperature or air flow sensitive coefficients can be recalculated as necessary each time step at the beginning of step (1), giving complete flexibility to handle temperature sensitive heat transfer and control changes at a time step level.

Note that step (2) treats the energy balance on \( Ta \) as a steady state balance, despite the fact that air mass makes it a transient problem. However, as shown in Section 2.3.1, if the air mass temperature is updated using an implicit-difference method, the effect of the air mass can be
2.1 Overview

The overall CSE Calculation Sequence is summarized below:

*Hour*
Determine and distribute internal gains.

*Sub-hour*
Determine solar gain on surfaces.
Determine surface heat transfer coefficients.
Update mass layer temperatures.
Find AirNet mass flows for non-venting situation (building leakage + last step HVAC air flows).
Find floating air temp in all zones / determine if vent possibly useful for any zone.
If vent useful
- find AirNet mass flows for full venting
- find largest vent fraction that does not sub-cool any zone; this fraction is then used for all zones.
- if largest vent fraction > 0, update all floating zone temperatures assuming that vent fraction

Determine HVAC requirements for all zones by comparing floating temp to setpoints (if any)
- System heating / cooling mode is determined by need of 1st zone that requires conditioning
- For each zone, system indicates state (t and w) of air that could be delivered at register (includes duct loss effects). Zone then requests air flow rate required to hold set-point temperature

Determine HVAC air flow to zones (may be less than requested); determine zone final zone air temperatures.
Determine system run fraction and thus fuel requirements.
Determine zone humidity ratio for each zone.
Calculate comfort metrics for each zone.

2.2 Updating Layered Mass Temperatures

The heat transfer through the layered constructions is assumed to be one dimensional. The heat conduction equation \( \frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t} \) is solved by using finite differences (\( \Delta t \) and \( \Delta x \)) to approximate the differential increments in time and distance; \( \alpha \) is the thermal diffusivity. The
smaller the finite increments, the more accurate the solution. The homogeneous layers are divided into lumps \( \Delta x \) thick, and the lumps are represented by the two-conductance/one-capacitance "T" circuits shown for each layer in Figure 2. Frequently the actual layer thicknesses as sufficiently thin that \( \Delta x \) can be taken as the layer thickness. However, at times the actual layer of homogeneous material must be divided into smaller thicknesses. See Section 2.4–Discretization Errors for the criterion used to determine \( \Delta x \) and \( \Delta t \).

The temperatures of the mass nodes are updated every time step using the Euler explicit numerical integration method (see Press et al), whereby the change in temperature of the mass during the time step is based only on the boundary conditions at the beginning of the time step. The boundary conditions are the temperatures of the surrounding nodes and other heat flow sources.

To update \( T_{i,1} \) in Figure 3, for example, if the rate of heat transfer into \( T_{i,1} \) is equated to its rate of change in internal energy, resulting in the differential equation for mass temperature \( T_{i,1} \):

\[
\frac{dT_{i,1}}{dt} = \frac{T_{SS_{i,1}} - T_{i,1}}{\tau}
\]

*Equation 3*

where \( T_{i,1} \) is the surface layer mass temperature, and \( T_{SS_{i,1}} \) is the temperature \( T_{i,1} \) would have if steady state were reached:

\[
T_{SS_{i,1}} = \frac{ccc_{i,1}Ta + crs_{i,1}Tr + Ubn_{i,1}T_{b2} + Qs_i'}{ccc_{i,1} + crs_{i,1} + Ubn_{i,1}}
\]

*Equation 4*

\( Qs_i' \) is given by Equation 1, \( ccc_{i,1} \) by Equation 2, \( T_{i,2} \) is the temperature of mass node 2, and \( \tau \) is the time constant of mass node 1 given by:

\[
\tau = \frac{cap_{i,1}}{ccc_{i,1} + crs_{i,1} + Ubn_{i,1}}
\]

*Equation 5*

The heat capacity of layer-1 is \( cap_{i,1} \) (Btu/ft\(^2\)-F). \( Ubn_{i,1} \) is the conductance between nodes 1 and 2, given by:

\[
Ubn_{i,1} = \frac{1}{\frac{1}{Uh_{i,1}} + \frac{1}{Uh_{i,2}}}
\]

*Equation 6*

To integrate of Equation 3 over a time step, the Euler procedure assumes that the right hand side of the equation remains constant over the time step at its value at the beginning of the time step. In this case the mass temperature at the end of the time step becomes:
\[
T_{i,1}(t + \Delta t) = T_{i,1}(t) \left(1 - \frac{\Delta t}{\tau}\right) + T_{ss}\left(\frac{\Delta t}{\tau}\right)
\]

Equation 7

If the capacitance of any layer is zero (a convecting air layer for example) its updated temperature is set equal to \(T_{ss}\). That is, the temperature at the central node is determined by a steady state energy balance.

All of the mass nodes are updated in an analogous fashion each time step. The order in which the masses are updated is irrelevant because they are updated based only on the values of variables at the beginning of the time step, not on the values that may have been updated since.

### 2.3 Zone Energy Balance

#### 2.3.1 Implicit Update of Air Temperature

Similar to the energy balance on the construction mass nodes, an energy balance on the air node gives the differential equation:

\[
\frac{dT_a}{dt} + \frac{T_a}{\tau_a} = \frac{T_{ss}}{\tau_a}
\]

Equation 8

where \(T_{ss}\), the asymptotic steady state temperature of \(T_a\), includes all the sources connected to \(T_a\). For simplicity, if the zone only contained the one construction \((i = 1)\) and one window \((j = 1)\), like in Figure 3, then from a steady state energy balance \(T_{ss}\) is given by:

\[
T_{ss} = [T_{out}(U_{inf} + U_v) + ccw_1 A_{win1} T_{out} + ccc_1 A_{con1} T_{1,1} + A_{con1} Q_{s1''} + A_{win1} Q_{sw1''} + Q_{int} * f_{intC} + Q_{hc} * f_{rConv} + CX * T_r] / U_{sum}
\]

Equation 9

where

\[
CX = CX_{air} + CX_{W1} + CX_{C1}
\]

Equation 10

\[
U_{sum} = U_{inf} + U_v + ccw_1 A_{win1} + ccc_1 A_{con1} + CX
\]

Equation 11

and the air time constant is:

\[
\tau_a = \frac{C_{air}}{U_{sum}}
\]

Equation 12
Equation 8 is solved using an full implicit (or backward time) difference, similar to the Euler explicit method except here the right hand side of the equation remains constant over the time step at its value at the end of the time step, not its value at the beginning as in the Euler method. Thus, Equation 8 then becomes:

\[
T_a(t + \Delta t) = \frac{T_a(t)\tau_a}{\Delta t} + Tss(t + \Delta t) + \frac{\tau_a}{\Delta t} + 1
\]

\textit{Equation 13}

Where the times \( t \) and \( t+\Delta t \) in parenthesis indicate the terms are evaluated at the beginning and end of the time step, respectively. Substituting Equation 12 for \( \tau_a \), Equation 13 can be put in the convenient form:

\[
T_a(t + \Delta t) = \frac{T_a(t)C_{air}}{\Delta t} + Usum * Tss(t + \Delta t) \]

\[
\frac{C_{air}}{\Delta t} + Usum
\]

\textit{Equation 14}

As this equation shows, with the implicit difference the effect of the air mass can be thought of as a resistance, \( \Delta t/C_{air} \), between the \( Ta \) node and a fictitious node set at the air temperature at the value it was at the beginning of the time step, \( TaL = Ta(t) \). This alternative is known as an 'associated discrete circuit'. Leaving out the explicit time references, Equation 14 can be written:

\[
Ta = \frac{TaL * C_{air}}{\Delta t} + Usum * Tss \]

\[
\frac{C_{air}}{\Delta t} + Usum
\]

\textit{Equation 15}

where \( Ta \) and \( Tss \) are evaluated at the end of the time step, and \( TaL \) stands for \( Ta(t) \) at the beginning of the time step. Note that Equation 15 still contains the variable \( Tr \) (hidden in \( Tss \)) which is unknown. \( Tr \) can be eliminated by making an energy balance on the \( Tr \) node and substituting the expression for \( Tr \) into Equation 15. This is done for the complete set of equations that follow.

\textbf{2.3.2 Zone Balance Equations}

The complete set of zone energy balance equations for multiple windows and constructions are given below. Terms containing \( Qv \) and \( Qhc \) are kept separate so that the resulting equations can be solved for \( Qv \) or \( Qhc \) when \( Ta \) is fixed at a setpoint.

\textbf{2.3.2.1 Air Node Balance}

The energy balance equation on the \( Ta \) node, comparable to Equation 15 above is:
\[ Ta = \frac{Q_v + Q_hc \cdot f rConv + Nair + CX \cdot Tr}{Dair + CX} \]

*Equation 16*

The Equation 16 form, using \( Q_v \), is used when heat is transferred to a conditioned zone with ventilation or infiltration air. When heat is transferred to an unconditioned zone due to ventilation or infiltration, \( Q_v \) is replaced by the essentially equivalent form given by Equation 17, wherein \( Q_v \) is replaced by \( Q_v = m_{C_p} \Delta T \) such that \( m_{dot} \cdot C_p \cdot T \) is added to the numerator and \( m_{dot} \cdot C_p \) is added to the denominator. This was implemented to eliminate oscillations in \( Ta \).

\[ Ta = \frac{ST + Q_hc \cdot f rConv + Nair + CX \cdot Tr}{SB + Dair + CX} \]

*Equation 17*

where,

\[ ST = \sum m_{dot} \cdot C_p \cdot T, \]

*Equation 18*

where \( T \) is the temperature of the air in the zone supplying the infiltration or ventilation air.

\[ SB = \sum m_{dot} \cdot C_p \]

*Equation 19*

\[ CX = CXair + \sum_{con} Acon \cdot cxc_i + \sum_{win} Awin_i \cdot cxw_i \]

*Equation 20*

with the sum's for all constructions and all windows respectively.

\[ Nair = T_a L \left( \frac{Cair}{dt} \right) + Qint \cdot fintC + \sum_{con} Acon \cdot \left( cc_i \cdot T_{ai} + \frac{Q_{si} \cdot hcl_i}{hcl_i + hr_i + U_{hi}} \right) + \sum_{win} Awin_i \left( ccw_i \cdot T_{ei} + I_j \cdot FP_j \right) \]

*Equation 21*

\[ Dair = \frac{Cair}{dt} + \sum_{con} Acon \cdot cc_i + \sum_{win} Awin_i \cdot ccw_i \]

*Equation 22*

\( Q_v \) is the heat transfer to the air node due to infiltration and forced or natural ventilation.
2.3.2.2 Radiant Node Balance

An energy balance on the $Tr$ node gives Equation 23.

$$\frac{Tr}{D_{rad} + CX} = \frac{Q_{hc} \cdot (1 - frConv) + N_{r}ad + CX \cdot Ta}{D_{rad} + CX}$$  \hspace{1cm} \text{Equation 23}

where,

$$N_{rad} = Q_{int} \cdot f_{int LW} + \sum_{i} A_{con_{i}} \left[ c_{rc_{i}} \cdot T_{i} + Q_{si_{i}} \cdot \frac{hr_{IC_{i}}}{h_{IC_{i}} + hr_{IC_{i}} + U_{h_{i}}} + \sum_{w} A_{win_{i}} \left[ c_{rw_{i}} \cdot T_{e_{o_{i}}} + I_{j} \cdot F_{M_{j}} \right] \right]$$  \hspace{1cm} \text{Equation 24}

$$D_{rad} = \sum_{i} A_{con_{i}} \cdot c_{rc_{i}} + \sum_{w} A_{win_{i}} \cdot c_{rw_{i}}$$  \hspace{1cm} \text{Equation 25}

2.3.2.3 Simultaneous Solution of $Ta$ and $Tr$ Equations

Equation 16 and Equation 23 can be solved simultaneously to eliminate $Tr$ and give $Ta$ explicitly:

$$Ta = \frac{(Q_{v} + Q_{hc} \cdot frConv + Nair)(D_{air} + D_{rad}) + CX(N_{rad} + Q_{hc}(1 - frConv))}{(D_{air} + D_{rad})CX + D_{air} \cdot D_{rad}}$$  \hspace{1cm} \text{Equation 26}

Similar to Equation 16 and Equation 17), the alternate form of Equation 26 is given by Equation 27.

$$Ta = \frac{(ST + Q_{hc} \cdot frConv + Nair)(D_{air} + D_{rad}) + CX(N_{rad} + Q_{hc}(1 - frConv))}{(SB + Dair + D_{rad})CX + (SB + Dair)D_{rad}}$$  \hspace{1cm} \text{Equation 27}

Substituting $Ta$ from Equation 26 into Equation 23 gives $Tr$.

2.3.2.4 $Q_{hc}$ and $Q_{v}$ Equations

When $Ta$ is at either the heating or cooling setpoints, Equation 26 is solved to determine the required $Q_{hc}$. In this case $Q_{v}$ is set to $Q_{v\text{Inf}}$.

$$Q_{hc} = \frac{Ta(Dair \cdot D_{rad} + CX(Dair + D_{rad})) - (Nair + Q_{v})(Dair + CX) - N_{rad} \cdot CX}{frConv \cdot D_{rad} + CX}$$  \hspace{1cm} \text{Equation 28}
Similarly, when \( T_a \) is at the ventilation setpoint, Equation 26 can be solved for \( Q_v \) to give:

\[
Q_v = \frac{(D_{air} \cdot D_{rad} + C X(D_{air} + D_{rad})) T_a - C X(N_{rad} + Q_{hc}(1 - f_{rad}))}{D_{rad} + C X} - (Q_{hc} \cdot f_{rad}) + N_{air}
\]

Equation 29

With \( Q_{hc} = 0 \) this becomes:

\[
Q_v = \frac{(D_{air} \cdot D_{rad} + C X(D_{air} + D_{rad})) T_a - N_{air}(D_{rad} + C X) - C X N_{rad}}{D_{rad} + C X}
\]

Equation 30

The zone balance is essentially an instantaneous balance, so all the temp inputs are simultaneous values from the end of the time step (with the exception of \( T_a \)L; see Section 2.3.1). Although the balance is with contemporary temperatures, many of the heat flows in \( N_{air} \) etc., are based on last time step conditions.

### 2.3.3 Thermostat Logic

At the end of each time step the program finds the floating temperature of the zone without HVAC (\( Q_{hc} = 0 \)) and with venting \( Q_v = Q_{vInf} \). This floating temperature found from Equation 26 is defined as TS1. Next, the venting capacity is determined (see Section 2.9.3.10, Heat Flow), and Equation 26 is solved for \( T_a \) at the full venting capacity. This \( T_a \) is defined as TS2.

TS1 will satisfy one of the four cases:

- \( TS1 > TC \)
- \( TC > TS1 > TD \)
- \( TD > TS1 > TH \)
- \( TH > TS1 \)

Similarly, TS2 will satisfy one of the four cases:

- \( TS2 > TC \)
- \( TC > TS2 > TD \)
- \( TD > TS2 > TH \)
- \( TH > TS2 \)

where TC, TD, and TH are the scheduled cooling, ventilation, and heating setpoints, with TC > TD > TH.

Based on the cases that TS1 and TS2 satisfy, nested logic statements determine the appropriate value of heating, cooling, venting, or floating.

For example, if TS1 and TS2 are both > TC, then \( Q_v \) is set \( Q_{vInf} \) and \( T_a \) is set to TC, and Equation 28 is solved for the required cooling, \( Q_{hc} \). If \( Q_{hc} \) is smaller than the cooling capacity at this time step then \( Q_{hc} \) is taken as the current cooling rate and the zone balance is finished and the
routine is exited. If Qhc is larger than the cooling capacity then Qhc is set to the cooling capacity, and Equation 26 is solved for Ta, floating above TC due to the limited cooling capacity. If Ta < TS2 then Ta and Qhc are correct and the zone balance routine is exited. If this Ta > TS2 then Ta is set equal to TS2, Qhc is set to zero, and Equation 29 is solved for the ventilation rate Qv, and the Zone Balance routine is complete.

Similar logic applies to all other logically possible combinations of the TS1 and TS2 cases above.

2.3.4 Limiting Capacities

The limiting capacity of the heating and cooling system is determined each time step by multiplying the scheduled nominal air handler input energy capacity by the duct system efficiency. To avoid iteration between the conditioned zone and unconditioned zone simulations, the duct system efficiency is taken from the last time-step’s unconditioned zone simulation, or unity if the system mode (heating, cooling, venting, or floating) has changed.

2.4 Discretization Errors

The temperatures predicted by Equation 7, which updates the layered mass temperatures, is subject to errors due to the finite lump size chosen to represent real wall homogeneous layers. It is also subject to errors due to the finite time step Δt. Similarly Equation 14 for updating the air mass temperature is subject to error due to the finite time step chosen.

Discretization errors can be made negligible by reducing the layer thicknesses and time step to very small values. However for practical run time minimization purposes it is useful to have large Δt and Δx layers, insofar as accuracy allows. The range of choices of Δt and Δx is narrowed if accurate results are only required for a limited range of frequencies of the driving boundary conditions. Only extremely thin lumped layers have the correct frequency response at high frequencies. To model environmental influences, 3 cycles/day (8-hr period sinusoid) is likely the highest frequency necessary to consider when determining the frequency response of buildings (Goldstein, Anderson and Subbarao). Higher frequencies may be desirable for accurately modeling things like control step changes. During the program development, accuracy was measured by analyzing the frequency response at 3 cycles/day.

The exact frequency response of a layered wall can be obtained using the matrix method (Section 3.7 of Carslaw & Jaeger) which gives the inside driving point admittance (from the inside air node), the outside driving point admittance, and the transfer admittance, for any frequency. The magnitude of the inside driving point admittance is the principle parameter used to assess algorithm accuracy.

At the frequency chosen, 3 cycles/day say, the exact driving point admittance of the real wall (with homogeneous layers) can be obtained from the matrix method. Similarly the exact driving point admittance of the lumped wall which the user has chosen to represent the real wall, can
also be determined by the matrix method. Comparing these two results shows the accuracy of the lumping assumptions, independent of time step considerations.

The time discretization error associated with Equation 7 at the frequency chosen can be assessed by comparing the driving point admittance predicted by the CSE code, when the air node is driven with a sinusoidal temperature at the chosen frequency, to the theoretical admittance of the lumped wall. Note that this procedure measures the global discretization error, larger potentially than the per time-step error.

Using this procedure for typical lightweight residential construction, we have confirmed that the errors in the temperature predictions made by the CSE finite difference algorithms indeed tend toward zero as Δt and Δx are reduced toward zero.

### 2.4.1 Layer Thickness of a Homogeneous Material

The lumped layer thickness, Δx, should be is chosen thin enough that the single temperature of the lumped layer is a good measure of the average temperature over a width Δx of the sinusoidal temperature distribution in the material. That is, the temperature of the sinusoidal wave should not vary much over the layer width. This criterion is similar to that used by Chirlian (1973) to determine the appropriate lump sizes in electrical circuits.

The wave length of the temperature distribution in a particular material is given by

$$\lambda = 2\pi d_p$$

_Equation 31_

where $d_p$, the penetration depth, an intrinsic characteristic of the material, is given by

$$d_p = \sqrt{\frac{2\alpha}{\omega}}$$

_Equation 32_

where the angular frequency $\omega = 2\pi/period$, $\alpha$ is the thermal diffusivity of the layer material, and $\omega$ is the highest angular frequency of the environmental boundary conditions for which good frequency response is desired. As a general guideline it is suggested that the lumped layer thicknesses, $\Delta x$, be chosen to be thinner than the penetration depth for the layer. That is, select

$$\Delta x \ll d_p$$

_Equation 33_

Substituting Equation 32 into Equation 33 shows that the rule of Equation 33 limits the lump size $\Delta x$ to about 16% of the wavelength:

$$\Delta x \ll dp = \lambda/2\pi = 0.16\lambda$$

_Equation 34_
The Equation 33 rule is more important for the modeling of layers on the inner side of the wall, where the layers are subjected to the higher frequency harmonics of inside driving conditions. Deeper into the wall the high frequency harmonics begin to be damped (by about a factor of $e^{-\frac{\Delta x}{d_p}}$), so accurate modeling is of less significance.

### 2.4.2 Choosing the Time Step

The time step used in the code is input by the user. For high accuracy Equation 7 and Equation 14 should be applied using a time step that is a small fraction of the smallest time constant of any layer.

$$\Delta t \ll \tau$$

**Equation 35**

Thin layers of a material have a smaller time constant $\tau$ than thick layers. The time constant of a layer scales as $\sim \beta^2$, where $\beta$ is the a layers dimensionless thickness defined as $\beta = \Delta x/d_p$. Thus, if a layers dimensionless thickness is reduced by a factor of two, the time constant is reduced by a factor of four. Therefore the time to run an annual simulation can increase rapidly for small $\beta$'s. Small tau layers have cv increased such that $\tau = dt$.

Note that the Euler mass layer update algorithm of Equation 7 becomes unstable when $\Delta t > \tau$. The predicted temperatures will oscillate with increasing amplitude each time step. The code outputs warnings whenever a mass node update is performed for which $\Delta t > \tau$.

Like the explicit Euler method, the implicit differencing used at the air node is most accurate for small time steps relative to the air's time constant (Equation 12). The implicit difference method is never unstable, and time steps larger than the air time constant give useful, if somewhat inaccurate predictions. The air balance could have been solved using an Euler difference, but since the air time constant is likely the smallest in the zone, it would dictate smaller time steps than is afforded using the implicit method.

### 2.5 Surface Heat Transfer Coefficients

The radiation coefficients for surfaces inside the conditioned zone are given in Section 2.6.1 where the long-wave radiant network model is discussed.

#### 2.5.1 Local Wind Velocity Terrain and Height Correction

The wind velocity as a function of height at the house site is obtained from the meteorological station wind measurement by making adjustments for terrain and height differences between the meteorological station and the house site.
2.5.1.1 Sherman-Grimsrud method

This method uses Equation 36 which determines the wind velocity \( V(z) \), in ft/sec, at any height \( z \) (ft) based on the wind velocity, \( V_{met} \) in ft/sec, measured at a location with a Class II terrain (see Table 1) and at a height of 10-meters (32.8 ft):

\[
V(z) = SC \times V_{met} \times \alpha \times \left( \frac{z}{32.8} \right)^{\gamma}
\]

\[ \text{Equation 36} \]

where,

- \( \alpha \) and \( \gamma \) are obtained from Table 1 for the terrain class at the building location.
- \( SC \) = shielding coefficient from Table 2 for the building location.
- \( V(z) \) = wind velocity at height \( z \) at the building location (ft/sec).
- \( V_{met} \) = wind velocity (ft/sec) measured at 10-meters height in a Class II location.

The terrain factor of Table 1 is a general factor describing the influence of the surroundings on a scale on the order of several miles. The shielding factor of Table 2 is a local factor describing the influence of the surroundings on a scale of a few hundred yards.

**Table 1: Parameters for Standard Terrain Classifications**

<table>
<thead>
<tr>
<th>Class</th>
<th>( \gamma )</th>
<th>( \alpha )</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.10</td>
<td>1.30</td>
<td>ocean or other body of water with at least 5km of unrestricted expanse</td>
</tr>
<tr>
<td>II</td>
<td>0.15</td>
<td>1.00</td>
<td>flat terrain with some isolated obstacles(buildings or trees well separated)</td>
</tr>
<tr>
<td>III</td>
<td>0.20</td>
<td>0.85</td>
<td>rural areas with low buildings, trees, etc.</td>
</tr>
<tr>
<td>IV</td>
<td>0.25</td>
<td>0.67</td>
<td>urban, industrial, or forest areas</td>
</tr>
<tr>
<td>V</td>
<td>0.35</td>
<td>0.47</td>
<td>center of large city</td>
</tr>
</tbody>
</table>

**Table 2: Local Shielding Parameters**

<table>
<thead>
<tr>
<th>Class</th>
<th>( C' )</th>
<th>SC</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.324</td>
<td>1.00</td>
<td>no obstructions or local shielding</td>
</tr>
<tr>
<td>II</td>
<td>0.285</td>
<td>0.880</td>
<td>light local shielding with few obstructions</td>
</tr>
<tr>
<td>III</td>
<td>0.240</td>
<td>0.741</td>
<td>moderate local shielding, some obstructions within two house heights</td>
</tr>
<tr>
<td>IV</td>
<td>0.185</td>
<td>0.571</td>
<td>heavy shielding, obstructions around most of the perimeter</td>
</tr>
<tr>
<td>V</td>
<td>0.102</td>
<td>0.315</td>
<td>very heavy shielding, large obstructions surrounding the perimeter within two house heights</td>
</tr>
</tbody>
</table>

2.5.1.2 Implementation

If it is assumed that the default value of the terrain classification at the building location is Class IV terrain of Table 1, and the default local shielding coefficient is \( SC = 0.571 \) of Class IV of Table 2, then the wind velocity at the building site at height \( z \) is given by:
\[ V(z) = SC \cdot V_{\text{met}} \cdot \alpha \left( \frac{z}{32.8} \right)^{0.25} = 0.571 \cdot V_{\text{met}} \cdot 0.67 \cdot \left( \frac{z}{32.8} \right)^{0.25} \]

or,
\[ V(z) = 0.16 \cdot z^{0.25} \cdot V_{\text{met}}\]

For example, for 1, 2, and 3 story buildings, of 9.8 ft (3-m), 19.7 ft (6-m), and 29.5 ft (9-m), respectively, then the local eave height wind velocities are:

- \[ V(9.8) = 0.16 \cdot 9.8^{0.25} \cdot V_{\text{met}} = 0.28 \cdot V_{\text{met}} \] for a 1-story building.
- \[ V(19.7) = 0.34 \cdot V_{\text{met}} \] for a 2-story building.
- \[ V(29.5) = 0.38 \cdot V_{\text{met}} \] for a 3-story building.


### 2.5.2 Convection Coefficient for the Inside and Outside Surfaces of the Zones

The schematic buildings in Figure 4 and Figure 5 show all of the possible interior heat transfer situations for which the convection heat transfer coefficients are determined. The figures symbolically show the nature of the heat transfer boundary layer, and the heat flow direction. The symbols used are explained at the end of this document. Similar schematics have not been done for the outside surfaces.

The equations are developed that give the heat transfer coefficient for each of the Figure 4 and Figure 5 situations, and for the building outside surfaces. The heat transfer coefficients depend on the surface tilt angle \( \theta \) (\( 0 \leq \theta \leq 90 \)), the surface and air temperatures, and on whether the heat flow of the surface has an upward or downward facing component.

The results, which apply to both the UZ and CZ zones, can be summarized as follows:

#### 2.5.2.1 Inside surfaces

- For floors, and either vertical walls, or walls pulled-in-at-the-bottom:
  - If \( T_{\text{air}} > T_{\text{surf}} \) use Equation 53. (heat flow down)
  - If \( T_{\text{air}} < T_{\text{surf}} \) use Equation 52. (heat flow up)

- For ceilings (horiz or tilted), and walls pulled-in-at-the-top:
  - If \( T_{\text{air}} > T_{\text{surf}} \) use Equation 52. (heat flow up)
  - If \( T_{\text{air}} < T_{\text{surf}} \) use Equation 53. (heat flow down)

#### 2.5.2.2 Outside surfaces

- For all vertical walls, and walls with moderate tilts use Equation 54.
For horizontal or tilted roof, use Equation 57.

**Figure 4: Heat Flow Down Situations**

Cold air below hot surface

\[ \theta = -x \]

Hot air above cold surface

\[ \theta = +x \]

**Figure 5: Heat Flow Up Situations**

Hot air below cold surface

\[ \theta = -x \]

Cold air above hot surface

\[ \theta = +x \]
2.5 Surface Heat Transfer Coefficients

Explanation of Symbols

- symbolizes the direction in which the boundary layer is thickening, and the direction of positive heat flow.

- symbolizes the air is stratified next to the surface and the direction the heat flow would be if there is any--the Figs. 1 eqns give zero heat flow in this case.

- na symbolizes the equations are n/a (not applicable) to the adjacent surface, because the surface doesn’t have an upward or downward facing component, as the case requires.

- symbolizes plumes of air buoyantly leaving the adjacent surface, and the direction of heat flow, due to Rayleigh-Benard instability.

2.5.2.3 Natural convection equations

Equation 37, from Churchill and Chu (see Eq. 4.86, Mills (1992)), is used to determine the natural convection coefficients for tilted surfaces. The choice of this equation is partly informed by the work of Wallenten (2001), which compares the Churchill and Chu equation with other correlations and experimental data.

Equation 37 is for turbulent convection ($10^9 < Ra < 10^{12}$), expected to be the dominant case in room heat transfer.

Equation 37 applies to either side of a tilted surface for angles ($0 \leq \theta \leq 88^\circ$) if the heat flow has a downward component, or the heat flow is horizontal.

Equation 37 also applies to either side of a tilted surface for angles $\theta < 60^\circ$ if the heat flow has an upward component, or the heat flow is horizontal.

$$Nu = 0.68 + 0.67(Ra \cdot \psi)^{0.25}(1 + 1.6 \times 10^{-8}Ra \cdot \psi)^{\frac{1}{12}}$$
where,

\[ Ra = \text{the Rayleigh number.} \]
\[ Nu = \text{the Nusselt number.} \]
\[ Pr = \text{the Prandtl number.} \]

\[ \psi = \left[ 1 + \left( \frac{0.492}{Pr} \right)^{16} \right]^{16} \]

Using \( \psi = 0.349 \) for \( Pr = 0.72 \), Equation 37 reduces to:

\[ Nu = 0.68 + 0.515 Ra^{0.25} (1 + 5.58 \times 10^{-9} Ra)^{1/12} \]

\textit{Equation 38}

For high \( Ra \) \( Ra \gg 10^9 \), neglecting the additive terms “1” and “0.68” in Equation 37 gives:

\[ Nu = 0.1057 Ra^{1/3} \]

\textit{Equation 39}

By the definition of the Nusselt number, the natural convection heat transfer coef, \( h_n \) is:

\[ h_n = Nu \times \frac{k(\text{air})}{L_{\text{char}}} \]

At 70°F, \( Ra = 1.66 \times 10^4 L^3 |\Delta T| \cos(\theta) \), and \( k = 0.0148 \), Equation 39 reduces to:

\[ h_n = 0.185 (|\Delta T| \cos(\theta))^{1/3} \]

\textit{Equation 40}

Note that \( h_n \) is independent of characteristic length \( L_{\text{char}} \).

\textit{Downward heat flow}

According to Mill’s(1992) Equation 37 doesn’t apply to downward heat flow for \( \theta > 88^\circ \). At 70 F, for a 20 ft characteristic length, the 0.68 term predicted by Equation 38 for \( \theta = 90^\circ \) corresponds to \( h_n = \frac{0.68k}{L} = 0.0005 \); essentially zero. Although the downward heat flow is ideally stably stratified (three cases shown in Figure 4\textbf{Error! Reference source not found.}), most measurements and modeling practice indicate \( h \) may be larger than zero. We use the equation of Clear et al. for the minimum, for heat flow down:

\[ Nu = 0.27 Ra^{0.25} \]

\textit{Equation 41}
Clear’s equation reduces to:

$$h_n = 0.27(0.0148)\left(\frac{4}{L}\right)\left(1.642E6\Delta T\left(\frac{L}{4}\right)^3\right)^{0.25}$$

or

$$h_n = 0.202\left[\frac{\Delta T}{L_{\text{char}}}\right]^{\frac{1}{2}}$$

*Equation 42*

where, $L_{\text{char}}$ is the wall characteristic length; see Equation 51 definitions.

Adding this $h$ to Equation 40 gives:

$$h_{\text{down}} = \text{MAX}\left[0.185\left(\left|\Delta T\right|\cos(\theta)\right)^{\frac{1}{3}}, 0.202\left[\frac{\Delta T}{L_{\text{char}}}\right]^{\frac{1}{2}}\right] \quad 0 \leq \theta \leq 90$$

*Equation 43*

The following simplification is made, where the exponent of the second term is changed to $1/3$, so that $|\Delta T|^{1/3}$ can be factored out:

$$h_{\text{down}} = |\Delta T|^{1/3}\text{MAX}\left[0.185\left(\cos(\theta)\right)^{\frac{1}{3}}, 0.202L_{\text{char}}^{-\frac{1}{3}}\right] \quad 0 \leq \theta \leq 90$$

*Equation 44*

Changing the exponent means Equation 44 gives same answer as Equation 43 only when $\frac{\Delta T}{L_{\text{char}}} = 1$. But Equation 44 would have acceptable error for other $\frac{\Delta T}{L_{\text{char}}}$ ratios, and gives more or less the right dependence on $\Delta T$. If in addition, one assumes a typical $L_{\text{char}} = 15$, say, then the minimum term becomes: $0.202L_{\text{char}}^{-\frac{1}{3}} = 0.08$, giving the final reasonable form:

$$h_{\text{down}} = |\Delta T|^{1/3}\text{MAX}\left[0.185\left(\cos(\theta)\right)^{\frac{1}{3}}, 0.08\right] \quad 0 \leq \theta \leq 90$$

*Equation 45*

**Upward heat flow for $\theta \leq 60^\circ$**

For the inside & outside of walls where the heat flow has an upward (or horizontal heat flow at the limit $\theta = 0^\circ$), and the outside of roofs, Equation 40 applies:

$$h_n = 0.185\left(|\Delta T|\cos(\theta)\right)^{1/3}$$

**Upward heat flow for $\theta > 60^\circ$**

To handle cases of upward heat flow for $\theta > 60^\circ$, $h_{\text{up}}$ is found by interpolating between Equation 40, evaluated at $\theta = 60^\circ$, and Equation 47 at $90^\circ$. Equation 46, for heat transfer from a
horizontal surface ($\theta = 90^\circ$), is from Clear et al. (Eq. 11a). It is close to the much used McAdams equation suggested by both the Mills (1992) and Incropera-Dewitt textbooks.

$$Nu = 0.15Ra^{1/3}$$

*Equation 46*

At 70-F, Equation 46 reduces to

$$h_r = 0.26(\Delta T)^{1/3}$$

*Equation 47*

Interpolating, for upward heat flow cases with $\theta \geq 60^\circ$:

$$h_{up} = 0.185(\Delta T \cos(60))^ {1/3} + \frac{\left(0.26(\Delta T)^{1/3} - 0.185(\Delta T \cos(60))^{1/3}\right)(\theta - 60)}{30}$$

which reduces to:

$$h_{up} = (0.00377 * \theta - 0.079)|\Delta T|^{1/3} \quad \text{for } 60^\circ \leq \theta \leq 90$$

*Equation 48*

where $\theta$ is in degrees.

### 2.5.2.4 Inside forced convection equation

Measured forced convection heat transfer coefficients are frequently correlated using an equation of the form

$$h_{ach} = h_{forcedIN} = C_{ach} \times ACH^{0.8}$$

*Equation 49*

The RBH model (Barnaby et al. (2004) suggests using $h_r = 0.88$ Btu/hr-ft$^2$F at ACH = 8. This gives $C_{ach} = 0.167$. Walton (1983) assumes $h = 1.08$ when the “air handler system is moving air through the zone.” If this was at 8 ach, then this implies $C_{ach} = 0.205$.

### 2.5.2.5 Outside forced convection equation for all walls and all roofs

From Clear et al. (2001, Eq. (11a)),

$$Nu = W_f R_f 0.037Re^{0.8} Pr^{1/3}$$

*Equation 50*

Clear et al. used the Reynolds number based on a free-stream wind velocity 26.2 ft (8 m) above the ground.

At 70F, Equation 50 reduces to:
where for walls,

\[ L = \text{wall char} = 4 \frac{\text{Wall Area}}{\text{Wall Perimeter}} (= 4 \frac{\text{Height} \times \text{Width}}{2(\text{Height} + \text{width})} \approx \text{height of square wall} = Z_{eave}) \]

\[ V = \text{wind velocity at eave height at building location, in ft/sec} = 0.16 \times Z_{eave}^{0.25} \times V_{met} \text{ from Section 2.5.1.2.} \]

\[ V_{met} = \text{freestream wind velocity, in ft/sec, 10 m (32.8 ft) above the ground at the meteorological station site.} \]

\[ R_f = \text{Table 3 value.} \]

\[ W_f = 0.63 \]

The wind direction multiplier, \( W_f \), is defined as the average \( h \) of all of the vertical walls, divided by the \( h \) of the windward wall, with this ratio averaged over all wind directions. We estimated \( W_f \) using the CFD and wind tunnel data of Blocken et al. (2009) for a cubical house. Blocken’s Table 6 gives a windward surface convection coefficient of \( h_c \approx 4.7V^{0.84} \) (SI units), averaged over wind direction. Blocken’s Figure 9 gives \( \bar{h}_c \approx 7.5 \) averaged over all vertical surfaces, for wind speed \( V_{met} = 3\text{-m/s}. \) Thus, we estimate \( W_f = \frac{7.5}{4.7V^{0.84}} = 0.63. \)

and for roofs,

\[ L = \text{roof char} = 4 \frac{\text{Roof Plan Area}}{\text{Roof Perimeter}} (= 4 \frac{\text{Length} \times \text{Width}}{2(\text{Length} + \text{width})} \approx \sqrt{\text{Roof Area}} \text{ for square roof} \approx Z_{eave}) \]

\[ V = \text{wind velocity 9.8 ft (3 m) above the eave height at building location, in ft/sec.} \]

\[ = 0.16 \times (Z_{eave} + 9.8)^{0.25} \times V_{met} \]

\[ W_f = 1 \]

\[ R_f = \text{Table 3 value.} \]

Walton (1983) assumed that the ASHRAE roughness factors of Table 3 apply to the convection coefficient correlations. The Clear et al. (2001) experiments tend to confirm the validity of these factors. Blocken et al. (2009) says, “The building facade has been assumed to be perfectly smooth. Earlier experimental studies have shown the importance of small-scale surface roughness on convective heat transfer. For example, Rowley et al. found that the forced convection coefficient for stucco was almost twice that for glass. Other studies showed the important influence of larger-scale surface roughness, such as the presence of mullions in glazed areas or architectural details on the facade, on the convection coefficient.”
2.5.2.6 Inside combined natural and forced convection

The combined convection coefficient is assumed to be the direct sum of the natural and forced convection coefficients:

For upward and horizontal heat flow:

\[ h_{combined} = h_{up} + h_{ach} \]

Equation 52

where,

\[ h_{up} = \text{Equation 40 or Equation 48 depending on whether } \theta \text{ is } < \text{ or } > 60^\circ. \]
\[ h_{ach} = \text{Equation 49} \]

For downward heat flow:

\[ h_{combined} = h_{down} + h_{ach} \]

Equation 53

where,

\[ h_{down} = \text{Equation 45} \]
\[ h_{ach} = \text{Equation 49} \]

2.5.2.7 Outside combined natural and forced convection

The conclusion of Clear et al. (2001) is that the combined convection coefficient is best correlated by assuming it to be the sum of the natural and forced coefficients. For roofs, Clear et al. (2001) assumes that the natural and forced convection are additive, but that natural convection is suppressed by the factor \( \eta \) given by Equation 56 when forced convection is large (\( \eta \rightarrow 0 \) as the

---

Table 3: Surface Roughness Parameter \( R_f \) (Walton 1981)

<table>
<thead>
<tr>
<th>Roughness Index</th>
<th>( R_f )</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (very rough)</td>
<td>2.1</td>
<td>Stucco</td>
</tr>
<tr>
<td>2 (rough)</td>
<td>1.67</td>
<td>Brick</td>
</tr>
<tr>
<td>3 (medium rough)</td>
<td>1.52</td>
<td>Concrete</td>
</tr>
<tr>
<td>4 (Medium smooth)</td>
<td>1.13</td>
<td>Clear pine</td>
</tr>
<tr>
<td>5 (Smooth)</td>
<td>1.11</td>
<td>Smooth plaster</td>
</tr>
<tr>
<td>6 (Very Smooth)</td>
<td>1</td>
<td>Glass</td>
</tr>
</tbody>
</table>
Reynolds number becomes large). We also assume this attenuation of the natural convection applies to the outside of the walls.

For all vertical walls, and walls with moderate tilts:

\[ h_{combined} = \eta h_n + h_V \]

*Equation 54*

where,

\[ h_n = \text{Equation 40} \]

\[ h_V = \text{Equation 51} \]

\[ \eta = \frac{1}{1 + \frac{1}{\ln\left(1 + \frac{0.06L|\Delta T|}{V^2}\right)}} \]

(to avoid divide by zero, if \( V = 0 \), could set to \( V = 0.001 \))

where \( L \) \& \( V \) are the same as used in Equation 51 for walls.

For roofs, Clear et al. (2001) assumes that the natural and forced convection are additive, but that natural convection is suppressed by the factor \( \eta \) when forced convection is large (\( \eta \rightarrow 0 \) as the Reynolds number becomes large). Clear gives \( \eta \) as:

\[ \eta = \frac{1}{1 + \frac{1}{\ln\left(1 + \frac{Gr_L}{Re_L^2}\right)}} \]

*Equation 55*

At 70F, with \( Gr = 2.28 \times 10^6 L^3 |\Delta T| \), \( Re^2 = (6140VL)^2 \), and \( L = L_{char} \) for surface, Equation 55 reduces to:

\[ \eta = \frac{1}{1 + \frac{1}{\ln\left(1 + \frac{0.06L|\Delta T|}{V^2}\right)}} \]

*Equation 56*

For roofs:

\[ h_{combined} = \eta h_n + h_V \]

*Equation 57*

where,

\[ h_n = \text{Equation 45 for downward heat flow.} \]

\[ h_n = \text{Equation 47 for upward heat flow.} \]

\[ h_V = \text{Equation 51 for upward or downward heat flow.} \]
\( \eta \) is from Equation 56

\( L \) & \( V \) are the same as used in Equation 51 for roofs.

2.5.2.8 Plots of equations

In Figure 6, the left hand column of plots are of Equation 53, for the downward heat flow cases shown in Figure 4. The right hand side plots are of Equation 52, for upward heat flow cases of Figure 5. All of the plots assume \( T_{film} = 70^\circ F \), and \( L_{char} = Z_{eave} = 20 \) ft.

**Figure 6: Plots of Equations for Downward and Upward Heat Flow**

**DOWNWARD HEAT FLOW (Equation 53):**

**UPWARD HEAT FLOW (Equation 52):**
OUTSIDE surface convection coefficient Plot for a horizontal roof:

For $\Delta T = 50\, F$, $L_{\text{char}} = 20\, \text{ft}$, $R_f = 1.67$:

Figure 7: Outside Convection Coefficients, Natural Up and Down, and Forced

2.5.3 Outside Radiation Coefficients

2.5.3.1 Wall surfaces

The net long wave radiation heat exchange between the outside surface and the environment is dependent on surface temperature, the spatial relationship between the surface and the surroundings, and the properties of the surface. The relevant material properties of the surface, emissivity $\varepsilon$ and absorptivity $\alpha$, are complex functions of temperature, angle, and wavelength. However, it is generally assumed in building energy calculations that the surface emits or reflects diffusely and is gray and opaque ($\alpha = \varepsilon$, $\tau = 0$, $\rho = 1 - \varepsilon$).
The net radiant heat loss from a unit area of the outside of a construction surface to the outside environment is given by:

\[ q_{rad} = \varepsilon g F_{gnd}(T_s^4 - T_g^4) + \varepsilon \sigma F_{sky}\beta (T_s^4 - T_{sky}^4) + \varepsilon \sigma F_{sky}(1 - \beta)(T_s^4 - T_a^4) \]

Equation 58

where,

\( \varepsilon = \) surface emissivity.

\( \varepsilon_g = \) ground emissivity is assumed to be 1.

\( \sigma = \) Stephan-Boltzmann constant.

\( T_s = \) outside surface temperature.

\( T_a = \) outside dry bulb temperature.

\( T_g = \) ground surface temperature.

\( T_{sky} = \) effective temperature of sky.

\( F_{gnd} = \) view factor from surface to ground.

\( F_{sky} = \) view factor from surface to sky.

\( \beta = \cos \left( \frac{\phi}{2} \right) \)

The sky irradiance is taken as a \( \beta \) weighted average of that from \( T_{sky} \) and that from \( T_a \).

2.5.3.2 \( F_{sky}, F_{gnd}, \) and \( \beta \)

Howell (1982, #C-8, p.94), gives the fraction of the radiation leaving the window surface and reaching the sky by:

\[ F_{sky} = \frac{1 + \cos \phi}{2} \]

The fraction leaving the window incident on the ground is:

\[ F_{gnd} = \frac{1 - \cos \phi}{2} \]

where, \( \phi = \) surface tilt angle, the angle between ground upward normal and window outward normal \((0^o \text{ corresponds to a horizontal skylight, } 90^o \text{ to a vertical surface})\).

The parameter \( \beta \) accounts for the sky temperature’s approach to the air temp near the horizon. \( \beta \) is the fraction of the sky effectively at \( T_{sky} \); \((1-\beta)\) is the fraction of the sky effectively at \( T_a \). \( \beta \) is used by Walton (1983), and Energy Plus (2009), but appears to have little theoretical or experimental basis.

Walton (1983) give \( \beta \) as:
\[ \beta = \cos\left(\frac{\phi}{2}\right) \]

Since \( \cos\left(\frac{\phi}{2}\right) = \frac{1 + \cos\phi}{2} \), it is noted that \( F_{sky} = \beta^2 \), and \( F_{sky}\beta = \beta^3 \).

### 2.5.3.3 Net radiant heat loss from a unit area

Equation 58 can be written as

\[ q_{rad} = h_{rg}(T_s - T_g) + h_{rsky}(T_s - T_{sky}) + h_{rair}(T_s - T_a) \]

\[ \text{Equation 59} \]

where,

\[ h_{rg} = \varepsilon\sigma F_{gnd}(T_s^2 + T_g^2)(T_s + T_g) \]

\[ h_{rsky} = \varepsilon\sigma F_{sky}\beta(T_s^2 + T_{sky}^2)(T_s + T_{sky}) \]

\[ h_{rair} = \varepsilon\sigma F_{sky}(1 - \beta)(T_s^2 + T_a^2)(T_s + T_a). \]

\( T_g \) is assumed to be equal to \( T_a \), so Equation 59 becomes

\[ q_{rad} = h_{rsky}(T_s - T_{sky}) + h_{rair}(T_s - T_a) \]

\[ \text{Equation 60} \]

where,

\[ h_{rsky} = \varepsilon\sigma F_{sky}\beta(T_s^2 + T_{sky}^2)(T_s + T_{sky}) \]

\[ \text{Equation 61} \]

\[ h_{rair} = \varepsilon\sigma(F_{sky}(1 - \beta) + F_{gnd})(T_s^2 + T_a^2)(T_s + T_a) \]

\[ \text{Equation 62} \]

For a vertical surface, \( F_{sky}\beta = 0.354 \), and \( F_{sky}(1 - \beta) + F_{gnd} = 0.646 \), so

\[ h_{rsky} = 0.354\varepsilon\sigma(T_s^2 + T_{sky}^2)(T_s + T_{sky}) \approx 4(0.354)\varepsilon\sigma T^3 \]

\[ h_{rair} = (0.146 + 0.5)\varepsilon\sigma(T_s^2 + T_a^2)(T_s + T_a) \approx 4(0.646)\varepsilon\sigma T^3 \]

### 2.5.3.4 Total effective conductance and outside effective temperature, \( T_{env} \), for walls

Adding the exterior convection coefficient, \( h_{co} \), of Equation 40 to Equation 60 gives the total net heat transfer from the outside surface:

\[ q_{rad+conv} = h_{rsky}(T_s - T_{sky}) + (h_{rair} + h_{co})(T_s - T_a) \]

\[ \text{Equation 63} \]
This can be written as,

\[ q_{rad+conv} = h_o(T_s - T_{env}) \]

Equation 64

where \( h_o \) is the effective exterior conductance to the conductance weighted average temperature, \( T_{env} \).

\[ h_o = h_{rsky} + h_{rair} + h_{co} \]

Equation 65

\[ T_{env} = \frac{h_{rsky}T_{sky} + (h_{rair} + h_{co})T_a}{h_{rsky} + h_{rair} + h_{co}} \]

Equation 66

2.5.3.5 Outside window surfaces

The ASHWAT window algorithm of Section 2.7 utilizes the irradiation intercepted by the window. From Equation 58 this can be deduced to be:

\[ G = F_{gnd} \sigma T_{gnd}^4 + F_{sky} \beta \sigma T_{sky}^4 + F_{sky}(1 - \beta)\sigma T_{air}^4 \]

Equation 67

2.5.4 Sky Temperature

It is possible to approximate the long wave radiation emission from the sky as a fraction of blackbody radiation corresponding to the temperature of the air near the ground. The sky emittance \( \varepsilon_{sky} \) is defined such that the sky irradiation on a horizontal surface is \( \sigma \varepsilon_{sky} T_a^4 \).

The effective temperature of the sky is obtained by equating the blackbody emissive power of the sky at \( T_{sky} \), to the sky irradiation:

\[ \sigma T_{sky}^4 = \sigma \varepsilon_{sky} T_a^4 \]

or,

\[ T_{sky} = \varepsilon_{sky}^{0.25} T_a \]

Equation 68

where \( T_{sky} \) and \( T_a \) are in degrees Rankine.

The value of \( \varepsilon_{sky} \) depends on the dewpoint temperature, cloud cover, and cloud height data. Martin and Berdahl (1984) give the \( \varepsilon_{sky} \) for clear skies as \( \varepsilon_o \):
\[ \varepsilon_o = 0.711 + 0.56 \frac{T_{dew}}{100} + 0.73 \left( \frac{T_{dew}}{100} \right)^2 + 0.013 \cos \left( \frac{\pi \ hr}{12} \right) + 0.00012 \left( P_{atm} - 1000 \right) \]

where,

- \( T_{dew} \) = the dewpoint temperature in Celsius.
- \( hr \) = hour of day (1 to 24).
- \( P_{atm} \) = atmospheric pressure in millibars.

### 2.5.4.1 Palmiter version of Martin-Berdahl model

The clear sky emissivity is corrected to account for cloud cover by the following algorithm, developed by Larry Palmiter (with Berdahl’s imprimatur), that represents the Martin and Berdahl model when weather tape values of cloud ceiling height, and total and opaque cloud fractions are available.

\[ \varepsilon_{sky} = \varepsilon_0 + (1 - \varepsilon_0) (n_{op} \varepsilon_{op} \Gamma_{op} + n_{th} \varepsilon_{th} \Gamma_{th}) \]

where,

- \( n_{op} \) = the opaque cloud fraction
- \( n_{th} \) = the thin cloud fraction: \( n_{th} = n - n_{op} \)
- \( n \) = the total sky cover fraction
- \( \varepsilon_{op} \) = the opaque cloud emittance is assumed to be 1.
- \( \varepsilon_{th} \) = the thin cloud emittance; assumed to be 0.4.

The cloud factor \( \Gamma \) is used to adjust the emissivity when the sky is cloudy due to the increasing cloud base temperature for decreasing cloud altitudes. The cloud base temperature is not available on the weather tapes, so assuming a standard lapse rate of 5.6°C/km, \( \Gamma \) is correlated with the more commonly measured cloud ceiling height, \( h \) (in meters), giving by the general expression:

\[ \Gamma = e^{-\frac{h}{8200}} \]

For thin clouds, \( \Gamma_{th} \) is determined using an assumed cloud height of 8000-m, so,

\[ \Gamma_{th} = e^{-\frac{8000}{8200}} = 0.377 \]

For opaque clouds,
\[
\Gamma_{op} = e^{-\frac{h}{2000}}
\]

Equation 72

If ceiling height data is missing (coded 99999 on TMY2), the Palmiter model assumes that the opaque cloud base is at \( h = 2000 \) m. If ceiling height is unlimited (coded as 77777) or cirroform (coded 88888), it is assumed that the opaque cloud base is at \( h = 8000 \) m.

Using the assumed cloud cover and emissivity factors, Equation 70 becomes:

\[
\epsilon_{sky} = \epsilon_0 + (1 - \epsilon_0)[n_o\Gamma_{op} + (n - n_o) * 0.4 * 0.377]
\]

or,

\[
\epsilon_{sky} = \epsilon_0 + (1 - \epsilon_0)\left[n_oe^{-\frac{h}{2000}} + 0.151(n - n_o)\right]
\]

Equation 73

2.5.4.2 When opaque cloud cover data, \( n_o \), is missing

In this case it is assumed that the cloud cover is opaque, \( n_o = n \), when the ceiling height is less than 8000 m, and half opaque, \( n_o = \frac{n}{2} \), when the ceiling height is equal or greater than 8000.

That is,

for \( h < 8000 \) m (from Equation 73 with \( n_o = n \)):

\[
\epsilon_{sky} = \epsilon_0 + (1 - \epsilon_0)n e^{-\frac{h}{2000}}
\]

Equation 74

For \( h \geq 8000 \) m (from Equation 73 with \( n_{op} = n_{th} = \frac{n}{2} \)):

\[
\epsilon_{sky} = \epsilon_0 + (1 - \epsilon_0)n\left[\frac{1}{2} e^{-\frac{h}{2000}} + 0.0754\right]
\]

Equation 75

2.5.4.3 When both opaque cloud cover and ceiling height data is missing

When only total sky cover is available using an \( h \) of 2000-m reduces Equation 74 to:

\[
\epsilon_{sky} = \epsilon_0 + 0.784(1 - \epsilon_0)n
\]

Equation 76
2.6 Distribution of SW and LW Radiation inside the Zone

2.6.1 Long Wave Radiation Distribution

2.6.1.1 Carroll model

The radiant model used in CSE is based on the “MRT Network Method” developed by Joe Carroll (see Carroll 1980 & 1981, and Carroll & Clinton 1980 & 1982). It was chosen because it doesn’t require standard engineering view factors to be calculated, and yet gives a relatively accurate radiant heat distribution for typical building enclosures (see Carroll 1981).

It is an approximate model that simplifies the “exact” network (see Appendix C) by using a mean radiant temperature node, $T_r$, that act as a clearinghouse for the radiation heat exchange between surfaces, much as does the single air temperature node for the simple convective heat transfer models. For n surfaces this reduces the number of circuit elements from $(n-1)!$ in the exact case, to n with the Carroll model.

For black surfaces the radiant network is shown in Figure 8. For n surfaces, $T_r$ floats at the conductance, $A_i F_i$, weighted average surface temperature:

$$T_r = \frac{\sum^n_i A_i F_i T_i}{\sum^n_i A_i F_i}$$

*Equation 77*

The actual areas, $A_i$, need not be equal, nor limited to three.

*Figure 8: Carroll Network for Black Surfaces*
The factor $F_i$, in the radiant conductance between the $T_i$ surface node and the $T_r$ node is Carroll's "MRT view factor", that corrects for the self-weighting (see Appendix D) of $T_i$ in the temperature $T_r$. The $F_i$ factors are obtained from the set of $n$ nonlinear equations for $n$ surfaces:

$$F_i = \frac{1}{1 - \sum_{j=1}^{n} A_j F_j}$$

*Equation 78*

Given the surface areas, these equations are easily solved at the beginning of the simulation by successive substitution, starting with all $F_i = 1$. This converges for realistic enclosures, but won’t necessarily converge for enclosures having only two or three surfaces, particularly if there are large area disparities.

$F_i$ is always larger than 1 because it’s role is to raise the conductance between $T_r$ and $T_i$ to compensate for the potential difference $|T_r - T_i|$ being smaller than it would be had $T_i$ not been part of the conductance weighted average $T_r$. The $F_i$ values can be seen to be close to 1, since

Equation 78 is roughly approximated by $F_i \approx 1 + (A_i/A_{all\,surfaces})$.

The net radiant heat transfer [Btu/hr] from surface $i$ is:

$$q_i = h_b A_i F_i (T_i - T_r)$$

*Equation 79*

Using a Y-$\Delta$ transformation, the Figure 8 circuit can put in the form of the exact solution network of Figure C-1 in Appendix C, showing the implicit view factors $F_{ij}$ to be:

$$F_{ij} = \frac{F_i A_j F_j}{\sum_{k=1}^{n} A_k F_k}$$

*Equation 80*

Thus the implicit view factors are independent of the relative spacial disposition of the surfaces, and almost directly proportional to the surface area $A_j$ of the viewed by surface $i$. Also, without special adjustments (see Carroll (1980a)), all surfaces see each other, so coplanar surfaces (a window and the wall it is in) radiate to each other.

Equation 79 is exact (i.e., gives same answers as the Appendix C model) for cubical rooms; for which

Equation 78 gives $F_i = 1.20$. Substituting this into Equation 80 gives the implied $F_{ij} = 0.2$. This is the correct $F_{ij}$ for cubes using view-factor equations Howell(1982). It is likely accurate for all of the regular polyhedra.
Grey surfaces

Carroll’s model handles gray surfaces, with emissivities $\varepsilon_i$, by adding the Oppenheim surface conductance $\frac{A_i \varepsilon_i}{1 - \varepsilon_i}$ in series with the conductances $h_b A_i F_i$. As shown in Figure 9, the conductance between $T_i$ and $T_r$ becomes $h_b A_i F_i'$, where the $F_i'$ terms are:

$$F_i' = \frac{1}{\frac{1}{F_i} + \frac{1 - \varepsilon_i}{\varepsilon_i}}$$

*Equation 81*

The net radiant heat transfer [Btu/hr] from surface $i$ is given by:

$$q_i = h_b A_i F_i' (T_i - T_r)$$

*Equation 82*

where for grey surfaces $T_r$ is the "$h_b A_i F_i'$" weighted average surface temperature given by:

$$T_r = \frac{\sum_i A_i F_i' T_i}{\sum_i A_i F_i'}$$

*Equation 83*

Similar to Equation 77 for a black enclosure, Equation 83 shows that $T_r$ for grey surfaces is the conductance, $A_i F_i'$, weighted average surface temperatures.

The role of $F_i$ hasn’t changed, but since the conductance $A_i F_i$ is now connected to the radiosity node rather than the surface node, $E_r (= \sigma T_r^4)$ can be thought of as the $A_i F_i$-weighted average radiosity of the surfaces, rather than the $A_i F_i$-weighted average emissive power of the surfaces as in the black enclosure case.

*Figure 9: Carroll Radiant Network for Grey Surfaces*
This completes the description of the basic Carroll model. The principle inputs are the interior surface areas in the zone, the emissivities of these surfaces, and the typical volume to surface area ratio of the zone (see Section 2.6.1.3). All of the interior surfaces, including ducts, windows, and interior walls, are assumed to exchange heat between each other as diffusely radiating gray body surfaces.

Longwave radiant internal gains can be added, in Btu/hr, to the radiant node Tr. This distributes the gains in proportion to the conductance $A_iF_i'$. 

**Conversion to delta**

Using a Y-$\Delta$ transformation, the radiant network of Figure 9 can be converted to the Appendix C, Figure C-3 circuit form, eliciting the $F_{ij}'$ interchange factors implicit in Carroll’s algorithm. Similar in form to Equation 80,

$$A_iF_{ij}' = \frac{A_iF_i'A_jF_j'}{\sum_{k=1}^{n} A_kF_k'}$$

*Equation 84*

Using these $A_iF_{ij}'$ values, $q_{ij}$ can be obtained from

$$q_{ij} = h_bA_iF_{ij}'(T_i - T_j)$$

*Equation 85*

The total net heat transfer from surface $i$ (i.e., the radiosity minus the irradiation for the un-linearized circuit) is given by summing Equation 85 for all the surfaces seen by surface $i$:

$$q_i = \sum_{j=1}^{n} h_bA_iF_{ij}'(T_i - T_j)$$

*Equation 86*

which will agree with the result of Equation 82.

**2.6.1.2 Accuracy of Carroll model**

The Carroll model of Figure 9 is exact for cubical enclosures with arbitrary surface emissivities. It is surprisingly accurate for a wide variety of shapes, such as hip roof attics and geodesic domes.

Carroll (1981) compared his model, and other simplified models, with the exact solution for the enclosure shown in Figure 10. Half the south wall and half of the west wall are glass with $\varepsilon = 0.84$, and the rest of the interior surfaces have $\varepsilon = 0.9$. 
Comparisons were made primarily regarding three types of errors:

**Heat balance errors**

The first law requires that the sum of the net radiation emitted by each of the surfaces, plus any internal gain source of long-wave radiation, must equal zero. That is, \( q_{\text{int}} + \sum_{i=1}^{n} q_i = 0 \).

Due to their fixed conductance circuits, both the Carroll method and the Walton (1983) method are inherently free of heat balance errors. Carroll found BLAST and NBSLD algorithms to have rms heat balance errors of 9.8% (12%) and 1.7% (3.4%) for the Figure 10 enclosure.

**Individual surface net heat transfer errors**

For a given enclosure, these are errors in an individual surfaces net heat flow, \( q_i \), compared to the exact method. For Carroll’s method, this finds the error in \( q_i \) determined from the \( A_i F'_{ij} \) values of Equation 84, compared to the \( q_i \) values found using the exact \( A_i F'_{ij} \) values (obtainable from Figure C-3 of Appendix C).

Carroll found the % rms error in the \( q_i \) values for a given enclosure in two different ways.

The first method, Equation 87, gives the rms error of \( q_i \) for each surface divided by the rms of the \( n \) net heat transfers from each surface:

\[
Err = \left( \frac{1}{n} \sum_{i=1}^{n} \frac{\Delta q_i^2}{\bar{q}_i^2} \right)^{\frac{1}{2}} \times 100
\]

Equation 87

where

\( \Delta q_i = q_i - \bar{q}_i \), is the error in \( q_i \).
\[ q_i = \sum_{j=1}^{n} h_i A_i F_{ij}'(T_i - T_j), \text{ using } F_{ij}' \text{ values from Carroll's model, Equation 87.} \]

\[ \bar{q}_i = \sum_{j=1}^{n} h_i A_i F_{ij}'(T_i - T_j), \text{ using the exact } F_{ij}' \text{ values of Figure C-3 of Appendix C} \]

\[ T_i - T_j = 1^\circ F \text{ assumed in all cases.} \]

\[ n = \text{the number of surfaces} \]

The second method, Equation 88, gives the rms of the percentage error in \( q_i \) of each surfaces. This method increases the weight of smaller surfaces such as windows.

\[ Err = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{\Delta q_i}{q_i} \right)^2 \times 100 \]

\textit{Equation 88}

Results

For the enclosure of Figure 10, Carroll found his method gives \( Err = 0.11\% \) for the first method and 0.19\% for the second method.

These results are shown in Table 4, along with the results for other shape enclosures, and the errors determined by Carroll using the radiant interchange algorithms of Walton (1980) and NBSLD and BLAST simplified models.

\textit{Table 4: Err = \% rms Error in } q_i \textit{ from Equation 87 and Equation 88 in Parenthesis}

<table>
<thead>
<tr>
<th></th>
<th>Figure 10 room</th>
<th>Corridor</th>
<th>Warehouse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.5:4:6</td>
<td>10:1:1</td>
<td>10:10:1</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>0.9 (.84 wdws)</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Carroll</td>
<td>0.11 (0.19)</td>
<td>0.06(0.05)</td>
<td>0.07 (0.04)</td>
</tr>
<tr>
<td>Walton(1980)</td>
<td>1.9 (1.30)</td>
<td>0.6 (0.6)</td>
<td>4.4 (3.0)</td>
</tr>
<tr>
<td>NBSLD, BLAST</td>
<td>3.2 (2.1)</td>
<td>3.2 (2.6)</td>
<td>7.5 (4.4)</td>
</tr>
</tbody>
</table>

Errors in an individual surface's distribution of heat transfer to other surfaces

These are errors in \( q_{ij} \), the heat exchanged between surfaces \( i \) and \( j \) (both directly and by reflections from other surfaces), relative to the exact total net heat transfer from surface \( i \) given by Figure C-3 of Appendix C.

Carroll gives two percentage error results.

By the first method, for each surface \( i \), the rms of the error, \( \Delta q_{ij} \), in heat exchange to each of the \( n-1 \) other \( j \) surfaces is obtained. Then the rms of these \( n \) rms error values is obtained, giving a
representative distribution error for the enclosure. Dividing this by the rms value of the exact net surface heat transfers, \( q_{it} \), of all the surfaces gives the final distribution error in percent:

\[
Err = \frac{\sqrt{\sum_{i=1}^{n} \left( \frac{\Delta q_{it}^2}{n(n-1)} \right)}}{\sqrt{\sum_{i=1}^{n} \left( \frac{\bar{q}_{it}^2}{n} \right)}} \times 100
\]

*Equation 89*

where

\( \Delta q_{ij} = q_{ij} - \bar{q}_{ij} \),

\( q_{ij} = h_{b} A_{i} F'_{ij} (T_{i} - T_{j}) \) with \( F'_{ij} \) values from Equation 84.

\( \bar{q}_{ij} = h_{b} A_{i} F'_{ij} (T_{i} - T_{j}) \) with the exact \( F'_{ij} \) values of Figure C-3 of Appendix C.

By the second method, for each surface \( i \), the rms of the percentage error in heat exchange \( q_{ij} \), relative to the exact net heat transfer from that surface, \( \bar{q}_{it} \), is obtained.

\[
Err = 100 \times \sqrt{\sum_{i=1}^{n} \left( \frac{\Delta q_{ij}}{\bar{q}_{it}} \right)^2 \left( \frac{1}{n(n-1)} \right)}
\]

*Equation 90*

**Distribution error results**

For the Figure 10 room, Carroll’s model gives errors of 2.1% and 3.9% for methods 1 and 2 respectively. Walton’s model has corresponding errors of 2.4% and 3.7%. Equation 91 was used for the results in parenthesis.
Table 5: % rms Error in $q_i$ from Equation 90

<table>
<thead>
<tr>
<th></th>
<th>Figure 10 room</th>
<th>Corridor</th>
<th>Warehouse</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.5:4:6 ε = 0.9 (.84 wds)</td>
<td>1:10:1 ε = 0.9</td>
<td>1:10:10 ε = 0.9</td>
</tr>
<tr>
<td>Carroll</td>
<td>2.1 (3.9)</td>
<td>3.3 (2.8)</td>
<td>0.6 (1.9)</td>
</tr>
<tr>
<td>Walton(1980)</td>
<td>2.4 (3.7)</td>
<td>3.3 (2.8)</td>
<td>2.8 (3.0)</td>
</tr>
<tr>
<td>BLAST</td>
<td>2.8 (4.4)</td>
<td>3.4 (4.4)</td>
<td>3.4 (15)</td>
</tr>
<tr>
<td>NBSLD</td>
<td>1.7 (3.5)</td>
<td>1 (0.83)</td>
<td>3.3 (1.9)</td>
</tr>
</tbody>
</table>

(Equation 91 was used for the results in parenthesis.)

Carroll’s model is seen to give very respectable results, despite giving no special treatment to coplanar surfaces.

2.6.1.3 Air absorption

The Carroll model also accounts for the absorption of long-wave radiation in the air, so that the air and mrt nodes are thermally coupled to each other as well as to the interior surfaces. Carroll (1980a) gives an air emissivity by the following dimensional empirical equation that is based on Hottel data from McAdams(1954):

$$\varepsilon_a = 0.08\varepsilon_s \ln\left(1 + \left(\frac{4V}{\varepsilon_s A_p} RP_{atm}\right)e^{(T_a F - 32)/30.6}\right)$$

Equation 91

The logarithm is natural, and,

- $\varepsilon_s = \text{the area-weighted average long-wave emissivity for room surfaces, excluding air.}$
- $V/A = \text{the room volume to surface area ratio, in meters.}$
- $R = \text{the relative humidity in the zone. (0 \leq R \leq 1).}$
- $P_{atm} = \text{atmospheric pressure in atmospheres.}$
- $T_a = \text{zone air temperature, in } ^\circ\text{F.}$

Following a heuristic argument Carroll assigns an effective area $A_a$ to the air that is the product of $\varepsilon_a$ and the sum of all of the zone surface areas, as if the absorbing part of the air were consolidated into a surface of area $A_a$.

$$A_a = \varepsilon_a \sum A_i$$

Equation 92
Using this area, the value of $F_a$ for this 'surface' can be calculated along with the other $F_i$ by Equation 80. The value of the conductance between the air and radiant nodes in Figure 11 is given by:

$$C_x = h_b A_a F_a$$

*Equation 93*

**Figure 11: Like Figure 9 but with Convective Network Added**

---

**Facets**

Suppose one of the interior surfaces of total area $A_i$ is composed of $N_i$ identical flat sub-surfaces, each at the same temperature, and similar views to each other, like the facets of a geodesic dome. The $F_i$ values would be the same if each facet is treated as a separate surface. To avoid redundant solutions to Equation 80, it is easy to show that $A_i$ can be treated as one surface in Equation 6-4 if $N_i$ is introduced into Equation 80 as follows:

$$F_i = \frac{1}{A_i F_i/N_i} \cdot \frac{1}{\Sigma(A_i F_i)}$$

*Equation 94*

The facet feature is utilized in the simulation to represent attic truss surfaces.
Short Wave Radiation Distribution

This routine was used in the development code for this program. It is not currently implemented in CSE, being replaced by a simplified but similar routine.

The short wave radiation (solar insolation from hourly input) transmitted by each window can, at the users discretion, be all distributed diffusely inside the zone, or some of the insolation from each window can be specifically targeted to be incident on any number of surfaces, with the remaining untargeted radiation, if any, from that window, distributed diffusely. The insolation incident on any surface can be absorbed, reflected, and/or transmitted, depending on the surface properties inputted for that surface. The radiation that is reflected from the surfaces is distributed diffusely, to be reflected and absorbed by other surfaces ad infinitum.

Since some of the inside surfaces will be the inside surface of exterior windows, then some of the solar radiation admitted to the building will be either lost out the windows or absorbed or reflected by the widows.

2.6.1.4 Radiation removed at each surface of a zone by a single source of targeted insolation

Assume a spherical zone with total insolation $S$ (Btu/hr) admitted into the zone through one window. Assume that the portion $a_i Q_i$ (ft$^2$·Btu/(hr·ft$^2$)) of $S$ (Btu/hr) is targeted to surface $i$ with area $a_i$ such that,

$$\sum_i a_i Q_i = S$$

where the sum is over all surfaces $i$. The total spherical area is $a_s = \sum_i a_i$. Also incident on surface $i$ will be the irradiation $G_i$ (Btu/hr-ft$^2$) from other surfaces that have reflected a portion of the radiation they have received. We distinguish between the $Q_i$ incident on the surface directly from the window, and the irradiation $G_i$ which is composed of radiation reflected to $i$ from all the surfaces, and that reflected by windows. All radiation (including Incident beam) is assumed to be reflected diffusely.

Each surface $i$ will also reflect short-wave radiation, with a radiosity $J_i$ [Btu/hr-sf].

**Figure 12: Radiation Terminology**
The derivation below determines the equations to obtain $J_i$ and $G_i$ for known $Q_i$ values, for all the surfaces of the sphere, $i = 1$ to $n$.

**First a relationship between $G_i$ and $J_i$ is developed:**

Since $G_i$ is composed only of reflected radiation,

$$a_i G_i = \sum_k J_k a_k F_{ik}$$  \hspace{1cm} \text{Equation 96}

where the sum is over all surfaces $n$ of the sphere of area $a_s$.

Using the view-factor reciprocity principle,

$$a_k F_{kt} = a_l F_{ik}$$

$G_i$ becomes

$$G_i = \sum_k J_k F_{ik}$$

For spherical geometry, the view factor is $F_{ik} = a_k / a_S$, where $a_S = \sum a_k$, so $G_i$ can be written

$$G_i = \frac{1}{a_S} \sum_k J_k a_k$$  \hspace{1cm} \text{Equation 97}

The right hand side is the area-weighted average radiosity, showing that $G_i$ is independent of $i$,

$$G_i = \bar{J}$$  \hspace{1cm} \text{Equation 98}

**Next a separate relationship between $J_i$ and $G_i$ is obtained, $G_i$ eliminated and $J_i$ solved for explicitly:**

The radiosity of surface $i$ is composed of the reflected part of both the irradiation and the targeted solar

$$J_i = \rho_i (G_i + Q_i)$$  \hspace{1cm} \text{Equation 99}

Substituting Equation 97 for $G_i$ gives

$$\frac{J_i}{\rho_i} = \frac{1}{a_S} \sum_k J_k a_k + Q_i$$  \hspace{1cm} \text{Equation 100}
Since by Equation 98 $G_i$ is independent of $i$, then Equation 99 shows that the radiosity of any surface $i$ is related to the radiosity of any surface $k$ by the relationship
\[
\frac{J_i}{\rho_i} - Q_i = \frac{J_k}{\rho_k} - Q_k
\]
Substituting this into Equation 100 gives
\[
\frac{J_i}{\rho_i} = \frac{1}{\alpha_s} \sum_k \left( a_k \rho_k \left( \frac{J_i}{\rho_i} + Q_k - Q_i \right) \right) + Q_i
\]
This can be solved explicitly for $J_i$:
\[
J_i = \frac{1}{\alpha_s \rho_i} \left( \sum_k a_k \rho_k (Q_k) \right) + Q_i \rho_i
\]
\[\text{Equation 101}\]
From Equation 101, the area weighted average $J$ is
\[
\bar{J} = \frac{1}{\rho} \sum_k \left( a_k \rho_k (Q_k) \right) + \frac{1}{\alpha_s} \sum_i a_i Q_i \rho_i
\]
\[\text{Equation 102}\]
where $\bar{\rho}$ is the area weighed average reflectivity.

**Now that $J_i$ and $G_i$ are known an energy balance will give the net heat transfer:**

The net energy rate (Btu/hr) absorbed and/or transmitted by surface $i$, is:
\[
Q_{net_i} = (G_i + Q_i - J_i)a_i = (\bar{J} - J_i + Q_i)a_i
\]
\[\text{Equation 103}\]
Substituting Equation 101 and Equation 102 into this gives
\[
Q_{net_i} = \frac{a_i}{\alpha_s} \left( \frac{1 - \rho_i}{1 - \bar{\rho}} \right) \sum_k a_k \rho_k Q_k + a_i Q_i(1 - \rho_i)
\]
\[\text{Equation 104}\]
The first term in Equation 104 is from the absorption and/or transmission of radiation that reached and is absorbed by surface $i$ after having been reflected, ad infinitum, by the interior surfaces. The second term is from the absorption of the "initially" incident insolation $Q_i$ on surface $i$.

If none of the insolation is specifically targeted, and instead $S$ is assumed to be distributed isotropically then $Q_i$ is the same for each surface:
\[ Q_i = \frac{S}{a_S} \]

*Equation 105*

Substituting this into Equation 104 gives \( Q_{\text{net}} \) for isotropically distributed insolation:

\[ Q_{\text{net}} i = \frac{a_i}{a_S \left(1 - \rho_i \right)} S \]

*Equation 106*

### 2.6.1.5 Radiation removed at each surface of a zone by multiple window sources of targeted insolation

The targeting can be different for each window. Adding an additional subscript "\( j \)" to Equation 104 allows it to represent the energy removal for each surface separately for each window \( j \). That is, Equation 104 becomes Equation 107, the rate of energy removal at each surface due to insolation \( S_j \), that is distributed according to the assigned targeted values \( Q_{ji} \).

\[ Q_{\text{net}}ji = \frac{a_i}{a_S \left(1 - \rho_i \right)} \sum_k a_k \rho_k Q_{jk} + a_i Q_{ji}(1 - \rho_i) \]

*Equation 107*

The targeting fractions \( H_{jk} \), to be user input, are defined as the fraction of insolation from window \( j \) that is incident on surface \( k \):

\[ H_{jk} = \frac{a_k Q_{jk}}{S_j} \]

*Equation 108*

With this definition, Equation 107 can be written as

\[ Q_{\text{net}}ji = a_i S_j (1 - \rho_i) \left( \frac{H_{ji}}{a_i} + \frac{1}{a_s \left( 1 - \rho_i \right)} \sum_k \rho_k H_{jk} \right) \]

*Equation 109*

The effective absorptivity of the targeted surfaces is defined as

\[ \alpha_{ef} T_{ji} = Q_{\text{net}}ji / S_j \]

*Equation 110*

Replacing the spherical surfaces \( a_i \) in Equation 109 by \( a_i = A_i F_i \), and substituting Equation 109 into Equation 110 gives the targeted gain equation used in the CZM code:

\[ \alpha_{ef} T_{ji} = A_i F_i (1 - \rho_i) \left( \frac{H_{ji}}{A_i F_i} + \frac{1}{(1 - \rho_i) \sum_i A_i F_i \sum_k \rho_k H_{jk}} \right) \]
If $\sum H_{jk} < 1$ then it is assumed that the remaining insolation $S_j(1 - \sum H_{jk})$ is distributed isotropically. From Equation 105 it is

$$\text{isotropic } Q_{net_{ji}} = \frac{a_i}{a_s} \left( \frac{1 - \rho_i}{1 - \rho} \right) S_j(1 - \sum H_{jk})$$

Equation 112

The definition of the effective absorptivity for isotropic insolation is:

$$a_{eff_{ji}} = Q_{net_{ji}} / S_j$$

Equation 113

Changing Equation 112 to utilize zone areas, $a_i = A_i F_{i'}$, and substituting Equation 112 into Equation 113 gives the amount of the diffuse part of the insolation from each window $j$ that is absorbed in each surface $i$. This is used in the CZM code.

$$a_{eff_{ji}} = \frac{A_i F_i}{\sum_k A_k F_k} \left( \frac{1 - \rho_i}{1 - \rho} \right) (1 - \sum_k H_{jk})$$

Equation 114

Note that no distinction has been made between surfaces that are opaque like walls, and partially transparent window surfaces. They are treated equally. The difference is that the energy removed by an opaque wall is absorbed into the wall, whereas that removed by the window surfaces is partly transmitted back out the window, and partly absorbed at the window inside surface. The CZM development code lets the user specify a fraction of the radiation that is absorbed in the room-side surface of the window, which slightly heats the window and thus the zone.

Adding Equation 111 and Equation 114 gives the total effective absorptivity of surface $i$ from the insolation admitted through window $j$:

$$a_{eff_{ji}} = A_i F_i (1 - \rho_i) \left( \frac{1}{(1 - \rho) \sum_k A_k F_k} \left[ 1 - \sum_k (1 - \rho_k) H_{jk} \right] + \frac{H_{ji}}{A_i F_i} \right)$$

Equation 115

The net radiation absorbed in surface $i$ from window $j$ is thus

$$Q_{net_{ji}} = A_i F_i (1 - \rho_i) S_j \left( \frac{1}{(1 - \rho) \sum_k A_k F_k} \left[ 1 - \sum_k (1 - \rho_k) H_{jk} \right] + \frac{H_{ji}}{A_i F_i} \right)$$

Equation 116
Summing this over all windows gives the total SW radiation absorbed and/or transmitted by surface $i$ as:

$$Q_{net_i} = A_i F_i (1 - \rho_i) \sum_j S_j \left( \frac{1}{(1 - \rho)} \sum_k A_k F_k \left[ 1 - \sum_k (1 - \rho_k) H_{jk} \right] + \frac{H_{ii}}{A_i F_i} \right)$$

Equation 117

### 2.7 Window Model

The ASHWAT algorithm is used to model complex windows with diatherminous layers and curtains, etc. (Wright and Kotey 2006, Wright, J.L. 2008). Given the environmental conditions on each side of the window, ASHWAT determines the long wave, short wave and convection heat transfers to the conditioned space.

For the following input and output discussion, ASHWAT is treated as a black box.

#### 2.7.1 Inputs

Each time step, for each window, ASHWAT is given the environmental inputs:

- $I = \text{insolation incident on window system.}$
- $I_{refl} = \text{insolation reflected diffusely from the other room surfaces.}$
- $T_{a,\text{out}} = \text{outside dry bulb air temperature.}$
- $T_{a,\text{in}} = \text{inside dry bulb air temperature.}$
- $T_{r,\text{in}} = \text{the temperature of the indoor plate.}$
- $T_{r,\text{out}} = \text{the temperature of the outdoor plate.}$
2.7.2 Outputs

ASHWAT’s output gives heat transfer rates and circuit elements of Figure 14. The circuit of Figure 14 is part of the conditioned zone radiant network of Figure 2 and Figure 3 (with some different nomenclature).

In Figure 14,
\[ FP = \text{fraction of the heat from Insolation absorbed in the various window layers that ends up being transferred to the inside radiant node.} \]

\[ FM = \text{fraction of the heat from Insolation absorbed in the various window layers that ends up being convected to the inside air node.} \]

\[ f_{rin} = \text{fraction of total non-solar heat transfer that goes to the inside radiant node; dimensionless.} \]

\[ f_{rout} = \text{fraction of non-solar heat transfer to the outside that goes to the outside radiant node.} \]

\[ U = \text{conductance between the inside and outside effective temperatures } T_{ei} \text{ and } T_{eo}; \]
\[ \text{Btu/(hr-sf-F), where } T_{ei} = T_{a,in}(1 - f_{rin}) + T_{r,in}f_{rin}. \]

\[ T_{eo} = T_{a,out} * (1 - f_{rout}) + T_{r,out} * f_{rout} = \text{the effective outdoor temperature; F.} \]

\[ G_{sw} = \text{the cross coupling term; Btu/(hr-sf-F).} \]

\[ \tau = \text{the short wave transmissivity of the window system.} \]

Note that the solar heat gain coefficient is: \[ SHGC = \tau + FP + FM. \]

Net energy into zone via window, per unit COG area = \[ + I (\tau + FP + FM) - I_{refl} + U(T_{eo} - T_{ei}) \]

### 2.7.3 Matching ASHWAT to CSE Radiant Network

#### 2.7.3.1 Outside boundary conditions

ASHWAT models the irradiation on the outside of the window system as if it were emitted by a black plate parallel to the window at temperature \( T_{r,out} \), as shown in Figure 13. The irradiation on the window system from the outside plate is thus \( G_{out} = \sigma T_{r,out}^4 \), so

\[ T_{r,out} = \left( \frac{G_{out}}{\sigma} \right)^{0.25} = \left[ F_{sky} \beta T_{sky}^4 + \left( F_{gnd} + F_{sky}(1 - \beta) \right) T_{air}^4 \right]^{0.25} \]

Equation 118

where \( G_{out} \) has been replaced by Equation 67.

#### 2.7.3.2 Inside boundary conditions

From Figure 13, the equivalent network between the radiosity of the window system, \( j_w \), and the inside plate is shown in Figure 15. The circuit parameters are in the conductance form. The “1” is the view factor between the plate and the window.
Figure 15: Equivalent Network between the Radiosity of the Window System, $J_w$, and the Inside Plate

\[
\begin{align*}
J_w & \xrightarrow{Q} J_r \\
1 & \xrightarrow{\frac{\varepsilon_r}{1 - \varepsilon_r}} E_r = \sigma T_{r,in}^4
\end{align*}
\]

Figure 15 reduces to:

Figure 16: Reduced Figure 15

\[
\begin{align*}
J_w & \xrightarrow{Q} E_r \\
\varepsilon_r & \xrightarrow{} \frac{\varepsilon_r}{1 - \varepsilon_r}
\end{align*}
\]

Thus the heat transfer rate per unit area, with $Q$ positive from window to room, is:

\[
Q = \varepsilon_r (J_w - E_r)
\]

Equation 119

From Figure 9 the network between the radiosity of a surface and the mean radiant temperature node is shown in Figure 17. This corresponds to Figure 16 for the ASHWAT algorithm:

Figure 17: Network between the Radiosity of a Surface and the Mean Radiant Temperature Node

\[
\begin{align*}
J_w & \xrightarrow{Q} E_r \\
F_w & \xrightarrow{}
\end{align*}
\]

with the corresponding heat transfer rate:

\[
Q = F_w (J_w - E_r)
\]

Equation 120

Comparing Equation 119 and Equation 120 shows that to obtain the heat flow consistent with the Carroll network ASHWAT must model the window by setting inside plate’s emissivity to the value of $F_w$.

\[
\varepsilon_r = F_w
\]

Equation 121

$F_w$ is the Carroll MRT view factor defined in Section 2.6.1. $F_w$ is slightly larger than 1, and serves to increase the heat transfer between $J_w$ and $E_r$ to compensate for the fact that $|J_w - E_r|$ is smaller than it would if $T_{r,in}$ had not included the window temperature in its average. This MRT view factor effect cannot be simulated by a parallel plate model without the trick of artificially raising the emissivity of the inside plate to the value $F_w$. 

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2.8 Slab Model

2.8.1 Bajanac Simplified Model

The CZM slab model is partly based on the Simplified Method for the calculation of heat flow through foundations, presented by Bazjanac et al. (2000). They divide a slab into two regions.

2.8.1.1 Perimeter region

The perimeter area of the slab is defined as a 2 ft wide strip along external walls. Through this perimeter path, the interior air is assumed to be coupled via conductances $\alpha_1$, $\alpha_2$, and $\alpha_3$ to three environmental temperatures: $T_{\text{week}}$, $T_{\text{ground}}$, and $T_{\text{year}}$.

Thus the instantaneous heat flow from the room Temp node to perimeter slab, in Btu/hr-sf-F, is given by:

$$Q_{\text{perim}} = \left[ \alpha_1(T_{\text{air}} - T_{\text{week}}) + \alpha_2(T_{\text{air}} - T_{\text{ground}}) + \alpha_3(T_{\text{air}} - T_{\text{year}}) \right]$$

Equation 122

where,

$T_{\text{air}}$ = the current interior-space effective temperature (involving both $T_a$ and $T_r$).

$T_{\text{week}}$ = the average outside air temperature of the preceding two-weeks.

$T_{\text{ground}}$ = the current average temperature of the earth from the surface to a 10 ft depth.

$T_{\text{year}}$ = the average yearly dry bulb temperature.

$\alpha$’s = conductances from Table 3 of Bazjanac et al; Btu/sf-hr-F.

2.8.1.2 Core region

The core region couples $T$ to $T_{\text{ground}}$ and $T_{\text{year}}$, via conductances $\alpha_4$ and $\alpha_5$. 

Bazjanac et al. determined the conductances $\alpha_1$ through $\alpha_5$ by multi-linear regression analysis of the numerical results from a two-dimensional finite-difference slab-earth model. The conductances were determined for 52 slab foundation conditions and given in their Table 3.

### 2.8.1.3 Properties

The Bozjanac Table 3 conductances were obtained assuming the following properties:

1. **Properties of earth:**
   - conductivity = 1 Btuh/ft-F. (The k chosen was justified by assuming that lawns and other vegetation around California houses was watered during the dry season).
   - density = 115 lbm/ft$^3$
   - specific heat = 0.2 Btu/lbm-F
   - thermal diffusivity = 0.0435 ft$^2$/hr.
2. **Slab: “heavy construction grade concrete”**
   - thickness = 4-inches
   - conductivity = 0.8
   - density = 144
   - specific heat = 0.139
3. **Rrug = 2.08 hr-ft$^2$-F/Btu (ASHRAE 2005HF, p.25.5 ’carpet fibrous pad’).**
4. **Rfilm = 0.77 Btu/hr-ft$^2$F, the inside surface-to-room-temperature combined convective and radiative conductance.**

### 2.8.1.4 Ground temperature

The above model uses the ground temperature determined by Kusuda and Achenbach (1965). Using the classical semi-infinite medium conduction equations for periodic surface temperature variation (Carslaw and Jaeger), they found the average ground temperature from the surface to a depth of 10 ft to be given by:

$$T_{ground} = T_{yrAve} - GM \left(\frac{TyrMax-TyrMin}{2}\right) \cos \left(\frac{2\pi}{8760} \theta - PO - \phi\right)$$
where,

\( T_{yrAve} \) = average outdoor temperature over year; F.

\( T_{yrMax} \) = highest average monthly outdoor temperature for the year; F.

\( T_{yrMin} \) = lowest average monthly outdoor temperature for the year; F.

\[ \text{GM} = \sqrt{\frac{e^{-2\beta - 2e^{-\beta} \cos \beta + 1}}{2\beta^2}} = \text{dimensionless amplitude for integrated depth average.} \]

\( \beta = L \sqrt{\frac{\pi}{D \cdot PY}} = \text{dimensionless depth}. \)

\( L = 10 \text{ ft}, \text{ the depth over which average is taken}. \)

\( D = \text{thermal diffusivity of soil, ft}^2/\text{hr}. \)

\( PY = 8760 \text{ hr} = \text{period of 1 year}. \)

\( \theta = 24 \left( \frac{365M}{12} - 15 \right) \approx \text{elapsed time from Jan-1 to middle of month M; hours}. \)

\( M = \text{month}, 1 \rightarrow 12. \)

\[ \phi = \text{atan} \left( \frac{1 - e^{-\beta(\cos \beta + \sin \beta)}}{1 - e^{-\beta(\cos \beta - \sin \beta)}} \right) = \text{phase angle for depth averaged } T_{ground}; \text{ radians}. \)

\( PO = 0.6 \text{ radians} = \text{phase lag of ground surface temperature (assumed equal to air temperature) relative to January 1}. \text{ From measured data, see Fig. 7 in Kusuda and Achenbach.} \)

### 2.8.2 Addition of a Layered Slab and Earth

The Bazjanac model assumes a constant indoor temperature, so cannot be applied directly to a whole building thermal-balance simulation model that allow changing indoor temperatures. To apply this model to CZM, with changing indoor temperatures, requires incorporating the dynamic effects of the slab and earth due to changing inside conditions.

This is done by putting a one-dimensional layered construction, representing the slab and some amount of earth mass, into the steady-state Bazjanac model circuit—replacing part of its resistance by a thermal impedance (which is equal to the resistance for steady state conditions). In this way the correct internal temperature swing dynamics can be approximated.

First, the circuit of Figure 18 is alternately expressed as shown in Figure 20(a), with Equation 122 taking the form:

\[ Q = A \ast u_g(T_{air} - T_{eff}) \]

\[ \text{Equation 125} \]
where $T_{geff}$ is the $\alpha$-weighted average ground temperature:

$$T_{geff} = \frac{\alpha_1 T_{week} + \alpha_2 T_{ground} + \alpha_3 T_{yrAve}}{\alpha_1 + \alpha_2 + \alpha_3}$$

Equation 126

and

$$R_g = \frac{1}{\alpha_1 + \alpha_2 + \alpha_3}$$

Equation 127

Similarly for the core region,

$$T_{geff} = \frac{\alpha_4 T_{ground} + \alpha_5 T_{yrAve}}{\alpha_4 + \alpha_5}$$

Equation 128

$$R_g = \frac{1}{\alpha_4 + \alpha_5}$$

Equation 129

Now a one-dimensional layered construction is added into the circuit as shown in Figure 20(b), consisting of a surface film layer, a carpet (if any), the concrete slab, and earth layer. The bottom of the earth layer is then connected to $T_{geff}$ through the what’s left of $R_g$.

A one-dimensional representation of the mass is appropriate for the core region. It is a bit of a stretch for the perimeter slab modeling, because the real perimeter heat flow is decidedly 2-dimensional, with the heat flow vectors evermore diverging along the path of heat flow.
The earth thicknesses required to adequately model the dynamic interaction between the room driving forces (sun and temperature) and the slab/earth model was determined by considering the frequency response of the slab earth model of Figure 20(b). In the frequency domain, the periodic heat flow from the Tair node is given by Equation 130.

\[ \tilde{Q}_{air} = \tilde{T}_{air}X - \tilde{T}_{geff}Y. \]

*Equation 130*

where,

- \( X \) = the driving point admittance at the air (or combined air/radiant effective temp) node, in the units of Btu/hr-sf-F. It is the contribution to \( \tilde{Q}_{air} \) per degree amplitude of \( \tilde{T}_{air} \). X and Y are complex numbers determined from the layer properties (conductivity, heat capacity, density) of the circuit layers in Figure 20(b). See Carslaw and Jaeger; Subbarao and Anderson.

- \( Y \) = the transfer admittance at the air node. It is the contribution to \( \tilde{Q}_{air} \) per degreee amplitude of \( \tilde{T}_{geff} \). [The same value of transfer admittance applies to the \( \tilde{T}_{geff} \) node, even if the circuit is not symmetrical, being the contribution to the \( \tilde{T}_{geff} \) node per degree amplitude of \( \tilde{T}_{air} \)]

- \( \tilde{Q}_{air} \) = the amplitude (Btu/hr-ft²-F) and phase of the heat transfer rate leaving \( \tilde{T}_{air} \), and is composed of the contribution from all of the frequencies that may be extant in the driving temperatures \( \tilde{T}_{air} \) and \( \tilde{T}_{geff} \).
Note that the layers shown, when modeled as a mass construction, may need to be subdivided into thinner layers, particularly the earth, in order to satisfy the discretization procedure discussed in Section 2.4; but this subdivision is irrelevant to the slab model discussion in this section.

The maximum possible thickness of the earth layer is limited by the need for \( R \) to be positive. The limiting maximum possible thickness value, \( d_{\text{max}} \), occurs in the perimeter case, when the foundation is uninsulated (i.e., the foundation insulation value \( R-0 \) in Bazjanac et al), and the slab is uncarpeted. In this case, \( d_{\text{max}} = 2.9 \) ft. The corresponding numbers for an uncarpeted core slab case is 11.8 ft.

A depth of 2 ft is implemented in the code, for both the perimeter and core slab earth layers.

The 2 ft value was chosen primarily because, for the frequencies of concern, the magnitude of the X admittance from the Tair node was almost independent of earth layer depth for earth layer depths greater than 2 ft. See Figure 21. The phase shift is similarly essentially independent of depth after 2 ft. This was also the case for the core region.

This is the case for all indoor driving frequencies periods of up to at least 384-hr = 16-days. Thus 2 ft of earth is able to portray the dynamics resulting from a cycle of 8-cloudy days followed by 8 sunny days.

![Figure 21: Room Node X Admittance](image)

The transfer admittance \( Y \) shown in Figure 22 also contributes to \( \tilde{Q}_{\text{air}} \) according to the frequencies extant in the driving temperature \( \tilde{T}_{\text{eff}} \).
As seen in Equation 128, for the slab core region, $\tilde{T}_{\text{eff}}$ has the same frequency content as $T_{\text{ground}}$ and $T_{\text{year}}$. $T_{\text{year}}$ is a constant, i.e., zero frequency, steady-state.

As seen in Equation 124, $T_{\text{ground}}$ contains only the annual 8760-hr period. Figure 22 shows that the 8760-hr waves are transmitted unaffected by the mass layer. That is, $Y$ becomes essentially equal to the steady state transfer admittance which is the $U$ factor of the assembly, the reciprocal of the $R_g$ value. Thus, for the core region, the magnitude of the slab loss rates produced by Equation 125 are preserved and unaffected by the added earth layers.

However, although the mass layers don’t affect the magnitude of the Bazjanac model slab losses, they do introduce a time lag that is in addition to that already implicit in the $\tilde{T}_{\text{eff}}$ values. For a 2 ft earth layer the lag is ~40-hours. A 22-day lag is already included by $\phi$ of Equation 124. To eliminate double-counting, the 40-hrs could be subtracted from phi, but this has not been done since 40-hr is inconsequential compared to 22 days.

For the perimeter region, $\tilde{T}_{\text{eff}}$ has the the additional frequency content of the $T_{\text{week}}$, the two-week running average outdoor temperature. $T_{\text{week}}$ is dominated by the annual period, but has small amplitude 6-month period component, and a bit of signal at higher frequencies. Like the annual cycle, the 6-month period component is transmitted through the layered construction without damping, but again with a small but inconsequential phase lag.

Thus it was concluded that 2 ft of earth thicknesses below a 4-inch concrete slab adequately models changes in room side conditions, and at the same time adequately preserves the same average "deep earth" slab losses and phase lags of the Bazjanac model.
The validity of the response of the core slab construction is expected to be better than for the perimeter slab construction since the perimeter layers added do not properly account for the perimeter two-dimensional effects.

2.8.2.1 Warm-up time

The longest pre-run warm-up time is expected to be for a carpeted core slab with the 2 ft earth layer. Using the classical unsteady heat flow charts for convectively heated or cooled slabs (Mills), the time to warm the slab construction 90% (of its final energy change) was found to be about 20-days. Most of the heat-up heat transfer is via the low resistance rug and air film, with less through the higher ground resistance (R in Figure 20(b)), so the 20-day estimate is fairly valid for the complete range of foundation insulation options given in Bazjanac’s Table 3.

2.8.2.2 Input properties

Strictly speaking, the same properties assumed in the Bazjanac model in Section 2.8.1.3 should also be used in describing the rug, the concrete slab, and the earth in the layered constructions inputs.

This is particularly true for the carpet, if a carpet is specified, because the regression coefficients (the conductances $a_1, a_2...$) obtained for the carpeted slabs were sensitive to the $R_{rug}$ value used. While inputting a different value than $R_{rug} = 2.08$ may give the desired carpeted room admittance response, the heat conducted from the deep ground will still give the heat flow based on $R_{rug} = 2.08$.

Small differences between the inputted and above properties is less important for the other layers, and is violated in the code with regard to $R_{film}$; its value is calculated each time-step and is used instead of 0.77, even though 0.77 is still the value subtracted from $R_g$ in the code. This allows the correct modeling of the admittance of the slab floor, at the expense of a slight error in the overall resistance of the slab earth circuit.
2.9 Ventilation and Infiltration Air Network

2.9.1 Overview

This section describes the flow network algorithm used to model infiltration and ventilation air flows between conditioned zones, unconditioned zones, and the outdoors based on pressure and density differences and leakage areas between the zones.

Figure 23 shows the flow network interconnecting two conditioned zones (Z1 and Z2), the unconditioned attic and crawl space zones (Z3 and Z4), and the outside zone (Z5).

![Figure 23. Schematic of Flow Network](image)

The black lines represent one or more pressure difference driven and/or buoyancy driven flows between zones.

The blue lines in Figure 23 represent scheduled fan flows not directly dependent on zone-to-zone pressure differences. These include individual house fans (circled x's) and fan driven duct system supply, return, and leakages flows. The fans will affect the zone pressures, but the
pressures won't affect the fan flow. The duct flows, determined by the load and air handler capacity, are assumed to not constitute leakage paths when the air handler is not operating.

Small leakage or ventilation openings will be modeled as orifices using a power law equations of Section 2.9.3 with an exponent of 0.5. Infiltration leaks are modeled with the power law equation exponent of 0.65.

Large vertical holes or infiltration surfaces, large enough that the vertical pressure difference distribution allows two-way flow, are modeled as two vertically separated small holes using the Wolozyn method (see Section 2.9.5–Large Vertical Openings).

The following kind of elements are modeled using the power law equations:

- Wall infiltration for vertical envelope walls, vertical interzone walls, and roof decks
- Ceiling, floor, and wall base infiltration
- Interzone doors, door undercuts, jump ducts, relief vents
- Openable window flow
- Attic soffit vents, gable vents, roof deck vents, ridge vents
- Crawl space vents
- Trickle Vents
- Fire Place leakage.
- Infiltration to garage.

Additional equations are used to model large horizontal openings, like stairwells; Section 2.9.4. This type of opening would typically be between zones $Z_1$ and $Z_2$ in Figure 23 when the zones are stacked vertically. The algorithm used is based on that implemented in Energy Plus (2009). In addition to using the power law equation above, the algorithm calculates buoyancy induced flows that can occur when the density of the air above the opening is larger than the density of the air below the opening, causing Rayleigh-Taylor instability.

To determine the flow rates at each time step, the flow through each flow element in the building is determined for an assumed set of zone reference pressures. If the flow into each zones does not match the flow out of the zone, the pressures are adjusted by the Newton-Raphson iterative method until the flows balance in all the zones within specified tolerances.

2.9.1.1 Wind direction independent air-network solution

For energy standards application, the air network for the four zone building model is designed to give results that are wind direction independent. In computing ventilation or infiltration air flows from holes in vertical walls exposed to outdoors, the program automatically calculates the sum of the flows through 4 holes each $\frac{1}{4}$ the area, one with each cardinal compass orientation, or an offset thereof. Thus, there will be wind induced flows through the envelope leakages that approximate the average flow expected over long periods, and they will be independent of wind direction. This approach is applied to all zone ventilation or infiltration flow elements connected to the outdoor conditions.
2.9.2 Vertical Pressure Distribution

The pressure at a given elevation in a zone, including outdoors, is a combination of stack and wind effects added to the zones reference pressure. The difference in pressure in the zones on each side of a leakage element connecting the zones determines the flow rate through the element.

The pressure on the zone \( i \) side of a flow element is given by:

\[
p_i = P_{z_i} - \rho_1 g z_i
\]

Equation 131

\( z_i \) is the height of the element above some datum \( z = 0 \). The datum is arbitrary but is nominally taken as ground level. \( P_{z_i} \) is zone \( i \)'s reference pressure. This is the pressure zone \( i \) would have at elevation \( z = 0 \), regardless of whether the zone actually extends to this level. For the interior zones the \( P_{z_i} \) reference pressures are the unknowns that are solved for using the Newton-Raphson method. This method determines what values of zone pressures simultaneously result in a balanced flow in each zone. The value of \( P_{z_i} \) for the outdoor side of a flow element is given by (\( i \) is 5 if there are 4 conditioned and unconditioned zones):

\[
P_{z_i} = \text{patm} + CP \cdot Pu
\]

Equation 132

The weather tape atmospheric pressure, \( \text{patm} \), is assumed to exist at the elevation \( z = 0 \) far from the building. \( \text{patm} \) is taken as zero so that the unknown zones pressures will be found relative to the weather tape atmospheric pressure. Of course the actual weather tape atmospheric pressure is used in determining inside and outside zone air densities.

The wind velocity pressures, \( Pu \), is:

\[
Pu = \rho_{\text{out}} (S \cdot U)^2 / 2
\]

Equation 133

where,

- \( U \) is the wind velocity at eave height.
- \( S \) is the shelter coefficient equal to SC of Table 2: Local Shielding Parameters.
- \( \rho_{\text{out}} \) is the outside air density.
- \( CP \) is the orientation sensitive pressure coefficient.

2.9.2.1 Pressure coefficients used

The wall pressure coefficients in Table 6 are those used by Walker et al. (2005). They are for the four vertical walls of an isolated rectangular house, with the wind perpendicular to the long wall (short wall = \( \frac{1}{2} \) long wall). As discussed in regard to hip roofs below, only data for the
normal wind direction is used. These coefficients are used for all ventilation and infiltration holes in the walls. Soffit vents also use these values since they are assumed to have the same pressure coefficient as the walls under them. This assumption is roughly corroborated by the data of Sharples (1997).

### Table 6: Pressure Coefficients for Wind Normal to One Wall

<table>
<thead>
<tr>
<th>Wind Pressure Coefficient, CP</th>
<th>Upwind wall</th>
<th>Side walls</th>
<th>Downwind Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.6</td>
<td>-0.65</td>
<td>-0.3</td>
<td></td>
</tr>
</tbody>
</table>

Table 7 gives hip roof’s pressure coefficients for a range of roof angles. These are used to determine the outside pressure on ridge vents and roof deck vents.

There is little data available for hip roof surface pressure coefficients, or for ridge pressure coefficients (needed to model ridge vents) for any roof type. The data in Table 7 is a simplified synthesis of the data given by Xu (1998) and Holmes (1993, 2003, etc.), informed by a review of ASHRAE, EU AIVC, and other data sets and research papers.

Xu used a wind tunnel to measure pressure coefficients for a hip roofed building which was otherwise identical to the gable roof building wind tunnel data obtained by Holmes. The building had an aspect ratio of 2:1, with 0° wind direction normal to the long side (and normal to the gable ridge and hip roof top ridge). The building eave height was 0.4 the length of the short side. The building had a relatively large eave overhang of about 35% of the eave height. Xu and Holmes presented data for this building for roof pitch angles of 15, 20, and 30°. Other Holmes data, for both larger and smaller roof angles was used to estimate the pressure coefficients beyond the 15 to 30 degree range. Neither Xu nor Holmes presented average surface pressures, so the average surface data and average ridge pressures given in the table are based on estimates from their surface pressure contour data.

The table is for wind normal to the long side of the building. Similar tables were obtained from Xu's data for the 45 and 90 degree wind angles. Table 7 would ideally be wind direction independent, implying some kind of average pressure coefficient; for example, for each surface take the pressure coefficient that is the average for the 0, 45, and 90 degree angles. However, infiltration flows depend on pressure differences, and the average of the pressure differences is not necessarily indicative of the difference of the average pressures. The soffit vents flows, driven by the pressure difference between the adjacent wall and the various roof vents complicate any averaging schemes.

Comparison of the pressure coefficients for the three wind directions, while showing plausible differences, arguably does not show a discernable pattern that would obviate just using the normal wind direction data. Given the variety of roofs and building shapes that will be represented by these coefficients, the variety of vent locations and areas, and the deficiencies of the data, using a consistent set of data for only one wind direction is deemed appropriate.
### Table 7: Hip Roof Wind Pressure Coefficients

<table>
<thead>
<tr>
<th>Roof Pitch $\psi$</th>
<th>Hip Roof Wind Pressure Coefficient, $CP$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upwind roof</td>
</tr>
<tr>
<td>$\psi &lt; 10^o$</td>
<td>-0.8</td>
</tr>
<tr>
<td>$10 \leq \psi &lt; 15$</td>
<td>-0.5</td>
</tr>
<tr>
<td>$15 \leq \psi &lt; 25$</td>
<td>-0.3</td>
</tr>
<tr>
<td>$25 \leq \psi &lt; 35$</td>
<td>+0.1(pos)</td>
</tr>
<tr>
<td>$35 \leq \psi &lt; 50$</td>
<td>+0.3 (pos)</td>
</tr>
</tbody>
</table>

#### 2.9.2.2 Density

Zone $i$’s air density $\rho_i$ is assumed to be only a function of zone temperature $T_i$. That is, assuming the air is an ideal gas, at standard atmospheric conditions, the pressure change required to change the density by the same amount as a change in temperature of $1^oF$ is $\frac{\partial \rho}{\partial T} = \frac{\rho}{\rho R_{air}}$, which is approximately $-200$ Pascals/F. Since zone pressure changes are much smaller than $200$ Pa, they are in the range of producing the same effect as only a fraction of a degree F change in zone temperature; thus the density is assumed to always be based on $p_{atm}$. (This has been changed in code so that $\rho_i$ depends on both $T_i$ and $p_{z_i}$).

Using the ideal gas approximation, with absolute temperature units,

$$\rho_i = \frac{p_{atm}}{R_{air}T_i}$$

*Equation 134*

The pressure difference across the flow element is given by

$$\Delta p_{ij} = p_i - p_j = p_{zi} - p_{zj} - g_z(\rho_i - \rho_j)$$

*Equation 135*

#### 2.9.3 Power Law Flow Equation

##### 2.9.3.1 Orifice flow power law

For an orifice, with fixed density of air along the flow path (from inlet to vena contracta), Bernoulli’s equation gives:

$$m = C_dA\sqrt{2\rho_{in} g_c (\Delta p)^{\frac{1}{2}}}$$

*Equation 136*
where

\[ C_D \text{ is the dimensionless orifice contraction coefficient.} \]
\[ C_D = \frac{\pi}{\pi+\frac{4}{3}} \text{ Kirchoff's irrotational flow value for a sharp edge orifice.} \]
\[ C_D = 0.6 \text{ default for CSE windows} \]
\[ C_D = 1 \text{ for rounded inlet orifice as used in ELA definition, and consistent with no vena contracta due to rounded inlet.} \]
\[ A = \text{Orifice throat area, } ft^2. \]
\[ \rho_{in} = \text{density of air entering the orifice; } lb_m/ft^3. \]
\[ g_c = 32.2 \frac{lb_m ft}{lb_f sec^2} \]

2.9.3.2 Infiltration flow power law

The following is based on Sherman (1998). English units are used herein. Measured blower door infiltration data is expressed empirically as a power law:

\[ Q = \kappa \Delta P^n \]

*Equation 137*

or

\[ m = \rho_{in} \kappa \Delta P^n \]

*Equation 138*

where

\[ Q = \text{volume flow in } ft^3/sec. \]
\[ m = \text{mass flow in } lb_m/sec. \]
\[ \rho_{in} = \text{entering air density, } lb_m/ft^3 \]
\[ \Delta P = \text{pressure difference in } lb_f/ft^2 = psf. \]
\[ n = \text{measured exponent, assumed to be } n = 0.65 \text{ if measured value is unavailable.} \]
\[ \kappa = \text{measured proportionality constant.} \]

Equation 137 and Equation 138 are dimensional equations. Thus \( \kappa \) is not a dimensionless number but implicitly has the dimensions \( ft^{3-2n}/(sec^2 lb^0) \). See Section 2.9.3.8–Converting Units of \( \kappa \).

Sherman defines equivalent leakage area, ELA, as the area of a rounded-entrance orifice that gives the same flow as the infiltration of Equation 137 when the pressure difference \( \Delta P \) is equal
to the reference pressure $P_r = 0.08354$ psf (= 4 Pa) By Equation 136, a rounded-entrance nozzle with throat area $ELA$ and $\Delta P = P_r$ has a flow rate:

$$m = ELA\sqrt{2\rho_{in}g_c(P_r)^{\frac{1}{2}}}$$

*Equation 139*

Equation 137 and Equation 139 with $\Delta P = P_r$ gives the ELA as:

$$ELA = \kappa P_r^{n-\frac{1}{2}}\sqrt{\frac{\rho_{in}}{2g_c}}$$

*Equation 140*

Solving Equation 140 for $\kappa$, gives

$$\kappa = ELA\sqrt{\frac{2g_c}{\rho_{in}}} P_r^{\frac{1}{2}-n}$$

*Equation 141*

Substituting Equation 140 into Equation 137 gives the general equation, equivalent to Equation 137, that is the infiltration flow at any pressure difference $\Delta P$:

$$m = ELA\sqrt{2\rho_{in}g_cP_r^{\frac{1}{2}-n}} \Delta P^n$$

*Equation 142*

(Note that substituting Equation 140 into Equation 142 recovers the empirical Equation 137).

### 2.9.3.3 General power law flow equation

CSE uses Equation 136 to model flow through elements such as windows, doors, and vents. Equation 142 is used for infiltration flows for elements with a defined ELA.

Both equations are special cases of the generalized flow power law Equation 143. For flow from zone $i$ to zone $j$.

$$m_{i,j} = SP * A_e \sqrt{2\rho_{in}g_c |\Delta p_{i,j}|^{n_g}}$$

*Equation 143*

SP is the sign of the pressure difference $\Delta p_{i,j} = p_i - p_j$, utilized to determine the sign of the flow, defined as + from $i$ to $j$. The exponent is $n_g$, “g” for generalized.

Equation 143 reduces to the orifice Equation 136 if:

- $A_e = A * C_D$ with $C_D = 0.6$.
- $n_g = \frac{1}{2}$
Equation 143 reduces to the infiltration Equation 142 if:

- \( A_e = \left( \frac{p_i^{2-n}}{r} \right) E L A \), where \( n \) here is the measured exponent.
- \( n_g = n \)
- \( p_r = 0.08354 \frac{lb}{ft^2} \)

[Although \( C_D \) is dimensionless in Equation 136, the generalization to Equation 143 requires \( C_D \) to implicitly have the units of \( (lb_m)^{\frac{1}{2}-n_g}(ft)^{2n_g-1} \).]

2.9.3.4 Dealing with unbounded derivative at \( \Delta P = 0 \)

The partial derivative of the mass flow of Equation 143 with respect to the pressure in zone \( i \) is given by:

\[
\frac{\partial m_{ij}}{\partial p_i} = A_e n_g \sqrt{2 \rho_{in} |\Delta p_{ij}|^{n_g-1}}
\]

Equation 144

Since \( n_g < 1 \) this derivative \( \to \infty \) as \( \Delta P \to 0 \), potentially causing problems with the Newton-Raphson convergence. In order to make the derivative finite for small pressure drops, whenever the pressure difference is below a fixed value, \( \Delta P_L \), the power law is extended to the origin by a linear power law \( (n_g = 1) \),

\[
m_{ij} = SP \times A_{linear} \sqrt{2 \rho_{in} g_c |\Delta p_{ij}|^{n_g-1}}
\]

Equation 145

as shown in Figure 24.

So that the flow rates match when \( \Delta P = \Delta P_L \), \( A_{linear} \) is determined by equating Equation 145 to Equation 143 with \( \Delta p = \Delta P_L \), giving:

\[
A_{linear} = A_e \Delta P_L^{n_g-1}
\]

Equation 146

Note that the derivative of \( m \) will be discontinuous when \( \Delta p = \Delta P_L \), which conceivably could also cause Newton-Raphson problems, but during extensive code testing, none have occurred.
2.9.3.5 Summary of inputs to the generalized flow equation

The generalized flow equation, Equation 143,

\[ m_{i,j} = SP \cdot A_e \sqrt{2 \rho_{in} g_c |\Delta p_{i,j}|^{n_g}} \]

is used with the following parameter values, depending on element type and pressure drop \( \Delta P \).

2.9.3.6 For windows, doors, and vents

If \( \Delta P > \Delta P_L \):
- \( A_e = A \cdot C_D \)
- \( A = \) area of flow element; \( ft^2 \).
- \( C_D = 0.6 \).
- \( n_g = \frac{1}{2} \)

If \( \Delta P < \Delta P_L \):
- \( A_e = C_D^\frac{1}{0.5-1} \cdot \Delta P_L^0.5-1 = C_D \cdot A/\sqrt{\Delta P_L} \)
- \( A = \) area of flow element; \( ft^2 \).
- \( C_D = 0.6 \)
- \( n_g = 1 \)
- \( \Delta P_L = \) determined by computational experiment.

2.9.3.7 For infiltration leakage elements

If \( \Delta P > \Delta P_L \):
\[ A_e = \left( \frac{1}{p_r^{2-n}} \right) ELA, \quad n \text{ here is the measured exponent, or 0.65 if not known. (Note that if } n = 0.65, \ A_e = 1.45 \times ELA, \text{ used in CEC ACM manual).} \]

\[ n_g = n \]

\[ P_r = 0.08354 \frac{lb_f}{ft^2} \]

- \( ELA \) is determined from either:
  - the measured parameters \( \kappa \) and \( n \) using Equation 140. See Section 2.9.3.8– Converting units of \( \kappa \).
  - code regulations, in which case \( n = 0.65 \) is assumed.

If \( \Delta P < \Delta P_L \):

\[ A_e = \Delta P_L^{n-1} \left( \frac{1}{p_r^{2-n}} \right) ELA, \quad \text{where } n \text{ here is the measured value, or 0.65.} \]

\[ n_g = 1 \]

\[ P_r = 0.08354 \frac{lb_f}{ft^2} \]

2.9.3.8 Converting units of \( \kappa \)

The \( \kappa \) in Equation 137 is not dimensionless, so \( \kappa \) changes value depending on the units of \( Q \) and \( \Delta P \) in Equation 137. The analysis herein (Section 2.9) assumes \( Q \) in \( ft^3/sec \) and \( \Delta P \) in \( lb_f/ft^2 \).

However, conventionally \( \kappa \) is obtained from measured data with \( Q \) in \( \left( \frac{ft^3}{min} \right) \) and \( \Delta P \) in \( \text{Pascals} \). With these units Equation 137 takes the form:

\[ Q[cfm] = \kappa'(\Delta P(Pa))^n \]

\[ \text{Equation 147} \]

Using dimensional analysis the value of \( \kappa \) to be used in Equation 137 with \( Q \) in \( (ft^3/sec) \) and \( \Delta P \) in \( (lb_f/ft^2) \) is:

\[ \kappa = \left( \frac{47.88^n}{60} \right) \kappa' \]

\[ \text{Equation 148} \]

where the numbers are from the conversion factors \( 47.88 \frac{Pa}{lb_f/n^3} \) and \( 60 \text{ sec/min.} \quad \kappa = 0.206 \kappa' \text{ for } n = 0.65. \]

\[ \kappa' = \text{the measured value from data with } Q \text{ in } \left( \frac{ft^3}{min} \right) \text{ and } \Delta P \text{ in Pascals.} \]

2.9.3.9 ACM Manual relationship between CFM50 and ELA

Using Equation 142 (in volume flow form) the infiltration volume flow, CFS50, with 50 Pa pressurization is:

\[ \text{CFS50} = \text{ELA} \sqrt{ \frac{2g_e}{\rho} } p_r^{1-n} \Delta P^n = \text{ELA} \sqrt{ \frac{64.4}{0.075} } 0.08354^{-0.15} 1.04428^{0.65} = 43.738 \times \text{ELA} \]
where

\[ \Delta P = 50 \text{ Pa} = 1.04428 \text{ psf} \]

\[ \text{CFS50} = \text{flow in units of ft}^3/\text{sec}. \]

For cfm units, and ELA in square inches,

\[ \text{CFM50} = (60/144)\text{CFS50} = 18.224*\text{ELA} \]

or alternately,

\[ \text{ELA} [\text{in}^2] = 0.055*\text{CFM50} \]

This is the equation used to get ELA from blower door data at 50 Pa pressure difference.

### 2.9.3.10 Heat Flow

When the flow \( m_{i,j} \) is positive, the heat delivered to zone \( j \) by this flow is given by

\[ Q_j = m_{i,j} C_p (T_i - T_j) \]

while the heat delivered to zone \( i \) by the flow \( m_{i,j} \) is zero:

\[ Q_i = 0 \]

When the flow \( m_{i,j} \) is negative, the heat delivered to zone \( j \) is zero,

\[ Q_j = 0 \]

while the heat delivered to zone \( i \) by the flow \( m_{i,j} \) is:

\[ Q_i = m_{i,j} C_p (T_i - T_j) \]

### 2.9.4 Large Horizontal Openings

An additional set of equations is needed to model large horizontal openings such as stairwells. The algorithm used is similar to that implemented in Energy Plus, which is based on that given by Cooper (1989). In addition to pressure driven flow using the power law equations of Section
2.9.3.3 this algorithm involves buoyancy induced flows that can occur when the density of the air above the opening is larger than the density of the air below the opening, causing Rayleigh-Taylor instability.

For a given rectangular opening this algorithm can produce three separate flows components between the zones:

a) a forced orifice flow in the direction dictated by the zone to zone pressure difference, Δp. This flow is independent of the following instability induced flows.

b) a buoyancy flow downward when the air density in the upper zone is greater than that in the lower zone, i.e., $T_{\text{upper-zone}} < T_{\text{lower-zone}}$. This flow is maximum when Δp is zero, and linearly decreases with increasing Δp until the buoyancy flow is zero, which occurs when the pressure difference is large enough that the forced flow "overpowers" the instability flow. The latter occurs if Δp is greater than the "flooding" pressure ΔpF.

c) an upward buoyancy flow equal to the downward buoyancy flow.

These three flows are modeled by two flow-elements. The first element handles the forced flow (a) and in addition whichever of the buoyancy flow component, (a) or (c), that is in the same direction as the forced flow. The second element handles the alternate buoyancy flow component.

2.9.4.1 Pressure driven flow

The pressure forced flow is modeled as orifice flow using Equation 143, except the area $A$ in the Section 2.9.3.5 is replaced by:

$$A_{\text{eff}} = L_1 * L_2 * \sin(\text{StairAngle}) * (1 + \cos(\text{StairAngle}))$$

Equation 156

$L_1$ and $L_2$ are the dimensions of the horizontal rectangular hole. To include the effect of stairs, a StairAngle can be set, where StairAngle = 90 deg corresponds to vertical stairs. The angle can be set to 90 degrees to exclude the effect of the stairs.

Equation 144 is used for the partial derivative of the flow, with the area $A_e$ using $A_{\text{eff}}$ in place of $A$.

2.9.4.2 Buoyancy flow

When the zone on top has a higher density than the zone on the bottom, the maximum possible buoyancy flow, $m_{\text{bm}}$, occurs when the pressure difference across the hole is zero:

$$m_{\text{bm}} = 0.055\sqrt{g\Delta\rho|\Delta p|D_{\text{hyd}}^5}$$

Equation 157

The 0.055 factor is dimensionless ; $g = 32.2 \text{ ft/s}^2$.

The hydraulic diameter of the hole is defined as:
\[ D_{hyd} = 2 \times A_{eff} / (L_1 + L_2) \]

Equation 158

When the zone on top has a higher density than the zone on the bottom, and the pressure difference is lower than the flooding pressure, then the buoyancy flow is given by:

\[ mb = mbm \times \left(1 - \frac{\lvert \Delta p \rvert}{\Delta p F} \right) \]

Equation 159

The flooding pressure difference \( \Delta p F \) is defined as:

\[ \Delta p F = C_s^2 g |\Delta \rho| D_{hyd}^5 / (2 A_{eff}^2) \]

Equation 160

The shape factor \( C_s \) is

\[ C_s = 0.942 \left( \text{minimum} \left( \frac{L_1}{L_2}, \frac{L_2}{L_1} \right) \right) \]

Equation 161

If the top zone density is lower than the bottom zones, or if \(|\Delta p| > \Delta p F\) then the buoyancy flow \( mb \) is zero.

The partial derivatives of the buoyancy flows with respect to adjacent zone pressures are all zero since the buoyancy flows are equal and opposite. That is, although the buoyancy flow magnitudes are sensitive to zone pressures, they have no influence on the zone mass balance.

Although the buoyancy flows don't directly influence zone pressures, they do affect the heat transfer rates.

When buoyancy flows exist, the heat transfer due to the buoyancy flow to the upper zone, \( i \) say, is

\[ Q_i = mb \times C_p (T_j - T_i) \]

Equation 162

and to the lower zone is

\[ Q_j = mb \times C_p (T_i - T_j) \]

Equation 163
2.9.5 Large Vertical Openings

The flow through large vertical rectangular openings are handled using the method suggested by Woloszyn (1999).

Woloszyn uses a simplified version of the common integrate-over-pressure-distribution scheme as used by Walker for example. Rectangular holes are divided in two, with the flow through the top half driven by a constant $\Delta p$ equal to the pressure difference $\frac{3}{4}$ the way up the opening (the midpoint of the top half of the opening area). Similarly, the flow through the bottom half uses the $\Delta p$ at $\frac{1}{4}$ the way up the hole, and assumes it is constant over the bottom half. Although approximate compared to the integration methods, it is expected to be able to reasonably accurately, if not precisely, portray one and two way flows through such elements. This procedure has the virtue of eliminating the calculation of the neutral level, thereby greatly reducing the number of code logic branches and equations. It also eliminates a divide by zero problem when $\Delta \rho \to 0$ in the exact integration methods.

Besides being used for large vertical holes, like open windows and doorways, the method is also used for distributed infiltration. That is, a rectangular wall with an effective leakage area ELA is represented by two holes, each of area $\text{ELA}/2$, located at the $\frac{1}{4}$ and $\frac{3}{4}$ heights. These holes are then modeled using Equation 138, Equation 141, Equation 144, and Equation 145.

2.9.5.1 Triangular surfaces

The method is generalized further to treat the tilted triangular surfaces assumed for hip roofs. In this case the lower Woloszyn hole, of area $\text{ELA}/2$, is placed at the height that is above $\frac{1}{4}$ of the area of the triangle. This can be shown to be a height of:

$$H_{\text{lower hole}} = Z_{\text{soffit}} + \left(1 - \frac{\sqrt{3}}{2}\right) (Z_{\text{ridge}} - Z_{\text{soffit}})$$

Equation 164

Similarly, the top hole is placed at the height above $\frac{3}{4}$ of the area of the triangle:

$$H_{\text{upper hole}} = Z_{\text{soffit}} + (1/2)(Z_{\text{ridge}} - Z_{\text{soffit}})$$

Equation 165

2.9.6 Newton-Raphson Solution

Assume there are a total of $nuc$ conditioned and unconditioned zones with unknown pressures. The outside conditions, of known pressure, are assigned a zone number $nout = nuc+1$.

The mass flow rate from zone $i$ to zone $j$ (including $j=nout$) is designated as $m_{i,j}$, and can be positive (flow out of zone $i$) or negative (flow into zone $i$).
where \( m_{i,j,k} \) is the flow rate through the \( k \)'th element of the \( K_{i,j} \) elements in surface \( i,j \). By symmetry,
\[
m_{i,j,k} = -m_{j,i,k}
\]

Equation 167

and
\[
m_{i,j} = -m_{ji}
\]

Equation 168

From Equation 167, \( m_{i,j,k} \) values are functions of the zone pressure difference \( (P_i - P_j) \).
\[
m_{i,j,k} = +A_e \sqrt{2 \rho_{in}} (P_i - P_j)^n \quad \text{for positive } \Delta P
\]
\[
m_{i,j,k} = -A_e \sqrt{2 \rho_{in}} (P_j - P_i)^n \quad \text{for negative } \Delta P
\]

Equation 169

This shows that in general,
\[
\frac{\partial m_{i,j,k}}{\partial P_i} = -\frac{\partial m_{i,j,k}}{\partial P_j}
\]

Equation 170

The net flow leaving zone \( i \) (\( i=1 \) to \( nuc \)) is the defined as the residual \( r_i \):
\[
r_i = \sum_{j=1, j \neq i}^{\text{nout}} m_{i,j} = \sum_{j=1, j \neq i}^{\text{nout}} \sum_{k=1}^{K_{i,j}} m_{i,j,k}
\]

Equation 171

The \( j \neq i \) criterion on the sums eliminates summing \( m_{i,j} \) terms which are zero by definition. The zone pressures \( P_i \) are to be determined such that the residuals \( r_i \) all become zero.

Equation 169 and Equation 171 constitute a set of \( n = \text{nuc} \) nonlinear equations with \( n = \text{nuc} \) unknown pressures. To linearize the equations, a Taylor’s series is used to determine the residual \( r_i' \) at the pressure \( P_j' \) near the guessed value of pressures \( P_j \), where the residual is \( r_i \).

Keeping only first order terms:
\[ r'_i = r_i + \sum_{j=1}^{\text{nuc}} \frac{\partial r_i}{\partial p_j} (p'_j - p_j) \]

*Equation 172*

In matrix form this is written:

\[ r' = r + J (P' - P) \]

*Equation 173*

where \( r' \) is the vector with elements \( r'_i \), and \( r \) is the vector with elements \( r_i \).

\( J \) is the \( \text{nuc-by-\text{nuc}} \) Jacobian matrix with elements:

\[ J_{i,l} = \frac{\partial r_i}{\partial p_l} = \sum_{j=1}^{\text{nout}} \frac{\partial m_{i,j}}{\partial p_l} = \sum_{j=1,j\neq i}^{\text{nout}} \sum_{k=1}^{\text{nuc}} \frac{\partial m_{i,j,k}}{\partial p_l} \]

*Equation 174*

where \( i = 1 \text{ to } \text{nuc}, \text{ and } l = 1 \text{ to } \text{nuc} \).

Setting \( r'_i = 0 \) and solving for \( p'_j \), Equation 173 becomes

\[ P' = P - J^{-1} r \]

*Equation 175*

\[ P' = P - C \]

*Equation 176*

where \( C \) is the correction vector:

\[ C = -J^{-1} r \]

*Equation 177*

\[ p'_i = p_i - C_i \]

*Equation 178*

Equation 178 gives the pressures \( p'_i \) that are predicted to make \( r'_i \) zero.

### 2.9.6.1 Convergence

Convergence is attained when the residuals \( r_i \) are sufficiently small. As employed by Energy Plus and Clarke, both absolute and relative magnitude tests are made.
Convergence is assumed when the absolute magnitude of the residual in each zone $i$ is less than a predetermined limit $ResMax$:

$$|res_i| < ResMax$$  

*Equation 179*

OR, the magnitude of the residual divided by the sum of the magnitudes of the flow through each element connected to zone $i$, is less than a predetermined limit $ResErr$:

$$\frac{|res_i|}{resmag_i} < ResErr$$  

*Equation 180*

where

$$resmag_i = \sum_{j=1}^{nout} |m_{i,j}|$$  

*Equation 181*

(code uses: sum of magnitude of flows to & from zone $iz$, resmag($iz$) += ABS(mdot($iz,jz,ke$)).

### 2.9.6.2 Relaxation

Equation 178 is more generally written as

$$P_i' = P_i - relax \cdot C_i$$  

*Equation 182*

where $relax$ is the relaxation coefficient, a factor less than one that reduces the correction applied to $P_i$. Relaxation factors on the order of 0.75 have been shown to reduce the number of iterations in cases normally having slowly decreasing and oscillating corrections. But a fixed value of 0.75 can slow what were formerly rapidly converging cases. The following approach is used to reduce the relaxation factor only when necessary.

Following Clarke, when the corrections $C_i$ from one iteration to the next changes sign, and the latest $C_i$ has a magnitude over half as big as the former $C_i$, then it is assumed that the convergence is probably slow and oscillating. This symptom is typically consistent over a few iterations, and if this were precisely the case, the correction history would follow a geometric progression with a negative common ratio $\frac{C_i}{C_{i\text{last}}}$. Thus by extrapolation a better estimate of correct solution will be obtained if the relaxation factor is taken as the sum of the infinite termed geometric progression:

$$relax = \frac{1}{1 - \frac{C_i}{C_{i\text{last}}}}$$
Thus, whenever, during an iteration for zone $i$,

\[ \frac{C_i}{C_i^{\text{last}}} < -0.5 \]

\textit{Equation 184}

then Equation 178 is replaced by

\[ P_i' = P_i - \frac{1}{1 - \frac{C_i}{C_i^{\text{last}}} * C_i} \]

\textit{Equation 185}

Insofar as the extrapolation is warranted, this should give a better prediction of the pressure $P_i'$ than would using $\text{relax} = 1$ for this iteration. For the iteration following that using Equation 185, $\text{relax} = 1$ is reverted to (i.e., Equation 178) so that only unrelaxed correction values are used to evaluate $\frac{C_i}{C_i^{\text{last}}}$. The following iteration, if any, is then again tested by Equation 184. The first iteration is always done with $\text{relax} = 0.75$ since at this point there is no value available for $C_i^{\text{last}}$. It would be reasonable to add a max $Ci$ limit; i.e., max pressure change allowed, a la Clarke, but code testing has not shown the need.

2.9.6.3 Off diagonal terms

Consider Equation 174 for off-diagonal terms. Since $i \neq l$, zone i’s flow $m_{i,j}$ varies with $P_l$ only if $j = l$. Thus setting $j = l$, and $i \neq l$, Equation 174 reduces to:

\[ J_{i,i\neq l} = \sum_{k=1}^{K_{il}} \frac{\partial m_{i,i,l}}{\partial P_l} \]

\textit{Equation 186}

where $i = 1$ to $\text{nuc}$, and $l = 1$ to $\text{nuc}$.

Equation 186, along with Equation 170, shows that all off diagonal terms have a negative magnitude. Since $m_{i,l,k} = -m_{i,l,k}$,

\[ J_{i,i\neq l} = \sum_{k=1}^{K_{il}} \frac{\partial m_{i,l,k}}{\partial P_l} = - \sum_{k=1}^{K_{il}} \frac{\partial m_{i,l,k}}{\partial P_l} \]

\textit{Equation 187}

Using Equation 170, Equation 187 becomes:
Thus the Jacobian matrix is symmetric:

\[ J_{i,i} = J_{i,i} \]

Equation 189

Thus only the upper (or lower) diagonal terms need be determined, with the other half determined by transposition. The off diagonal terms only involve partials of flows between zones with unknown pressures.

2.9.6.4 Diagonal terms

For \( i = j \) Equation 174 gives:

\[ J_{i,i} = \frac{\partial r_i}{\partial p_i} = \sum_{j=1}^{\text{nout}} \frac{\partial m_{i,j}}{\partial p_i} = \sum_{j=1}^{\text{nout}} \sum_{k=1}^{k=i,j} \frac{\partial m_{i,j,k}}{\partial p_i} \]

Equation 190

where \( i = 1 \) to \( \text{nuc} \).

Equation 190 terms can be regrouped to show a simpler numerical way to determine \( J_{i,i} \) by using the off diagonal terms already calculated:

\[ J_{i,i} = \frac{\partial m_{i,\text{nout}}}{\partial p_i} - \sum_{k=1}^{k=\text{nuc}} J_{k,i} \]

Equation 191

This shows that the diagonal elements use the derivatives of mass flows to the outdoors minus the off diagonal terms in the same column of the Jacobian.

Equation 191 shows that matrix will be singular if \( \frac{\partial m_{i,\text{nout}}}{\partial p_i} = 0 \), so that at least one connection to outdoors is necessary.
2.10 Duct System Model

2.10.1 Description of Model

The duct model builds on the procedure given by Palmiter (see Francisco and Palmiter, 2003), that uses a steady state heat exchanger effectiveness approach to get analytical expressions for instantaneous duct loss and system efficiencies. The duct model, developed for this program by Palmiter, makes use of many of the same fundamental steady state equations and approach, but given the considerable complexity of the multiple duct systems, does not do a simultaneous solution of all the equations which a generalized Francisco and Palmiter scheme may imply. Instead the approach takes advantage of the small time steps used in the code, and in effect decouples the systems from each other and the zone by basing all losses and other heat transfers occurring during the time step on the driving conditions of Tair and Tmrt known at the beginning of the time step, similar to how heat transfers are determined during mass temperature updates.

Other assumptions made in the duct program: mass and thermal siphon effects in the duct system are ignored.

The duct system performance is analyzed at every time step. The duct air temperatures are calculated assuming they are operating at steady state, in equilibrium with the thermal conditions at the beginning of the time-step in the attic. Heat capacity effects of the ducts are ignored.

During each time step, the following steps are taken to find the duct system operating conditions such as the air temperatures in each duct, the losses, the heating or cooling delivered, etc.

Initially, for each time step, the duct systems performance is determined when operating at full capacity, independent of the load. The procedure starts at the return registers in each conditioned zone, where the duct air temperatures are the current timesteps conditioned zone air temperatures. The conditioned zone air entering the return register heats or cools, or both, as it traversed through each component of the duct system: the return duct, the return plenum, the heating/cooling device, and the supply ducts. That is, the duct air temperature rises or drops immediately downstream of the return register (where returns leaks are assigned to occur) due to mixing of leakage air at the air temperature in the unconditioned zone in which the return duct is located with the return air from the conditioned zone. It may also increase or decrease in temperature in the return plenum as it mixed with the air from the return duct in another unconditioned zone. After being heated or cooled by the air handler at its applicable heating/cooling capacity, it is then additionally heated or cooled by supply duct conductive gains/losses to the interior of the unconditioned zone.

Summing all the gains and losses in temperature of the duct air as it travels through the system gives the supply temperature for the supply duct, allowing the heat delivered at full capacity, $Q_{del}$, to be determined.
If the above useful heat delivered at full capacity is more than required by the load, then the equipment capacity is reduced to meet the load by assuming the system is only running the fraction \( \frac{Q_{load}}{Q_{del}} \) of the time step. The needed capacity, \( Q_{need} \), is this fraction of the nominal capacity. The duct losses for the time step are also reduced by this fraction.

The above calculations are done each time step and the average \( Q_{need} \) summarized in the hourly output.

The above steps are presented in detail in the following sections, in the same sequence as described above.

### 2.10.2 Duct System Inputs

#### 2.10.2.1 Subscripts

In most cases in this section, the subscripted variables stand for arrays.

The subscript \( u \) stands for the unconditioned zone in which the duct is located.

The subscript \( c \) stands for conditioned zone number and its associated air handler system.

The subscript \( m \) stands for the mode of air handler operation: 0 off, 1 heating, 2 cooling.

#### 2.10.2.2 Annual run inputs

The following data is input to model the duct/air handler system(s):

**Duct inside areas**

- \( A_{sd_{c,u}} \) = supply duct inside area for air handler \( c \) in unconditioned zone \( u \).
- \( A_{rd_{c,u}} \) = return duct inside area for airhandler \( c \) in unconditioned zone \( u \).

**Duct insulation rated R values**

- \( R_{sd_{c,u}} \) = supply duct rated R for air handler \( c \) in unconditioned zone \( u \); hr-ft\(^2\)-F/Btu.
- \( R_{rd_{c,u}} \) = return duct rated R for air handler \( c \) in unconditioned zone \( u \); hr-ft\(^2\)-F/Btu.

**Inside duct area and inside area based resistance, and the outside duct area and outside area based resistance when there is a single duct segment in the return and supply branches**

Consider one duct of constant inside diameter, \( d_i \), and length \( L \). The duct is insulated with insulation having a thermal conductivity \( k \), and rated R value, \( R_{rate} \). All R values herein are in the units of (hr-ft\(^2\)-F/Btu).

Layed flat, the thickness the insulation layer is:

\[
t = R_{rate} \times k
\]
If the insulation is wrapped at this thickness around a duct of diameter $d_i$, the outside diameter, $d_o$, of the insulation will be:

$$d_o = d_i + 2 \times \text{Rate} \times k$$

so,

$$\frac{d_o}{d_i} = 1 + \frac{2k\text{Rate}}{d_i}$$

Equation 193

Conduction heat transfer texts gives the overall conductance $C$ of length $L$ of an annular insulation layer as:

$$C = \frac{2\pi kL}{\ln \left( \frac{d_o}{d_i} \right)}$$

Equation 194

Dividing this by inside area, $A_i = \pi d_i L$, gives the conductance per unit inside area:

$$C_i = \frac{2k}{d_i \ln \left( \frac{d_o}{d_i} \right)}$$

The duct resistance value per unit inside area is the reciprocal,

$$R_i = \frac{d_i \ln \left( \frac{d_o}{d_i} \right)}{2k}$$

Equation 195

This can be written in terms of areas, and length $L$, as:

$$R_i = \frac{A_i \ln \left( \frac{A_o}{A_i} \right)}{2\pi kL}$$

Equation 196

The duct resistance value based on outside area can be determined from $R_i$ and $A_i$ as:

$$R_o = \frac{d_o}{d_i} R_i$$

Equation 197

$$A_o = \frac{d_o}{d_i} A_i$$
The $R$ values of Equation 195 and Equation 197, divided by $R_{\text{rated}}$, are plotted in Figure 25 as a function of the inside diameter of the duct branch.

**Figure 25: Ratio of Actual R to Rated R**

![Figure 25: Ratio of Actual R to Rated R](image)

**Duct system composed of multiple segments in the supply and return branches**

Suppose the supply ducts from an air handler system are branched, with each branch having different sizes, lengths, rated insulation $R_{\text{rate}}$, and conductivity $k$ values, and all the branches are in one unconditioned zone. These could be combined into one equivalent duct as follows.

The duct branches, $j=1 \rightarrow n$, are combined, each of inside areas $A_i(j)$, outside areas $A_o(j)$, conductivities $k(j)$, and inside area based resistances $R_i(j)$. Using the method of Palmiter and Kruse (2003), the overall conductance of the branched duct system, based on inside area, is the sum of the conductances of each branch:

$$U'A' = \sum_{j=1 \rightarrow n} \left( \frac{A_i(j)}{R_i(j)} \right)$$  \hspace{1cm}  \text{Equation 198}

where $R_i$ for each branch segment $j$ is given by Equation 196 as

$$R_i(j) = \frac{A_i(j) \ln \left( \frac{A_o(j)}{A_i(j)} \right)}{2\pi k(j)L(j)}$$  \hspace{1cm}  \text{Equation 199}

With $A_i(j) = \pi d_i(j)L(j)$, and using Equation 193, this can be written as
The total branch inside area is:

\[ A_i = \sum_{j=1}^{n} A_i(j) \]  

Equation 201

The effective overall resistance of the branched duct, based on inside area \( A_i \), is thus:

\[
R_i = \frac{A_i}{UA'} = \frac{A_i}{\sum_{j=1}^{n} \left( \frac{A_i(j)}{R_i(j)} \right)} = \frac{A_i}{\sum_{j=1}^{n} \left[ d_i(j)ln\left(1 + \frac{2k(j)R_{rate}(j)}{d_i(j)}\right) \right]}
\]

Equation 202

The values of the terms needed for each branch segment, shown on the right hand side of Equation 202 are not available since the former ACM manual only requires that the following \( R \) is known:

\[ "R" = \frac{A_i}{\sum_{j=1}^{n} \frac{A_i(j)}{R_{rate}(j)}} \]

Equation 203

Equation 202 and Equation 203 would be equivalent if Equation 203 had the term \( R_i(j) \) in place of \( R_{rate}(j) \). As it is, Equation 203 gives the area weighted average \( R_{rate} \), not \( R_i(j) \).

The total outside area is:

\[ A_o = \sum_{j=1}^{n} A_o(j) \]

Equation 204

Based on outside area, the effective duct system resistance would be:

\[ R_o = \frac{A_o}{A_i} R_i \]

Equation 205
2.10.2.3 Emissivities

\[ e_{ps\text{s}_{c,u}} = \text{supply duct emissivity for air handler } c \text{ in unconditioned zone } u. \]
\[ e_{psr_{c,u}} = \text{return duct emissivity for air handler } c \text{ in unconditioned zone } u. \]

2.10.2.4 Duct leakage

\[ L_{s_{c,u}} = \text{the fraction of the flow through the system } c \text{ air handler fan that is leaked from the supply duct in unconditioned zone } u. \] The leak is assigned to occur near the supply register so that the leakage air is at the supply register temperature.

\[ L_{r_{c,u}} = \text{the fraction of the flow through the system } c \text{ air handler fan that is leaked into the return duct in unconditioned zone } u. \] The leak is assigned to occur at the return register. The air leaking into the duct is at the unconditioned zone temperature.

2.10.2.5 System flow

\[ \text{Flow}_{w_{m,c}} = \text{the flow rate in cfm (at standard conditions) through the air handler for the cooling and heating modes, for each system.} \]

2.10.2.6 Flow distribution

How much of the air handler flow of system \( c \) goes through each of its return and supply ducts is given by the per run input flow fractions:

\[ F_{mr_{c,u}} = \text{fraction of flow of system } c \text{ in the return duct located in unconditioned zone } u. \]
\[ F_{ms_{c,u}} = \text{fraction of flow of system } c \text{ in the supply duct located in unconditioned zone } u. \]
\[ F_{mr_{c,c}} = \text{fraction of flow of system } c \text{ in the return duct located in conditioned zone } c. \]
\[ F_{ms_{c,c}} = \text{fraction of flow of system } c \text{ in the supply duct located in conditioned zone } c. \]

For a given system \( c \), the sum of the return duct fractions must add to one: \( F_{mr_{c,1}} + F_{mr_{c,2}} + F_{mr_{c,c}} = 1 \). Similarly for the supply duct fractions.

2.10.3 Return Duct Air Temperatures

Following the procedure indicated in Section 2.10.1, the return duct air temperatures are determined first. Utilizing the heat exchanger effectiveness approach (see Mills (1992), and Appendix A), the temperature of the system \( c \) return duct air entering the return plenum from a return duct located in unconditioned zone number \( u \) is given by:

\[ T_{out_{c,u}} = Er_{m,c,u} T_{eqr_{c,u}} + \left( 1 - Er_{m,c,u} \right) \cdot T_{mix_{c,u}} \]

where \( Er_{m,c,u} \) is the effectiveness of the return duct of system \( c \) in unconditioned zone \( u \) when operating in mode \( m \):

\[ Er_{m,c,u} \]
where $U_{rtot,c,u}$ is the total conductance between the return duct air and the equivalent surroundings temperature $T_{eqr,c,u}$:

$$T_{eqr,c,u} = (Frda_{c,u} \cdot T_{air,u} + Frdr_{c,u} \cdot T_{mrt,u}).$$

$Frda_{c,u}$ is the fraction of return duct (dissolved surface node) conductance that goes to the $T_{air,u}$ node.

$$Frda_{c,u} = \frac{U_{rc,c,u}}{U_{rc,c,u} + U_{rr,c,u}}$$

$Frdr_{c,u}$ is the fraction of the conductance from the $c,u$ return duct air that goes to the $T_{mrt,u}$ radiant node.

$$Frdr_{c,u} = \frac{U_{rr,c,u}}{U_{rc,c,u} + U_{rr,c,u}}$$

The $U$ terms are the conductances from the duct air to the mrt and air nodes, determined as described in Appendix A. These conductance values, and the similar supply duct values of Section 2.10.6 are used in the energy balance of the unconditioned zone(s) containing ducts.

$U_{rr,c,u}$ = conductance from return duct air to $T_{mrt}$.

$U_{rc,c,u}$ = conductance from return duct air to $T_{air}$.

$U_{rtot,c,u} = U_{rc,c,u} + U_{rr,c,u}$

The term $M_{cp}^{m,c,u}$ is the flow conductance (see below) for the return duct flow:

$$M_{cp}^{m,c,u} = M_{cp}^{m,c} \cdot F_{mr,c,u}$$

The total system flow, $M_{cp}^{m,c}$ is in the "flow conductance" form with the units Btu/hr-F:

$$M_{cp}^{m,c} = Flow_{m,c} \cdot c_p$$

where $c_p$ is the volumetric heat capacity, which is taken as 1.08 Btu/(hr-F-cfm) for dry air at the ASHRAE standard conditions of density = 0.075 lbm/ft$^3$ and $c_p = 0.24$ Btu/lb-m-F.

The term $T_{mix,c,u}$ is the mixed air just downstream of the return duct leakage, given by:

$$T_{mix,c,u} = Lr_{c,u} T_{air,u} + (1 - Lr_{c,u}) Temp_c$$

where $Temp_c$ is the temperature of conditioned zone c's air, assumed to be well-mixed.

2.10.4 Return Plenum Temperature and Return Duct Conductive Heat Losses

The heat loss rate from the return duct via convection and radiation, needed in the unconditioned zone energy balance, is:

$$q_{lr,c,u} = M_{cp}^{m,c,u} \cdot (T_{mix,c,u} - T_{out,c,u})$$
The final return plenum temperature of system c is found by summing the contributions to its plenum temperature from the return ducts in each unconditioned zone and the return ducts located in the conditioned zone. That is,

\[ T_{rp_c} = F_{mr_c} \cdot Temp_c + \sum_{all\;u} F_{mr_{c,u}} \cdot Tout_{c,u} \]

### 2.10.5 Temperature Rise through Air Handler Heating or Cooling Equipment

If the mode is heating or cooling, the temperature rise through the air handler heating or cooling equipment of system c at sensible capacity \( Cap_c \) is given by:

\[ dte_c = \frac{Cap_c}{Mcp_{m,c}} \]

Equation 206

The program considers no heat losses or gains from the air handler components other than from the ducts.

### 2.10.6 Supply Plenum and Supply Register Temperatures

The supply plenum temperature is given by:

\[ T_{sp_c} = T_{rp_c} + dte_c \]

Equation 207

The supply register temperature for the supply duct of system c in unconditioned space u is:

\[ T_{sr_{c,u}} = Teqs_{c,u} + (1 - E_{s_{m,c,u}}) \cdot (T_{sp_c} - Teqs_{c,u}) \]

Equation 208

where \( E_{s_{m,c,u}} \) is the effectiveness of the supply duct of system c in unconditioned zone u when operating in mode m:

\[ E_{s_{m,c,u}} = 1 - e^{-\frac{\text{Ulost}_{c,u}}{Mcp_{s_{m,c,u}}}} \]

Substituting the \( T_{sp_c} \) equation above into Equation 208 and rearranging gives:

\[ T_{sr_{c,u}} = (1 - E_{s_{m,c,u}})dte_c + T_{srhx_{m,c,u}} \]

Equation 209

where

\[ T_{srhx_{m,c,u}} = (1 - E_{s_{m,c,u}})T_{rp_c} + E_{s_{m,c,u}}Teqs_{c,u} \]
2.10 Duct System Model

The term \(s_{c,u}\), similar to \(Teqr_{c,u}\) of Section 2.10.3, is an equivalent environmental temperature defined by

\[
Teqs_{c,u} = (Fsda_{c,u} \cdot Tair_{u} + Fsdr_{c,u} \cdot Tmrt_{u})
\]

where

\[
Fsda_{c,u} = \frac{Usc_{c,u}}{Usc_{c,u} + Usr_{c,u}}
\]
\[
Fsdr_{c,u} = \frac{Usr_{c,u}}{Usc_{c,u} + Usr_{c,u}}
\]

\(Usr_{c,u}\) = conductance from supply duct air to \(Tmrt\).

\(Usc_{c,u}\) = conductance from supply duct air to \(Tair\).

\(Usto_{c,u} = Usc_{c,u} + Usr_{c,u}\)

The supply duct flow rate is:

\[
Mcps_{m,c,u} = Mcp_{m,c} \cdot Fms_{c,u}
\]

### 2.10.7 Heating/Cooling Delivered and Supply Duct Conductive Heat Loss

Given \(Ts_{c,u}\), from above, the heat delivered to the conditioned zones by way of the supply ducts located in one or more of the unconditioned zones is given by summing the sensible heat delivered via each unconditioned zones:

\[
Q \text{ delivered from ducts } = \sum_{u} Mcpsr_{m,c,u} \cdot (Ts_{c,u} - Temp_{c})
\]

\(Equation \ 210\)

where \(Mcpsr_{m,c,u}\), the flow out the supply register after the supply leakage is removed, is given by:

\[
Mcpsr_{m,c,u} = (1 - Ls_{c,u}) \cdot Mcps_{m,c,u}
\]

The heat delivered to the conditioned zones by way of ducts in the conditioned zone, which are assumed to have no losses or unbalanced leakage, is given by:

\[
Q \text{ delivered directly to conditioned zone } = Fmsc \cdot Cap_{c}
\]

\(Equation \ 211\)

Adding the Q’s of Equation 210 and Equation 211 gives the net heating (+), or cooling (-), delivered by the system \(c\) as:
\[ Q_{del_c} = F_{msc} \cdot C_{ap_c} + \sum_{u} [M_{cpsr_{m,c,u}} \cdot (T_{sr_{c,u}} - T_{temp_c})] \]

Substituting the expression for \( T_{sr_{c,u}} \) from Equation 209 into this, \( Q_{del_c} \) can be put in the form:

\[ Q_{del_c} = Q_{del1_c} + Q_{del2_c} \]

where \( Q_{del1_c} \) is the part of \( Q_{del} \) that is independent of air handler capacity. That is, it is the \( Q \) delivered if \( dte \) is zero, and is the heat exchanged between the unconditioned and conditioned zones via the duct system:

\[ Q_{del1_c} = \sum_{u} [M_{cpsr_{m,c,u}} \cdot (T_{srhx_{m,c,u}} - T_{temp_c})] . \]

\( Q_{del2_c} \) is the part of \( Q_{del} \) that is linearly dependent on the air handler capacity:

\[ Q_{del2_c} = F_{msc} \cdot C_{ap_c} + \sum_{u} [M_{cpsr_{m,c,u}} \cdot (1 - E_{s_{m,c,u}}) \cdot dte_c] \]

The rate of supply duct conduction losses this time step is given by:

\[ q_{ls_{c,u}} = M_{cpsr_{m,c,u}} \cdot (T_{sp_{c}} - T_{sr_{c,u}}) \]

2.10.8 Duct System Performance when the Load is Less than the Heat Delivered at Full Capacity

If \( Q_{ld_c} \) is smaller than the capacity \( Q_{del_c} \), then the system runs only part of the time step. In this case the run time fraction is:

\[ F_{run_c} = \frac{Q_{ld_c}}{Q_{del_c}} \]

The capacity required to meet the load is \( Q_{need_c} \):

\[ Q_{need_c} = F_{run_c} \cdot C_{ap_c} \]

The duct conductive and leakage losses are also reduced by the same \( F_{run_c} \) fraction.

2.10.9 Duct System Performance when the Load is Greater than the Heat Delivered at Full Capacity

In principle this won’t occur because the conditioned zone load is limited to the system capacity when it is calculated by the conditioned zone thermostat logic. However, the capacity thus calculated is based on the duct efficiency [defined as \( \eta = Q_{load}/Q_{need} \)] determined for the unconditioned zone during the last time-step, and as a result the load might exceed the capacity determined by the duct model efficiency this time-step.

That is, when the conditioned zone energy balance is performed, and for example heating is called for, then the output capacity of the heating system needs to be known, which requires
knowing the duct system efficiency. But the duct efficiency is only known after the attic simulation is run.

To avoid iteration between the conditioned zone and attic zone modules, the most recent duct efficiency is used to determine the capacity in the conditioned zones thermostat calculations. When the attic simulation is next performed, if the conditioned zone was last running at capacity, and if the efficiency now calculated turns out to be higher than was assumed by the thermostat calculations, then the load will have exceeded the limiting capacity by a small amount depending on the assumed vs. actual efficiency. In cases like this, to avoid iteration, the limiting capacity is allowed to exceed the actual limit by a small amount, so that the correct air handler input energy demand is determined for the conditioned zone load allowed.

In this case, the system is set to run for the full sub-hour time step and the air handler meets the load by increasing its capacity with the following procedure. This procedure, a carryover from the 2008 Residential Building Standards ACM procedures, wherein no capacity limits were imposed on the air handler systems, is as follows.

From the $Q_{del1}$ and $Q_{del2}$ equations it can be seen that the capacity needed in this case is:

$$Q_{need} = \frac{Q_{ld} - Q_{del1}}{Q_{del2}} \cdot Cap_c$$

Thus, the temperature rise through the air handler needs to be:

$$dte_c = \frac{Q_{need}}{Mcp_{m,c}}$$

The supply plenum temperature becomes:

$$Tsp_{c} = Trp_{c} + dte_c$$

The supply register temperatures is determined reusing Equation 208:

$$Ts_{r,c,u} = Teq_{s} + (1 - Es_{m,c,u}) \cdot (Tsp_{c} - Teq_{s,c,u})$$

The supply duct losses now become:

$$qls_{c,u} = Mcps_{m,c,u} \cdot (Tsp_{c} - Ts_{r,c,u})$$

The $Q_{need}$'s from each of the time steps during the hour are summed over the hour and reported in the output as $Q_{need}$. The supply and return duct conduction loss terms $qls_{c,u}$ and $qlr_{c,u}$ are used in the energy balance of the unconditioned zone each time step.

### 2.11 Variable Insulation Conductivity

The following correlation is used. It is based on the correlation used in EnergyGauge USA (Parker, et al, 1999) which is based on Wilkes (1981) data:
2.11 Variable Insulation Conductivity

\[ k = (kn) \cdot (1 + 0.00418(T_{\text{insul}} - 70)) ; \text{temperatures in } ^\circ\text{F}. \]

where,

- \( k \) = insulation conductivity (Btu/hr-ft-R) at the average insulation temperature, \( T_{\text{insul}} \).
- \( kn \) = nominal insulation conductivity (Btu/hr-ft-R) for insulation at 70 F.

2.12 Ceiling Bypass Model

A simple model was implemented to simulate ceiling bypass heat transfer, the heat that is transported from the conditioned zone to the attic via miscellaneous inter-wall cavities in the conditioned zone that may be partially open to the attic, as for example around a fireplace unit. Natural convection in the cavity when the conditioned zone is hotter than the attic is assumed to be the main mechanism for the bypass heat transfer. The conductance, when the conditioned zone air temperature \( T_{\text{air}_c} > T_{\text{air}_u} \), the attic air temperature:

\[ q_{bp} = U(T_{\text{air}_c} - T_{\text{air}_u}) \]

where, the conductance follows a simple power law dependence on the temperature difference:

\[ U = U_{bp}(Temp_1 - T_{air_u})^{nbp} \]

\( U_{bp} \) is a coefficient depending on the cavity geometry. Although an exponent of \( nbp \) on the order of 1/4 can be assumed for laminar convection, there is no current empirical basis for determining the exponent. If the ACM rule of \( U = 0.02Ac_{ceil} \) were implemented, then \( nbp \) would be chosen as zero.

2.13 Zone Humidity Balance

2.13.1 Zone Humidity Balance

Given a zone with various flows, \( m_j \), with humidities \( w_j \), entering the zone, and with a scheduled source of water vapor, \( m_{sched} \), a water mass balance on the zone gives:

\[ \frac{dM_w}{dt} = \sum_j m_j(w_j - w) + m_{sched} \]

which can be written as:

\[ M \frac{dw}{dt} = \sum_j m_j(w_j - w) + m_{sched} - w \frac{dM}{dt} \]

Equation 212
where,

\[ M = \text{mass of dry air in the zone; Lbm of dry air.} \]

\[ \frac{dw}{dt} = \text{the rate of change of humidity ratio in zone.} \]

\[ m_j = \text{air flow rate from source } j \text{ into zone; Lbm-dry-air/unit-time. Source } j \text{ can be outdoors, a supply register, adjacent zone, etc.} \]

\[ w_j = \text{humidity ratio of air coming from source } j; \text{ Lbm H}_2\text{O/lbm dry air.} \]

\[ w = \text{humidity ratio of air in zone; Lbm H}_2\text{O/lbm dry air.} \]

\[ m_{sched} = \text{scheduled rate of moisture addition to zone; Lbm H}_2\text{O/unit time.} \]

Using the air perfect gas equation the last term in Equation 213 can be written

\[ \frac{dM}{dt} = -w \frac{M}{T} \frac{dT}{dt} \]

so that Equation 213 becomes

\[ M \frac{dw}{dt} = \sum_j m_j (w_j - w) + m_{sched} + w \frac{M}{T} \frac{dT}{dt} \]

Equation 214

where \( T \) is the air temperature in absolute degrees.

This equation is solved using a forward difference rather than a backward or central difference since a forward difference uncouples the moisture balance equations of each of the zones. Integrating from time \( t \) to time \( t + \delta t \), where \( \delta t \) is the time step, using a forward difference, gives:

\[ w(t + \delta t) \]

\[ = \left( m_{sched}(t) + \sum_j m_j(t)w_j(t) \right) \frac{\delta t}{M(t)} \]

\[ + w(t) \left( 1 - \frac{\delta t}{M(t)} \sum_j m_j(t) - \frac{T(t + \delta t) - T(t)}{T(t)[\text{deg R}]} \right) \]

Equation 215

Notice that all of the values on the right hand side of Equation 215 are determined at \( t \) (the beginning of the integration period) except for the \( T(t + \delta t) \) term which represents the zone air temperature at the end of the integration period. \( T(t + \delta t) \) is known from the zone energy.
sensible energy balance at time $t$ (see Section 2.3). The term $\frac{T(t+\delta t) - T(t)}{T(t)[\text{deg R}]}$ is assumed to be negligible and not included in the CSE code.

### 2.13.2 Stability of Solution

The time series solution of Equation 215 will become unstable unless the second term is positive. That is, stability requires

\[
\left( \frac{\delta t \sum_j m_j(t) + T(t+\delta t) - T(t)}{M(t)} \right) < 1
\]

Equation 216

Solving for $\delta t$, stability requires

\[
\delta t < \frac{M(t)}{\sum_j m_j(t)} \left( 1 - \frac{T(t+\delta t) - T(t)}{T(t)[\text{deg R}]} \right)
\]

Equation 217

Since the zone air changes per unit time is $AC = \frac{\sum_i m_i(t)}{M(t)}$ then the stability requirement can be written in terms of air changes as:

\[
AC < \frac{1}{\delta t} \left( 1 - \frac{T(t+\delta t) - T(t)}{T(t)[\text{deg R}]} \right)
\]

Equation 218

If the solution is unstable at the given $\delta t$, the zone air mass $M(t)$ can be temporarily boosted up such that:

\[
M(t) > \frac{\delta t \sum_j m_j(t)}{\left( 1 - \frac{T(t+\delta t) - T(t)}{T(t)[\text{deg R}]} \right)}
\]

This will lead to a higher latent capacity for the zone air, introducing some error in the zone humidity prediction. This will also lead to a zone latent heat imbalance unless this artificial increase in zone air is accounted for.

### 2.13.3 Hygric Inertia of Zone

The absorption/desorption of moisture in the zone is accounted for using the hygric inertial model of Vereecken et al. whereby a multiplier $X$ is added to the $M(t)$ term of Equation 10 and Equation 11. An appropriate value of $X$ can be measured for the complete zone and all of its furnishings by using the protocol given by [Vereecken E, Roels S, Janssen H, 2011. In situ...

2.14 Zone Comfort Algorithm

CSE includes an implementation of the ISO 7730 comfort model. The model is documented in ASHRAE Standard 55-2010 (ASHRAE 2010) among other places. The model calculates Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) for each zone at each time step. These statistics are averaged over days, months, and the full year.

The inputs to the ISO 7730 model are:

- Air dry-bulb temperature
- Air humidity ratio
- Mean radiant temperature
- Air velocity
- Occupant metabolic rate
- Occupant clothing level

Zone conditions calculated by CSE are used for the first three of these inputs. The remaining inputs are set by user input. They can be varied during the simulation using the CSE expression capability.

2.15 HVAC Equipment Models

Air conditioning systems shall be sized, installed, tested and modeled according to the provisions of this section.

2.15.1 Compression Air-Conditioner Model

The Compliance Software calculates the hourly cooling electricity consumption in kWh using Equation 219. In this equation, the energy for the air handler fan and the electric compressor or parasitic power for the outdoor unit of a gas absorption air conditioner are combined. The Compliance Software calculates the hourly cooling gas consumption in therms using Equation 219.

\[
AC_{\text{kWh}} = \frac{\text{Fan}_{\text{Wh}} + \text{Comp}_{\text{Wh}}}{1,000}
\]

Equation 219
Where:

$AC_{kWh} = \text{Air conditioner kWh of electricity consumption for a particular hour of the simulation. This value is calculated for each hour, combined with the TDV multipliers, and summed for the year.}$

$Fan_{Wh} = \text{Indoor fan electrical energy for a particular hour of the simulation, Wh.}$

$Comp_{Wh} = \text{Electrical energy for all components except the indoor fan for a particular hour of the simulation, Wh. This value includes consumption for the compressor plus outdoor condenser fan and is calculated using Equation 221.}$

CSE calculates the energy for electrically driven cooling using the algorithms described in this section.

**Primary model parameters.** The following values characterize the AC unit and are constant for a given unit:

- $Cap_{95} = \text{AHRI rated total cooling capacity at } 95 \, ^\circ\text{F, Btuh}$
- $CFM_{per\, ton} = \text{Air flow rate per ton of cooling capacity, cfm/ton.}$

\[
= \frac{\text{Operating air flow rate, cfm}}{\text{Cap}_{95} / 12000}
\]

- $EFan = \text{Fan operating electrical power, W/cfm. Default } = 0.365.$
- $SEER = \text{AHRI rated Seasonal Energy Efficiency Ratio, Btuh/W. EER shall be used in lieu of the SEER for equipment not required to be tested for a SEER rating.}$
- $EER = \text{AHRI rated energy efficiency ratio at } 95 \, ^\circ\text{F, Btuh/W. If EER is not available, it is derived from SEER as follows:}$

<table>
<thead>
<tr>
<th>If SEER</th>
<th>$&gt;=16$</th>
<th>$&gt;=13 &amp; &lt;16$</th>
<th>$&lt;13$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EER</td>
<td>13</td>
<td>$11.3 + 0.57 \times (\text{SEER}-13)$</td>
<td>$10+0.84 \times (\text{SEER}-11.5)$</td>
</tr>
</tbody>
</table>

- $F_{chg} = \text{Refrigerant charge factor, default } = 0.9. \text{ For systems with a verified charge indicator light (Reference Residential Appendix RA3.4) or verified refrigerant charge (Reference Residential Appendix RA3), the factor shall be } 0.96.$

- $F_{size} = \text{Compressor sizing factor, default } = 0.95. \text{ For systems sized according to the Maximum Cooling Capacity for compliance software Credit (see Section <TODO>), the factor shall be } 1.0.$

**Derived model parameters.** The following values are used in the formulas below and depend only on model parameters.

- $Tons = \text{Nominal cooling capacity defined as } Cap_{95} / 12000$
- $QFan_{rat} = \text{Assumed fan heat included at AHRI test conditions, Btuh}$
<table>
<thead>
<tr>
<th>Fan motor type</th>
<th>$QF_{Fan_{rat}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSC</td>
<td>$500 \times \text{Cap95} / 12000$</td>
</tr>
<tr>
<td>BPM</td>
<td>$283 \times \text{Cap95} / 12000$</td>
</tr>
</tbody>
</table>

$Q_{Fan_{op}} = \text{Fan heat assumed during operation (i.e., during simulation), Btuh}$

$$Q_{Fan_{op}} = \frac{CFM_{per\ ton} \times \text{Cap95} \times EF_{Fan} \times 3.413}{12000}$$

*Equation 220*

**Model inputs.** The following values vary at each time step in the simulation and are used in the formulas below to determine AC unit performance under for that time step.

$DB_t = \text{Dry bulb temperature of air at the condensing unit, } ^\circ\text{F (typically outdoor air temperature)}$.

$WB_{ec} = \text{Coil entering air wet bulb temperature, } ^\circ\text{F (return air temperature adjusted for blow-through fan heat if any)}$.

$DB_{ec} = \text{Coil entering air dry bulb temperature, } ^\circ\text{F (return air temperature adjusted for blow through fan heat if any)}$.

$Q_{need} = \text{Cooling system sensible cooling output, Btuh. } Q_{need} \text{ is calculated across the unit and thus includes both the building load and distribution losses.}$

Compressor energy for a particular time step of the simulation shall be calculated using Equation 221.

$$\text{Comp}_{wh} = \frac{Q_{Fan_{op}} + Q_{need}}{CE_t}$$

*Equation 221*

Where:

$\text{Fan}_{wh} = \text{Fan power for this time step, Wh.}$

$CE_t = \text{Sensible energy efficiency at current conditions, Btuh/W. This is calculated using Equation 222 below.}$

$$CE_t = EER_t \times SHR$$

*Equation 222*
Where:

\[ \text{EER}_t = \text{Energy efficiency ratio at current conditions, Btuh/W. EER}_t \text{ is calculated using Equation 226 below.} \]

\[ \text{SHR} = \text{Sensible Heat Ratio (sensible capacity / total capacity), derived as follows:} \]

\[ \text{SHR} = \min(1, \quad A_{\text{SHR}} \times DB_{ec} + B_{\text{SHR}} \times WB_{ec} + C_{\text{SHR}} \times DB_t + D_{\text{SHR}} \times \text{CFM}_{\text{per ton}} + E_{\text{SHR}} \times DB_{ec} \times DB_t + F_{\text{SHR}} \times DB_{ec} \times \text{CFM}_{\text{per ton}} + G_{\text{SHR}} \times WB_{ec} \times DB_t + H_{\text{SHR}} \times WB_{ec} \times \text{CFM}_{\text{per ton}} + I_{\text{SHR}} \times DB_t \times \text{CFM}_{\text{per ton}} + J_{\text{SHR}} \times WB_{ec}^2 + K_{\text{SHR}} / \text{CFM}_{\text{per ton}} + L_{\text{SHR}}) \]

**SHR coefficients:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{\text{SHR}} )</td>
<td>0.0242020</td>
</tr>
<tr>
<td>( B_{\text{SHR}} )</td>
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<td>( C_{\text{SHR}} )</td>
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<td>( D_{\text{SHR}} )</td>
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<td>( E_{\text{SHR}} )</td>
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<tr>
<td>( F_{\text{SHR}} )</td>
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<td>( G_{\text{SHR}} )</td>
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<tr>
<td>( H_{\text{SHR}} )</td>
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<td>( I_{\text{SHR}} )</td>
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<tr>
<td>( K_{\text{SHR}} )</td>
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</tr>
<tr>
<td>( L_{\text{SHR}} )</td>
<td>1.5085285</td>
</tr>
</tbody>
</table>

\( \text{CAP}_{nf} = \text{Total cooling capacity across coil (that is, without fan heat) at current conditions, Btuh} \)
\[ CAP_{nf} = (\text{Cap95} + Q\text{Fan}_{rat}) \times F_{chg} \times F_{size} \times F_{\text{cond\_cap}} \]

\[ F_{\text{cond\_cap}} = A_{\text{CAP}} \times DB_{ec} + 
B_{\text{CAP}} \times WB_{ec} + 
C_{\text{CAP}} \times DB_{t} + 
D_{\text{CAP}} \times CFM_{\text{per\_ton}} + 
E_{\text{CAP}} \times DB_{ec} \times DB_{t} + 
F_{\text{CAP}} \times DB_{ec} \times CFM_{\text{per\_ton}} + 
G_{\text{CAP}} \times WB_{ec} \times DB_{t} + 
H_{\text{CAP}} \times WB_{ec} \times CFM_{\text{per\_ton}} + 
I_{\text{CAP}} \times DB_{t} \times CFM_{\text{per\_ton}} + 
J_{\text{CAP}} \times WB_{ec}^{2} + 
K_{\text{CAP}} / CFM_{\text{per\_ton}} + 
L_{\text{CAP}} \]

Coefficients as follows:

<table>
<thead>
<tr>
<th>SHR Condition</th>
<th>SHR &lt; 1</th>
<th>SHR = 1</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>B\text{CAP}</td>
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<td>C\text{CAP}</td>
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<td>D\text{CAP}</td>
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<td>E\text{CAP}</td>
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<td>F\text{CAP}</td>
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<td>J\text{CAP}</td>
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<tr>
<td>L\text{CAP}</td>
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<td>0.430751600</td>
</tr>
</tbody>
</table>
\[ \text{CAP}_{\text{sen}} = \text{Sensible capacity including fan heat, Btuh} \]
\[ \text{CAP}_{\text{sen}} = \text{CAP}_{nf} \times SHR - QF_{an_{op}} \]

Equation 224

\[ \text{CAP}_{\text{lat}} = \text{Latent capacity, Btuh} \]
\[ \text{CAP}_{\text{lat}} = \text{CAP}_{nf} - \text{CAP}_{\text{sen}} \]

Equation 225

Note: The air leaving the AC unit is limited to 95% relative humidity. If that limit is invoked, \( \text{CAP}_{\text{lat}} \) is reduced and \( \text{CAP}_{\text{sen}} \) is increased.

\text{EER}_t \text{ is calculated as follows:}

When

\begin{align*}
\text{DB}_t & \leq 82 \, ^\circ\text{F} \quad \text{EER}_t = \text{SEER}_{nf} \\
82 < \text{DB}_t < 95 \, ^\circ\text{F} \quad \text{EER}_t = \text{SEER}_{nf} + ((\text{DB}_t - 82)(\text{EER}_{nf} - \text{SEER}_{nf}) / 13) \\
\text{DB}_t & \geq 95 \, ^\circ\text{F} \quad \text{EER}_t = \text{EER}_{nf}
\end{align*}

Equation 226

Where:

\begin{align*}
\text{SEER}_{nf} & = \text{Seasonal energy efficiency ratio at current conditions without distribution fan consumption (“nf” = no fans). This is calculated using Equation 227.} \\
\text{EER}_{nf} & = \text{Energy efficiency ratio at current conditions without distribution fan consumption (“nf” = no fans) and adjusted for refrigerant charge and airflow. This is calculated using Equation 228.}
\end{align*}

\[
\text{SEER}_{nf} = \frac{F_{\text{chg}} \times F_{\text{size}} \times F_{\text{cond,SEER}} \times (1.09 \times \text{Cap}_{95} + QF_{an_{rat}})}{1.09 \times \text{Cap}_{95} / \text{SEER} - QF_{an_{rat}} / 3.413}
\]

Equation 227

\[
F_{\text{cond,SEER}} = F_{\text{cond,cap}} / (A_{\text{SEER}} \times \text{DB}_{\text{sec}} + B_{\text{SEER}} \times \text{WB}_{\text{sec}} + C_{\text{SEER}} \times \text{DB}_t + D_{\text{SEER}} \times \text{CFM}_{\text{per ton}} + E_{\text{SEER}} \times \text{DB}_{\text{sec}} \times \text{DB}_t + F_{\text{SEER}} \times \text{DB}_{\text{sec}} \times \text{CFM}_{\text{per ton}} + G_{\text{SEER}} \times \text{WB}_{\text{sec}} \times \text{DB}_t + H_{\text{SEER}} \times \text{WB}_{\text{sec}} \times \text{CFM}_{\text{per ton}} +
\]
\[ ISEER \times DB_t \times CFM_{\text{per ton}} + \]
\[ JSEER \times WB_{ec}^2 + \]
\[ KSEER / CFM_{\text{per ton}} + \]
\[ LSEER \]

Coefficients as follows:

<table>
<thead>
<tr>
<th>SHR Condition</th>
<th>SHR &lt; 1</th>
<th>SHR = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_SEER</td>
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<td>B_SEER</td>
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<tr>
<td>L_SEER</td>
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</tr>
</tbody>
</table>

\[
EER_{nf} = \frac{Cap_{nf}}{F_{\text{cond EER}} \times (\text{Cap} 95/\text{EER} - \text{QFan rat}/3.413)}
\]

Equation 228

Where:

\[
F_{\text{cond EER}} = (A_{\text{EER}} \times DB_{ec} + B_{\text{EER}} \times WB_{ec} + C_{\text{EER}} \times DB_t + D_{\text{EER}} \times CFM_{\text{per ton}} + E_{\text{EER}} \times DB_{ec} \times DB_t + F_{\text{EER}} \times DB_{ec} \times CFM_{\text{per ton}} + \)

2013 Residential ACM Algorithms 100
\[ G_{EER} \times W_{Bec} \times D_B + H_{EER} \times W_{Bec} \times CFM_{per\ ton} + I_{EER} \times D_B \times CFM_{per\ ton} + J_{EER} \times W_{Bec}^2 + K_{EER} / CFM_{per\ ton} + L_{EER} \]

Coefficients as follows:

<table>
<thead>
<tr>
<th>SHR Condition</th>
<th>SHR &lt; 1</th>
<th>SHR = 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_{EER}</td>
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</tbody>
</table>

2.15.2 Air-Source Heat Pump Model (Heating mode)

The air source heat pump model is based on methods presented in AHRI Standard 210/240-2008.

**Primary model parameters.** The following values characterize the ASHP and are constant for a given unit:

- **Cap47** = Rated heating capacity at outdoor dry-bulb temperature = 47 °F
- **COP47** = Coefficient of performance at outdoor dry bulb = 47 °F (if available, see below)
Cap35 = Heating capacity under frosting conditions at outdoor dry-bulb temperature = 35 °F (if available, see below)
COP35 = Coefficient of performance at outdoor dry bulb = 35 °F (if available, see below)
Cap17 = Rated heating capacity at outdoor dry-bulb temperature = 17 °F
COP17 = Coefficient of performance at outdoor dry bulb = 17 °F (if available, see below)
HSPF = Rated Heating Seasonal Performance Factor, Btuh/Wh
COPbu = COP of backup heating, default = 1 (electric resistance heat)
Capbu = Available backup heating capacity, Btuh

Derived model parameters.
Inp47 = Electrical input power at 47 °F = Cap47 / COP47, Btuh (not W)
Inp17 = Electrical input power at 17 °F = Cap17 / COP17, Btuh (not W)

Estimation of unavailable model parameters.

\[
COP47 = 0.3038073 \times \text{HSPF} - 1.984475 \times \frac{\text{Cap17}}{\text{Cap47}} + 2.360116
\]

\[
COP17 = 0.2359355 \times \text{HSPF} + 1.205568 \times \frac{\text{Cap17}}{\text{Cap47}} - 0.1660746
\]

\[
\text{Cap35} = 0.9 \times [\text{Cap17} + 0.6 \times (\text{Cap47} - \text{Cap17})]
\]

\[
\text{Inp35} = 0.985 \times [\text{Inp17} + 0.6 \times (\text{Inp47} - \text{Inp17})]
\]

\[
\text{COP35} = \frac{\text{Cap35}}{\text{Inp35}}
\]

Simulation

Full-load capacity and input power of the ASHP is determined each time step as a function of outdoor dry-bulb temperature T, as follows --

If (17 °F < T < 45 °F)

\[
\text{Cap}(T) = \text{Cap17} + \frac{(\text{Cap35} - \text{Cap17}) \times (T - 17)}{35 - 17}
\]
\[ I_{np}(T) = I_{np17} + \frac{(I_{np35} - I_{np17}) \times (T - 17)}{35 - 17} \]
Else
\[ C_{ap}(T) = C_{ap17} + \frac{(C_{ap47} - C_{ap17}) \times (T - 17)}{47 - 17} \]
\[ I_{np}(T) = I_{np17} + \frac{(I_{np47} - I_{np17}) \times (T - 17)}{47 - 17} \]

Resistance heat.

Load in excess of Cap(T) is met with backup heating at COPbu.

### 2.15.3 Equipment Sizing

CSE determines the capacity of HVAC equipment via an auto-sizing capability. Autosizing is conducted prior to the main annual simulation. It is done by using the hourly simulator for a set of design days and increasing capacity as needed to maintain thermostat set points. Each design day is repeated several times until the required capacity converges. The set of design days includes one cold day with no solar gain and several hot days at with clear-sky solar at different times of the year. This ensures that maximums of both heating and cooling loads will be found. Equipment characteristics other than capacity are specified on a per-unit basis (e.g. “cfm per ton”), so a full description of the system can be derived from the primary capacity.

The sizing procedure uses the equipment models in an inverse mode. For example, the sensible cooling load for a given set up conditions is back-converted to the required rated total capacity (Cap95) by using inverted forms of the model equations. The general simulation calculation sequence is used, but the logic of the HVAC models is altered during the autosizing phase.

Note that for air-source heat pumps, only the backup heating capacity is autosized. In addition, modeled duct sizes are not sized and must be specified.

The equipment sizes calculated by CSE are used for compliance analysis only and are not substitutes for load calculations used for selecting equipment or meeting other code requirements.
3 Compliance Manager

3.1 Overview

To be written
3.2 One-dimensional Roof Edge Heat Transfer Model

3.2.1 Construction Practice

This document describes the one-dimensional model used to represent the heat flow between the conditioned zone and the outdoors through the portion of the ceiling insulation, along the outside edge of the attic, through which the heat flows to the outdoors without passing through the attic air. This portion will be modeled in CSE as cathedral ceilings, and is referred herein as the roof edge. The rest of the heat flow path through the ceiling insulation will be modeled as part of the attic zone, and is not discussed here.

Two types of roof construction are considered, standard-heel and raised-heel trusses, shown in Figure 26 and Figure 27, with the geometries assumed to be representative of current practice. The roof trusses are assumed to be framed with 2x4’s. Although the figures are for a roof with a 4-in-12 pitch, the 1-D model will handle any standard pitch. The distance between the wall plate and roof deck (shown, for example, as 12 inches in Figure 27) is also not restricted to the distances implied by Figure 26 and Figure 27.

The 1-D model is developed in order to simplify the heat transfer calculation for roof edges, while preserving the steady state and transient characteristics (layer mass) of the typical roof constructions addressed. The 1-D model produces the dimensions of the construction layers needed to represent the roof edges.
Figure 26: Standard-Heel Geometry

L and D determine where the top of the ceiling insulation meets the roof deck plane.

Figure 27: Raised-Heel Geometry

L and D determine where the top of the ceiling insulation meets the roof deck plane.
3.2.2 One-Dimensional Model

Using the parallel path method, the heat transfer is determined separately for the insulation and framing paths of the constructions.

First consider modeling the standard-heel truss of Figure 26.

3.2.2.1 Standard heel insulation path

For the path through the insulation, Figure 26 is approximated as the simpler 2-D configuration of Figure 28 and Figure 30, with the left vertical edge assumed to be adiabatic and of height $Y$. The right vertical edge is also assumed to be adiabatic. To partly compensate for not allowing heat flow out the left side tilted edge board in Figure 26, the ceiling is assumed to extend to the outer edge of the vertical wall.

The width, $W_A$ of roof edge path A, is taken as the width of the vertical path of solid wood in the framing section view of Figure 30.

**Figure 28: Standard-Heel Simplified Geometry for Insulation Path**

Figure 28 is then reduced to the 1-D form shown in Figure 29, where the layer thicknesses are taken as the average height of the layer in Figure 28.
3.2 One-dimensional Roof Edge Heat Transfer Model

Figure 29: Standard-Heel 1-D Geometry for Insulation Path

The left hand portion represents the insulation path of the 1-D model of roof edge A. The right side represents the insulation path of the 1-D model of roof edge B.

The 1-D model just considers the ceiling insulation and framing. When implemented as part of a cathedral ceiling in CSE, a sheetrock layer would be added to the bottom of Figure 29 paths. Layers added to the tops of the layers in Figure 29 would be decking, asphalt shingles, and tile, for example.

3.2.2.2 Standard heel framing path

Similar to the insulation path, the framing heat transfer path starts with Figure 30, which is reduced to Figure 31. The widths of A and B are the same as for the insulation path figures. $H_{B1}$, and $H_{B3}$ are the vertical thickness of the 2x4’s and $H_{B2}$ is the average thickness of insulation.

Figure 30: Standard-Heel Simplified Geometry for Framing Path

The left hand portion represents the insulation path of the 1-D model of roof edge A. The right side represents the insulation path of the 1-D model of roof edge B.

The 1-D model just considers the ceiling insulation and framing. When implemented as part of a cathedral ceiling in CSE, a sheetrock layer would be added to the bottom of Figure 29 paths. Layers added to the tops of the layers in Figure 29 would be decking, asphalt shingles, and tile, for example.

3.2.2.2 Standard heel framing path

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Figure 30: Standard-Heel Simplified Geometry for Framing Path

The left hand portion represents the insulation path of the 1-D model of roof edge A. The right side represents the insulation path of the 1-D model of roof edge B.

The 1-D model just considers the ceiling insulation and framing. When implemented as part of a cathedral ceiling in CSE, a sheetrock layer would be added to the bottom of Figure 29 paths. Layers added to the tops of the layers in Figure 29 would be decking, asphalt shingles, and tile, for example.

3.2.2.2 Standard heel framing path

Similar to the insulation path, the framing heat transfer path starts with Figure 30, which is reduced to Figure 31. The widths of A and B are the same as for the insulation path figures. $H_{B1}$, and $H_{B3}$ are the vertical thickness of the 2x4’s and $H_{B2}$ is the average thickness of insulation.
Figure 31: Standard-Heel 1-D Geometry for Framing Path

- $H_{B1}$ wood
- $H_{B2}$ insulation
- $H_{B3}$ wood

3.2.2.3 Raised heel

The 1-D model for the raised-heel case of Figure 27 is different than for the standard-heel case of Figure 26. The geometry is illustrated in Figure 32 and Figure 33 for a ceiling insulation of R38.

As the edge height, $Y$, in Figure 30 is increased, the deck and ceiling 2x4’s separate vertically near the roof edge, and a vertical 2x4 is assumed to fill the gap. That is, as $Y$ is increased, the standard truss geometry of Figure 28 and Figure 30 morphs into the raised truss geometry of Figure 32 and Figure 33. The 1-d roof edge algorithm below, gives the layering outputs for both the standard-heel truss and the raised-heel truss and everything in between.

3.2.2.4 Raised heel insulation path

Figure 32: Raised-Heel 1-D Insulation Path Geometry
3.2.2.5 Raised heel frame path

Figure 33: Raised-Heel 1-D Framing Path Geometry

![Diagram of Raised-Heel 1-D Framing Path Geometry]

$h_{B1}$ and $H_{B3}$ are the vertical thickness of the 2x4’s and $H_{B2}$ is the average thickness of insulation.

3.2.2.6 Roof edge algorithm

The following algorithm, written in succinct pseudo-code form, determines the layer widths and thicknesses for roof edge paths A and B. [This algorithm is implemented in RoodEdgeAlgorithm-1.xlsx].

All dimensions are assumed to be feet.

**Input:**

- $Y$ = edge height, ft.
- $w$ = framing width, ft. [nominally (3.5/12)-ft]
- $R_{tot}$ = total R value of ceiling insulation, hr-ft²-F/Btu.
- $R_{perin}$ = R value of the ceiling insulation for one inch thickness, hr-ft²-F/Btu.
- $P$ = pitch = rise/12

**Calculation of $W_A, W_B, H_A, H_B, H_{B1}, H_{B2},$ and $H_{B3}$:**
\[ D = \frac{R_{tot}}{12 \cdot R_{perin}} \] insulation depth, ft

\[ Y_i = w \left( 1 + \sqrt{1 + P^2} \right) \] vertical thickness at position \( x = X_i \).

\[ X_i = \frac{Y_i - Y}{p} \] horiz distance from left edge to intersection of deck and ceiling 2x4's (see * in Figure 30). In Figure 33, the corresponding point would be outside the roof section, and near the left edge of the page, and as opposed to the * point, this \( X_i \) will is a negative number since it is to left of origin at outside surface of top wall plate.

IF \( X_i \geq w \):

\[ Y_M = Y_i \] \( Y_M \) is the height of roof section at the vertical line between A and B.

ELSE \( X_i < w \):

\[ Y_M = (w - X_i)P + Y_i \]

END IF

IF \( D \geq Y_M \):

\[ W_B = \frac{D - Y_M}{P} \]

\[ H_A = \frac{Y + Y_M}{2} \]

\[ H_B = \frac{Y_M + D}{2} \]

\[ H_{B1} = w \sqrt{1 + P^2} \]

\[ H_{B2} = H_B - Y_i \]

\[ H_{B3} = w \]

IF \( X_i \geq w \):

\[ W_A = X_i \]

ELSE \( X_i < w \):

\[ W_A = w \]

END IF

ELSE IF \( D < Y_M \) AND \( D > Y \):

\[ W_A = \frac{D - Y}{P} \]

\[ H_A = \frac{D + Y}{2} \]
\[ W_B = H_B = H_{B1} = H_{B2} = H_{B3} = 0 \]

ELSE (\( D \leq Y \))
\[ W_A = H_A = 0 \]
\[ W_B = H_B = H_{B1} = H_{B2} = H_{B3} = 0 \]
END IF

PRINT OUTPUT: \( W_A, W_B, H_A, H_B, H_{B1}, H_{B2}, H_{B3} \)

3.2.3 Roof Edge Model Validation

The roof edge heat transfer is basically a 3-D problem. The 1-D model makes a number of simplifications. For example, the parallel insulation and framing path assumption ignores lateral heat transfer between the insulation and framing path, and leads to an underestimation of the overall heat transfer. The assumption of an adiabatic right hand border, where in reality the heat flow lies are not quite vertical, also underestimates the heat transfer through the cathedral ceilings with an accompanying overestimation of the remaining heat transfer through the attic portion of the ceiling insulation. The assumption of the layer thicknesses taken as the average layer thickness ignores 2-D effects. The complicated 2-D heat transfer at the junction of the vertical wall and roof is simplified by assuming the left border is adiabatic, and the ceiling continuation to the outside of the wall. Corner effects for the roof edge, where vertical walls meet at right angles, results in a 3-D heat flow situation that can only be estimated.

Because of these complexities, it is difficult to assess the accuracy of the 1-D model.

However, in order to obtain some perspective on the accuracy of the 1-D model, the heat transfer was calculated for two cases, of different insulation depths, using both the 1-D roof edge algorithm, and a 2-D (using FEHT finite-element program) solution with the roof edge 2-D geometry of Figure 26. The 2-D model still requires many of the assumptions made in the 1-D model, including the parallel path assumption.

3.2.3.1 1-D model, \( R_{tot} = 30 \), \( Y = 4 \)-inches

Using the 1-D Roof Edge Algorithm, the heat transfer rates through roof edges A and B was calculated for the following inputs.

**Input to Roof Edge Algorithm**

\[ R_{tot} = 30 \text{ hr-ft}^2\text{-F/Btu}. \]
\[ P = 4/12 \]
\[ Y = 0.3333 \text{ ft} \]
\[ w = 0.2917 \text{ ft} \]
\[ R_{perin} = 2.6 \text{ hr-ft}^2\text{-F/Btu}. \]
Output of Roof Edge Algorithm

\[ W_A = 0.797 \text{ ft} \]
\[ W_B = 1.087 \text{ ft} \]
\[ H_A = 0.466 \text{ ft} \]
\[ H_B = 0.780 \text{ ft} \]
\[ H_{B_1} = 0.292 \text{ ft} \]
\[ H_{B_2} = 0.182 \text{ ft} \]
\[ H_{B_3} = 0.307 \text{ ft} \]

Insulation Path Results

The insulation conductivity is \( k = \frac{1}{12R_{perin}} = 0.03205 \text{ Btu/hr-ft-F} \).

The thermal resistance of A and B are:

\[ R_A = \frac{H_A}{k_{insul}} = 14.546 \text{ hr-ft}^2-\text{F/Btu} \]
\[ R_B = \frac{H_B}{k_{insul}} = 24.346 \text{ hr-ft}^2-\text{F/Btu} \]

If no additional layers are added (sheetrock, etc.), and the top and bottom surface temperature difference is 100 F, the heat transfer rate in this case, per foot of roof perpendicular to the section, becomes:

\[ Q_A = \frac{W_A \times \Delta T}{R_A} = \frac{0.797 \times 100}{14.546} = 5.48 \text{ Btu/hr-ft} \]
\[ Q_B = \frac{W_B \times \Delta T}{R_B} = \frac{1.087 \times 100}{24.346} = 4.465 \text{ Btu/hr-ft} \]

The total is:

\[ Q_{insulpath} = Q_A + Q_B = 9.944 \text{ Btu/hr-ft} \]

Framing Path Results

Assume wood framing conductivity \( k = 0.084 \text{ hr-ft-F/Btu} \).

The thermal resistance of A, per foot of roof edge perpendicular to the section:

\[ R_A = \frac{H_A}{k_{wood}} = 5.55 \text{ hr-ft}^2-\text{F/Btu} \]

The thermal resistance of path B; sum of layer resistances:

\[ R_B = \frac{H_{B_1}}{k_{wood}} + \frac{H_{B_2}}{k_{insul}} + \frac{H_{B_3}}{k_{wood}} = 3.66 + 5.654 + 3.473 = 12.786 \text{ hr-ft}^2-\text{F/Btu} \]

The sum of the heat transfers in this case is (from CathedralWorksheet.xlsx).
\[ Q_A = \frac{W_A \cdot \Delta T}{R_A} = \frac{0.797 \times 100}{5.550} = 14.36 \]
\[ Q_B = \frac{W_B \cdot \Delta T}{R_B} = \frac{1.087 \times 100}{12.786} = 8.50 \]
\[ Q_{framingpath} = Q_A + Q_B = 22.86 \text{ Btu/hr-ft} \]

3.2.3.2 1-D model, \( R_{tot} = 60, \ Y = 4\)-inches

**Input to Roof Edge Algorithm**

\( R_{tot} = 60; \) other inputs the same as in \( R_{tot} = 30 \) case above.

**Output of Roof Edge Algorithm**

\( W_A = 0.797 \text{ ft} \)
\( W_B = 3.972 \text{ ft} \)
\( H_A = 0.466 \text{ ft} \)
\( H_B = 1.261 \text{ ft} \)
\( H_{B1} = 0.292 \text{ ft} \)
\( H_{B2} = 0.662 \text{ ft} \)
\( H_{B3} = 0.307 \text{ ft} \)

**Insulation Path Results**

Similar to the \( R_{tot} = 30 \) case, the thermal resistance of A and B are:

\[ R_A = \frac{H_A}{k_{insul}} = 14.546 \text{ hr-ft}^2\text{-F/Btu} \]
\[ R_B = \frac{H_B}{k_{insul}} = 39.346 \text{ hr-ft}^2\text{-F/Btu} \]

The heat transfer rates are:

\[ Q_A = \frac{W_A \cdot \Delta T}{R_A} = \frac{0.797 \times 100}{14.546} = 5.48 \]
\[ Q_B = \frac{W_B \cdot \Delta T}{R_B} = \frac{3.972 \times 100}{39.346} = 10.095 \]
\[ Q_{framingpath} = Q_A + Q_B = 15.57 \text{ Btu/hr-ft} \]

**Framing path results**

The thermal resistance of A, per foot of roof edge perpendicular to the section:

\[ R_A = \frac{H_A}{k_{wood}} = 5.55 \text{ hr-ft}^2\text{-F/Btu} \]

The thermal resistance of path B is the sum of layer resistances. \( k = 0.084 \text{ hr-ft-F/Btu} \) is assumed.
The sum of the heat transfers in this case is:

\[ Q_A = \frac{W_A \cdot \Delta T}{R_A} = \frac{0.797 \cdot 100}{5.55} = 14.36 \]

\[ Q_B = \frac{W_B \cdot \Delta T}{R_B} = \frac{3.972 \cdot 100}{27.79} = 14.29 \]

\[ Q_{framingpath} = Q_A + Q_B = 28.65 \text{ Btu/hr-ft} \]

3.2.3.3 2-D Model, Rtot = 30, Y = 4-inches

Insulation Path

The Figure 26 case is modeled with the simplified geometry of Figure 34, shown for a ceiling insulation of R30. The top of the plate capping the vertical wall is assumed to be adiabatic. The tilted block assumed to be wood, exposed to ambient conditions on its outside sides. The outside of the wood and insulation assumed to be at a uniform 100°F. The ceiling side of the insulation is set to at 0°F. The same material properties were used as in the 1-D model.

Figure 34: Standard Truss, Insulation Path, 2-Dimensional Heat Transfer Model Geometry

The resulting isotherms and heat transfer vectors are shown in Figure 35.
3.2 One-dimensional Roof Edge Heat Transfer Model

Figure 35: Standard-Heel, Insulation Path, 2-Dimensional Heat Transfer Isotherms and Heat Transfer Vectors

The overall heat transfer, per foot of perimeter, for this case was determined (RUN std30.FET) to be:

\[ Q = 9.67 \text{ Btu/hr-ft} \]

*Equation 229*

**Framing Path**

The frame path was modeled similarly, with the Figure 36 graphic results.

Figure 36. Standard-Heel, Frame Path, 2-Dimensional Heat Transfer Isotherms and Heat Transfer Vectors

The overall heat transfer, per foot of perimeter, for this case was determined (RUN std30F.FET) to be:

\[ Q = 21.94 \text{ Btu/hr-ft} \]

*Equation 230*

3.2.3.4 2-D Model, Rtot = 60, Y = 4-inches

Similar to the R30 case above, Figure 37 and Figure 38 show the insulation and framing path 2-D results.
The overall heat transfer, per foot of perimeter, for this case was determined (RUN: std60.fet) to be:

\[ Q = 16.342 \text{ Btu/hr-ft} \]

*Equation 231*

The overall heat transfer, per foot of perimeter, for this case was determined (RUN: std60F.FET) to be:

\[ Q = 31.543 \text{ Btu/hr-ft} \]

*Equation 232*
3.2.3.5 Comparison of 1-D and 2-D results

The above 2-D results are compared with the simplified 1-D model in Table 8.

<table>
<thead>
<tr>
<th></th>
<th>R30 ceiling insulation</th>
<th>R60 ceiling insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>insulation path</td>
<td>framing path</td>
</tr>
<tr>
<td>$Q_{1D}$</td>
<td>9.94</td>
<td>22.86</td>
</tr>
<tr>
<td>$Q_{2D}$</td>
<td>9.67</td>
<td>21.94</td>
</tr>
<tr>
<td>$Q_{1D}$ is</td>
<td>3% &gt; $Q_{2d}$</td>
<td>4% &gt; $Q_{2d}$</td>
</tr>
<tr>
<td></td>
<td>5% &lt; $Q_{2d}$</td>
<td>9% &lt; $Q_{2d}$</td>
</tr>
</tbody>
</table>

Because the 2-D model used is itself of limited accuracy considering the numerous approximations made, the above results are not considered to be definitive. However they do indicate that a number of the assumptions made in the 1-D model are reasonably accurate. While this comparison is limited to steady state heat transfer performance, mass effects are expected to have comparable accuracy.

3.3 How to Build an Airnet

3.3.1 Background

3.3.2 Approach

IZXFER is the building block input for an Airnet. There will be many IZXFERs in an input file, each representing a single air transfer object (leak, vent, window, fan, duct leak). Each IZXFER needs a unique name if detailed reports on its activity are needed. IZXFER is a command at the same level as HOLIDAY.

MATERIAL, CONSTRUCTION, METER, ZONE and REPORT which means that it can be located anywhere except inside another object (like a zone).

The main objects in the Airnet are:

- Infiltration
- Window ventilation
- IAQ ventilation
- Mechanical cooling ventilation
- Duct leakage

Units are ft$^2$.

CBECC inputs to add for Airnet:

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
</table>
| WinHHTop      | Head height of the highest windows in the zone. Used to get the vertical location of the window ventilation holes. In the development program this was done on a building wide basis:  
#define WnHeadHeight 7.67 // Average head height above the floor of operable windows |
| Ventilation Height Difference | This rule needs to be changed to refer to Zone instead of Building: "The default assumption for the proposed design is 2 feet for one story buildings and 8 feet for two or more stories. Greater height differences may be used with special ventilation features such as high, operable clerestory windows. In this case, the height difference entered by the user is the height between the average center height of the lower operable windows and the average center height of the upper operable windows. Such features shall be fully documented on the building plans and noted in the Special Features Inspection Checklist of the CF-1R." (2008 RACM pp 3-9) |
| Floor Height  | The height of each floor over outdoors, crawl or garage is needed to set the Z dimension of the hole in the floor. |
| Soffit height | The height of the attic floor. Probably can be determined by the height of the ceiling below attic. Trouble for Split level? |
| Interzone Door | May need input for whether an interzone door exists between each 2 conditioned zones. Assuming it for now. |
| ReturnRegister | The conditioned zone(s) where the return/exhaust register is located. Make this an input on the HVAC System Data screen |

**3.3.2.1 Problems**

- The window scheme doesn't work for 3 story zones!!!
- The Econ and NightBreeze cooling ventilation systems are multizone and use ducts. I suggest we set them up as part of the duct system.

**3.3.3 Inputs**

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACH50</td>
<td>7.6 (Air Changes per Hour at 50 Pascals pressure difference that leak through the envelope of the conditioned zones)</td>
</tr>
</tbody>
</table>
1. **Infiltration Setup.** Infiltration is uncontrolled air leakage through the cracks and intentional vents in the building. The first step is to determine the total size of the openings and then distribute them over the conditioned zones in proportion to surface areas.

It is modeled in a single conditioned zones with 8 holes (IZXFERs) to represent the leakage in vertical walls and 1 hole each in the floor and ceiling.

Calculate:

a. For conditioned zones the total Effective Leakage Area \( \text{ELA}_{\text{tot}} = \frac{\text{CFA} \times \text{ACH}_{50}}{2 \times 10000} \) (CFA is conditioned floor area)

b. Determine Envelope Areas

1. \( \text{ExCeiltotSF} = \text{sum} (\text{AceilGross} + \text{area of exterior ceilings}) \) (exterior ceilings are surfaces in conditioned zones of type ceiling whose outside condition is Ambient, Ignore Knee walls for infiltration (walls between the conditioned zone and the attic)

2. \( \text{ExWalltotSF} = \text{sum} (\text{Gross Area of Exterior Walls}) \) (walls in conditioned zones whose outside condition is Ambient)

3. \( \text{ExFloortotSF} = \text{sum} (\text{Gross Area of Exterior floors}) \) (floors in conditioned zones whose outside condition is Ambient, Crawl or GROUND)

4. \( \text{ExFloorSlabSF} = \text{sum} (\text{Gross Area of Exterior slab on grade floors}) \) (slab on grade floors in conditioned zones)

5. \( \text{SlabRatio} = \frac{\text{ExFloorSlabSF}}{\text{ExFloortotSF}} \)

6. \( \text{GaragetotSF} = \text{sum} (\text{Gross Area of Surfaces to Garage}) \) (walls and floors in conditioned zones whose outside condition is Garage)

c. Determine leakage distribution:

1. \( \text{ELAceilsf} = \frac{\text{ELA}_{\text{tot}} \times (0.4 + 0.1 \times \text{SlabRatio})}{(\text{AceilGross} + \text{area of exterior ceilings})} \)

2. \( \text{ELAraisedFloorsf} = \frac{\text{ELA}_{\text{tot}} \times (0.2 - \text{SlabRatio})}{(\text{ExFloortotSF} - \text{ExFloorSlabSF})} \)

#If there is a garage zone

3. \( \text{ELAGaragesf} = \frac{\text{ELA}_{\text{tot}} \times 0.1}{\text{GaragetotSF}} \)

4. \( \text{ELAwallsf} = \frac{\text{ELA}_{\text{tot}} \times (0.3 + 0.1 \times \text{SlabRatio})}{\text{ExWalltotSF}} \)

#Else

3. \( \text{ELAGaragesf} = 0 \)
4. \( ELA_{\text{walls}} = ELA_{\text{tot}} \cdot (0.4 + 0.1 \cdot \text{SlabRatio}) / \text{ExWalltotSF} \)

\#endif

2. **Cooling Ventilation Setup**: Four types: Windows only (all types have windows for some part of the year), Whole house fan, Smart Vent, NightBreeze

Set up seasonal window control

\#if Smart Vent or NightBreeze //Windows are on in Winter, but off in summer when mechanical ventilation is on

\#redefine Windowmode select( @weather.taDbAvg07 > 60., 0.00001, default 1.)

\#define VentDiffMult select( @top.tDbOSh < (@znRes[Single].prior.S.tAir-VentDiff), 1, default 0.000001) //Vent off if Tin-Vendiff > Tout

\#Else //everything but Econ and NightBreeze Windows are on year round

\#reDefine Windowmode 1. //Always available

\#Define VentDiff 0 // Differential. No differential for windows or WWF

\#endif // multiplier for window and whole house fan vent availability, .00001 is proxy for Off

Revised to start at dawn end at 11 PM.

\#redefine Win_hr select( $hour < 24, select($radDiff <1., select($hour>12,1.0, default .00001), default 1.0 ), default .00001 )

3. **Airnet for Each Conditioned Zone**:
   a. Calculate

\[
\begin{align*}
ELA_{\text{Aceil}}(zone) &= ELA_{\text{ceil}}sf \cdot \text{AceilGross(zone)} \\
ELA_{\text{Xceil}}(zone) &= ELA_{\text{ceil}}sf \cdot (\text{AEdge}(zone) + \text{area of exterior ceilings}(zone)) \\
&\quad //\text{AEdge is determined in the Ceiling Surface setup BAW 120517} \\
ELAXwall(zone) &= ELA_{\text{walls}}sf \cdot \text{Gross Area of Exterior Walls}(zone) \\
ELAGwall(zone) &= ELA_{\text{Garages}}sf \cdot \text{Gross Area of walls and floors next to the Garage}(zone) \\
ELA_{\text{floor}}(zone) &= ELA_{\text{raisedFloors}}sf \cdot \text{AreaExtfloor}(zone) \quad (\text{gross area of floors whose outside condition is Ambient, Crawl}) \\
\end{align*}
\]

\[
\begin{align*}
\text{ZoneBotZ} &= \text{Bottom}(zone) \cdot \text{- height of the lowest floor in the zone} \\
\text{ZoneTopZ} &= \text{ZoneBotZ} + \text{FloortoFloor}(zone)\cdot\text{NumofStories}(zone) \\
\text{ZoneHeightZ} &= \text{ZoneTopZ} - \text{ZoneBotZ}
\end{align*}
\]
WinHHTop = ZoneBotZ + FloortoFloor(zone)*(NumofStories(zone)-1) + Window head height

b. Exterior wall of conditioned zones infiltration objects Calculate height of bottom and top holes.

// All infiltration leaks in walls are assumed to be spread uniformly over the exposed wall surfaces areas. There are no LEAKS associated with windows, doors etc.

// 8 Wall Holes in each zone to Outdoors 1 upwind, 2 side walls, 1 downwind. Sidewalls are identical so combine them into 1 hole with 2*area

// Low is at 1/4 of wall height, high is at 3/4 of wall height

// izCpr (default = 0) = Wind Coef Upwind wall +0.6 Side walls -0.65
\[ \text{Downwind Wall} \quad -0.3 \]

ELAXwall(zone) = ELAwallsf * Gross Area of Exterior Walls(zone)

WH = ELAXwall(zone)*1.45/8 //Wall Hole size. Conversion from ELA to airnet infiltration opening is 1.45*

Write Airnet Objects to CSE Input  WILU stands for Wall Low Upwind etc.

IZXFER (ZoneName)WILU  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = WH  izHD = ZoneBotZ + (0.25 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=0.6

IZXFER (ZoneName)WILS  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = 2*WH  izHD = ZoneBotZ + (0.25 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=-.65

IZXFER (ZoneName)WILD  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = WH  izHD = ZoneBotZ + (0.25 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=-0.3

IZXFER (ZoneName)WIHU  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = WH  izHD = ZoneBotZ + (0.75 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=0.6

IZXFER (ZoneName)WIHS  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = 2*WH  izHD = ZoneBotZ + (0.75 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=-.65

IZXFER (ZoneName)WIHD  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = WH  izHD = ZoneBotZ + (0.75 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=-0.3
3.3 How to Build an Airnet

c. Windows

// Operable window openings for ventilation. Assumes effect of screens is included in open area Revised 120409 BAW

// IZXFER izALo and izAHi are the min and max vent areas. Both are hourly.

// 8 Window Holes in zone Single to Outdoors Assumes no orientation so 1/4 each orientation, 1/8 low and 1/8 high. Sidewalls are identical so combine them into 1 hole with 2*area

// high is at 1/2 default Hdiff below Window WinHHTop, Low is at WinHdiff below high

// Note that this scheme doesn't work for 3 story zones!!!

Inputs

WnVentArea // ft2, Nonzero - operable window open area. Default is 10 percent of the window area. Assume a single window is 4 feet high with openings centered at -1 and -3' from the top

WnVentHDiff 2.0 // Window vent height difference between center of high opening and low opening

WinHHTop // Head height of highest windows in the zone

Calculate

WnHole = 0.5*(WnVentArea/8.)*Win_hr*Windowmode // 1/8th in each hole, ft2. 1/2 of nominal area to account for screens etc. Hourly and seasonal availability

Write Airnet Objects to CSE Input WnLU stands for Window Low Upwind etc

IZXFER (ZoneName)WnLU  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo=.00001  izAHi = WnHole izHD = WinHHTop - (3+WnVentHDiff) izNVEff =.5 izCpr=0.6

IZXFER (ZoneName)WnLS  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo=.00001  izAHi = 2*WnHole izHD = WinHHTop - (3+WnVentHDiff) izNVEff =.5 izCpr=-.65

IZXFER (ZoneName)WnLD  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo=.00001  izAHi = WnHole izHD = WinHHTop - (3+WnVentHDiff) izNVEff =.5 izCpr=-0.3
IZXFER (ZoneName)WnHU  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo=.00001 izAHi = WnHole izHD = (WinHHHTop-1) izNVEff =.5 izCpr=0.6

IZXFER (ZoneName)WnHS  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo=.00001 izAHi = 2*WnHole izHD = (WinHHHTop-1) izNVEff =.5 izCpr=−.65

IZXFER (ZoneName)WnHD  izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo=.00001 izAHi = WnHole izHD = (WinHHHTop-1) izNVEff =.5 izCpr=−.3

d. Ceiling

Calculate

If ceiling below attic

ELA_Aceil(zone) = ELAceilsf * AceilGross(zone) //knee walls to attic not included in determining the conditioned to attic leakage distribution of

If Whole House fan, Ceiling leak through WWF when off

If Improved WHFela = .05 // Average of Motor Damper Models

else  WHFela = .11 // Average of Gravity Damper Models

If ceiling to outside

ELA_Xceil(zone) = ELAceilsf * AEdge(zone) + area of exterior ceilings(zone)

CeilHole   = (ELA_Aceil(zone) + WHFela )*1.45 //Ceil Hole size. Conversion from ELA to airnet infiltration opening is 1.45*

CathCeilHole = ELA_Xceil(zone) * 1.45 //Cathedral Ceiling Hole size. Conversion from ELA to airnet infiltration opening is 1.45*

Write Airnet Objects to CSE Input

IZXFER (ZoneName)xAttic  izNVTYPE = AirNetIZ izZN1=(ZoneName) izALo=CeilHole izHD = ZoneTopZ izNVEff=1. izExp=0.65 izZN2 = Attic

IZXFER (ZoneName)CC  izNVTYPE = AirNetExt izZN1=(ZoneName) izALo=CathCeilHole izHD = ZoneTopZ izNVEff=1. izExp=0.65

e. Floor over outside
For each floor over outside calculate:

\[
ELA_{\text{floor}}(\text{Name}) = ELA_{\text{raisedFloors}} f \times \text{Area}_{\text{Extfloor}} \times 1.45 \quad \text{(floors whose outside condition is Ambiant)}
\]

Write Airnet Object to CSE Input

\[
IZXFER (\text{Name}) \quad \text{izNVTYPE} = \text{AirNetExt} \quad \text{izZN1} = (\text{ZoneName}) \quad \text{izALo} = ELA_{\text{floor}}(\text{Name}) \quad \text{izHD} = \text{Floor Height} \quad \text{izNVEff} = 1 \quad \text{izExp}=0.65 \quad \text{izCpr}=0. \quad // \text{located at the Extfloor elevation, no wind effect}
\]

f. Floor over Crawl

For each floor over outside calculate:

\[
ELA_{\text{floor}}(\text{Name}) = ELA_{\text{raisedFloors}} f \times \text{Area}_{\text{Crawlfloor}} \times 1.45 \quad \text{(floors whose outside condition is Crawl)}
\]

Write Airnet Object to CSE Input

\[
IZXFER (\text{Name}) \times \text{Crawl} \quad \text{izNVTYPE} = \text{AirNetIZ} \quad \text{izZN1} = (\text{ZoneName}) \quad \text{izALo} = ELA_{\text{floor}}(\text{Name}) \quad \text{izHD} = \text{Floor Height} \quad \text{izNVEff}=1. \quad \text{izExp}=0.65 \quad \text{izZN2} = \text{Crawl}
\]

g. Floor over Garage

For each floor over garage calculate:

\[
ELA_{\text{floor}}(\text{Name}) = ELA_{\text{Garages}} f \times \text{Area}_{\text{Garfloor}} \times 1.45 \quad \text{(floors whose outside condition is Garage)}
\]

Write Airnet Object to CSE Input

\[
IZXFER (\text{Name}) \times \text{Garage} \quad \text{izNVTYPE} = \text{AirNetIZ} \quad \text{izZN1} = (\text{ZoneName}) \quad \text{izALo} = ELA_{\text{floor}}(\text{Name}) \quad \text{izHD} = \text{Floor Height} \quad \text{izNVEff}=1. \quad \text{izExp}=0.65 \quad \text{izZN2} = \text{Garage}
\]

h. Garage wall

Calculate:

\[
GWH = ELA_{\text{Garages}} f \times \text{Gross Area of walls next to the Garage(zone)} / 2 \quad //\text{size of the 2 holes (high and low) between zone and garage}
\]

\[
GWall\text{topZ} = \text{Min(ZoneTopZ(zone)),(ZoneTopZ(Garage))} \quad //\text{The top of the shared wall}
\]

\[
GWall\text{BotZ} = \text{Max(ZoneBotZ(zone)),(ZoneBotZ(Garage))} \quad //\text{The bottom of the shared wall}
\]
GwallH = GWalltopZ - GWallBotZ // Height of shared wall
GWHhZ = GWallBotZ + .75 GwallH // Height of top hole
GWHlZ = GWallBotZ + .25 GwallH // Height of bottom hole

Write Airnet Objects to CSE Input

IZXFER (ZoneName)xGarageH izNVTYPE = AirNetIZ izZN1=(ZoneName) izALo=GWH izHD = GWHhZ izNVEff=1. izExp=0.65 izZN2 = Garage
IZXFER (ZoneName)xGarageL izNVTYPE = AirNetIZ izZN1=(ZoneName) izALo=GWH izHD = GWHlZ izNVEff=1. izExp=0.65 izZN2 = Garage

4. Airnet for Each Unconditioned Zone:

a. Attic

If Ventilated attic Calculate

(4 soffit vents at attic floor elevation plus sloped deck vents at 2/3 of Attic high if frac high > 0

// Pitch types for roof wind pressure coeffs: 0 deg, <10deg, <15 deg,<25, <35 ,all the rest. Flat same as low slope.
#define PitchType select( Pitch <= 0, 1,Pitch <= 0.18, 1,Pitch <= 0.27, 2,Pitch <= 0.47, 3,Pitch <= 0.7, 4,default 5)

AventTot = AceilGross * AVent
SoffitVent 0.5*0.25 *(1.-FracHigh)*Max(AventTot, AtticRelief) //Attic relief is minimum vent needed to vent mechanical cooling air dumped to attic
Deckvent 0.5*0.25*FracHigh*Max(AventTot, AtticRelief)

If sealed attic [to be developed]

Write Airnet Objects to CSE Input

IZXFER AtticSU izNVTYPE = AirNetExt izZN1 = Attic izALo = SoffitVent izHD = SoffitHeight izNVEff = .6 izExp=0.65 izCpr=0.6
IZXFER AtticSS izNVTYPE = AirNetExt izZN1 = Attic izALo = 2*SoffitVent izHD = SoffitHeight izNVEff = .6 izExp=0.65 izCpr=-.65
IZXFER AtticSD izNVTYPE = AirNetExt izZN1 = Attic izALo = SoffitVent izHD = SoffitHeight izNVEff = .6 izExp=0.65 izCpr=-.3
IZXFER AtticDU izNVTYPE = AirNetExt izZN1 = Attic izALo = DeckVent izHD = 0.67 * AtticHeight + SoffitHeight izNVEff=.6 izExp=0.5 izCpr=testx*choose(Pitchtype,-.5,-.8,-.5,-.3,.1,.3)

IZXFER AtticDS izNVTYPE = AirNetExt izZN1 = Attic izALo = 2*DeckVent izHD = 0.67 * AtticHeight + SoffitHeight izNVEff=.6 izExp=0.5 izCpr=testx*choose(Pitchtype,-.5,-.5,-.5,-.5,-.5)

IZXFER AtticDD izNVTYPE = AirNetExt izZN1 = Attic izALo = DeckVent izHD = 0.67 * AtticHeight + SoffitHeight izNVEff=.6 izExp=0.5 izCpr=testx*choose(Pitchtype,-.5,-.3,-.5,-.5,-.5)

b. Garage – Assume California garage with a water heater and combustion air vents so it is pretty leaky Guess 1 ft² of free area. Ignore other infiltration

Calculate

Gvent = 1/4

Write Airnet Objects to CSE Input

IZXFER GarageU izNVTYPE = AirNetExt izZN1 = Garage izALo = Gvent izHD = GarageBotZ +1 izNVEff = .6 izExp=0.65 izCpr=0.6

IZXFER GarageS izNVTYPE = AirNetExt izZN1 = Garage izALo = 2*Gvent izHD = GarageBotZ +1 izNVEff = .6 izExp=0.65 izCpr=-.65

IZXFER GarageD izNVTYPE = AirNetExt izZN1 = Garage izALo = Gvent izHD = GarageBotZ +1 izNVEff = .6 izExp=0.65 izCpr=-0.3

c. Vented crawl space [To Be Developed]
d. Sealed crawl space [To Be Developed]
e. Basement [To Be Developed]

5. Interzone Holes – Assume an open door or stair between any twp conditioned zones with common surfaces, except between units in multi-family

If 2 or more conditioned zones

Error if not at least one common surface for every conditioned zone (a surface in zone A whose outside condition is another conditioned zone)

Door calculation for each pair of zones with a common wall surface (zoneA<>zoneB, zoneB<>zoneC, zoneA<>zoneC, etc)

\[ \text{DoortopZ} = \min(\text{ZoneTopZ}(\text{zone A}),\text{ZoneTopZ}(\text{zone B})) \quad \text{//The top of the shared wall} \]
DoorBotZ = Max(ZoneBotZ(zone A), (ZoneBotZ(zone B))  //The bottom of the shared wall
DoorH = DoortopZ - DoorBotZ // Height of shared opening
DH = 20/ // Area of half of assumed door
DHhZ = GwallBotZ + .75 GwallH // Height of top hole
DHHlZ = GwallBotZ + .25 GwallH // Height of bottom hole

For each zone pair write Airnet Objects to CSE Input
IZXFER (ZoneNameA)DHx(ZoneNameB)DH izNVTYPE = AirNetIZ
izZN1=(ZoneNameA) izALo=DH izHD = DHhZ izNVEff=1. izExp=0.5 izZN2 = (ZoneNameB)
IZXFER (ZoneNameA)DLx(ZoneNameB)DL izNVTYPE = AirNetIZ
izZN1=(ZoneNameA) izALo=DH izHD = DHHlZ izNVEff=1. izExp=0.5 izZN2 = (ZoneNameB)

Stair calculation for each pair of zones with only a floor/ceiling surface (zoneA<>zoneB, zoneB<>zoneC, zoneA<>zoneC, etc)
StairZ = Max(ZoneBotZ(zone A), (ZoneBotZ(zone B))  //The height of the stair hole is at the upper floor

For each zone pair write Airnet Objects to CSE Input  Note that izZN1 MUST be the lower of the 2 zones or the model doesn’t work
IZXFER (ZoneNameA)Sx(ZoneNameB)S izNVType = AIRNETHORIZ
izZN1=(ZoneName of lowerzone) izZN2 = (ZoneName of upper zone) izL1=3 izL1=10 izHD =StairZ

6. IAQ ventilation

Inputs for each zone
IAQVentCFM // CFM of IAQ vent
IAQfanWperCFM  // W/CFM of IAQ vent
Type IAQExhaust // "IAQExhaust", "IAQSupply", "IAQBalanced" "NoIAQVent"
IAQVentHtrcv 0.0  // Heat recovery efficiency of Balanced type, frac

Write Airnet Objects to CSE Input
If Exhaust
IZXFER (Zone)IAQfan izNVTYPE = AirNetExtFan izZN1 = (Zone) izVFmin=IAQVentCFM izVFmax=IAQVentCFM izFanVfDs=IAQVentCFM
izFanElecPwr=IAQfanWperCFM izFanMtr=IAQventMtr

If IAQSupply

IZXFER (Zone)IAQfan izNVTYPE = AirNetExtFan izZN1 = (Zone)
izVFmin=IAQVentCFM izVFmax=IAQVentCFM izFanVfDs=IAQVentCFM
izFanElecPwr=IAQfanWperCFM izFanMtr=IAQventMtr

If IAQBalanced // Needs heat recovery

IZXFER (Zone)IAQfanS izNVTYPE = AirNetExtFan izZN1 = (Zone)
izVFmin=IAQVentCFM izVFmax=IAQVentCFM izFanVfDs=IAQVentCFM
izFanElecPwr=IAQfanWperCFM izFanMtr=IAQventMtr

IZXFER (Zone)IAQfanE izNVTYPE = AirNetExtFan izZN1 = (Zone) izVFmin=IAQVentCFM izVFmax=IAQVentCFM izFanVfDs=IAQVentCFM
izFanElecPwr=IAQfanWperCFM izFanMtr=IAQventMtr

7. Mechanical Cooling Ventilation // The following does not work for multi-zone systems with Econ, NightBreeze. Revise along with ducts model

For each Cooling Ventilation System

Inputs

CoolVentType //type of MECHANICAL cooling ventilation, Choice of WHF, Econ, NightBreeze

CoolVentCFM //Rated air flow of the mechanical cooling system

CoolVent W/CFM //

ReturnRegister // If WHF the conditioned zone where it is located

Calculate

Relief = CoolVentCFM/375 // The minimum size of the attic vents required to let the WHF flow out of the attic

If WHF // Whole House Fan

Calculate

Relief = CoolVentCFM/375 // The minimum size of the attic vent required for this fan to let the WHF flow out of the attic

Write Airnet Objects to CSE Input
IZXFER (Zone) WHF izNVTYPE=AirNetIZFan izZN1=(Zone) izVFmin=0.
izVFMax=-CoolVentCFM*Win_hr izFanVfDs=CoolVentCFM izZn2=Attic
izFanElecPwr=CoolVentWperCFM izFanMtr=CoolVentMtr

If Econ // Economizer ventilation option on the Central Forced Air System such as Smartvent

Calculate

Relief = CoolVentCFM/375 // The minimum size of the attic vent required for this fan to let the WHF flow out of the attic

Write Airnet Objects to CSE Input

ZXFER Econ# izNVTYPE=AirNetExtFan izZN1=(zone) izVFmin=0.
izVFMax=CoolVentCFM*Coolmode*VentDiffMult izFanVfDs=CoolVentCFM
izFanElecPwr=CoolVentWperCFM izFanMtr=CoolVentMtr //!! 110413

IZXFER Relief# izNVTYPE=AirNetIZFlow izZN1=ReturnRegister izZn2=Attic
izVFmin=0 izVFmax=-CoolVentCFM*Coolmode*.9*VentDiffMult

If NightBreeze // Model for NightBreeze variable flow night ventilation system !! needs lower limit @ CFA<1000/unit and multiple systems @ CFA> 3333 ft2

Calculate

Relief = CoolVentCFM/375 // The minimum size of the attic vent required for this fan to let the WHF flow out of the attic

Write Airnet Objects to CSE Input

IZXFER NightBreeze izNVTYPE=AirNetExtFan izZN1=(zone) izVFmin=0.
izFanMtr=CoolVentMtr
izFanVfDs=CoolVentCFM * CFA // CoolVentCFM = CFM/CFA for NightBreeze. Default is 0.6
izFanElecPwr = (616.47-0.6159*CFA + .000246 *CFA*CFA)/(CoolVentCFM * CFA) // W/CFM DEG 9/29/2010 Equation 1
izVFMax=CoolVentCFM*Coolmode*VentDiffMult*CFA / max((17.91554 - 3.67538 * logE(@weather.taDbPvPk)),1) // DEG 9/29/2010 Equation 3 110411
izFanCurvePy = 0, -0.026937155, 0.187108922, 0.839620406, 0 // Fit to DEG flow^2.85

IZXFER NBRelief izNVTYPE=AirNetIZFlow izZN1=ReturnRegister izZn2=Attic
izVFmin=0 izVFmax=-CoolVentCFM * CFA * Coolmode*.9 *VentDiffMult
Next Zone

Calculate

\[
\text{AtticRelief} = \text{Sum(CoolVentCFM)/375} \quad // \text{The sum of all zonal cool vent CFM determines the minimum size of the attic vents required to let the vent air out of the attic}
\]

//Used in Attic Zone AirNet above

//Min Attic Vent area for relief Tamarac

7. Duct system leaks and pressurization. These are generated by automatically by CSE based on the duct system inputs.

3.4 How to Create CSE Conditioned Zone Internal Mass Inputs

3.4.1 Background

3.4.2 Approach

Internal mass objects are completely inside a zone so that they do not participate directly in heat flows to other zones or outside. They are connected to the zone radiantly and convectively and participate in the zone energy balance by passively storing and releasing heat as conditions change. For now only in Conditioned Zones.

The main internal mass objects in the are:

- Interior walls
- Interior floors
- Furniture
- Cair
- Specific masses (for addition later)

CBECC inputs to add:

- Specific masses (for addition later)

3.4.3 Inputs

Floor Area of zone

For each Conditioned Zone
1. Interior Floor Setup. Input for inside the conditioned zone interior floors as mass elements.

   Calculate:
   
   a. \( X_{flr} = \text{sum of the area of floors to ground, crawl space, exterior or other zones} \)
   
   b. \( Int_{Flr} = \text{Floor Area} - X_{flr} \)

2. Interior Wall Setup. Input for inside the conditioned zone interior walls as mass elements.

   Calculate:
   
   a. \( IZ_{wall} = \text{sum of the area of interior walls to other conditioned zones} \)
   
   b. \( Int_{wall}(zone) = \text{floor area} - 0.5 \times IZ_{wall} \)

3. Write objects to the CSE input

   Light stuff
   
   1. \( znCAir = \text{floor area} \times 2 \)
   
   2. Interior wall if \( Int_{wall}(zone) > 0 \)

      SURFACE IntWallC(zone) sfType=Wall sfArea=0.75*Intwall(zone)
      sfCon=IntwallCav; sfAZM=0 sfExCnd=ADJZN sfAdjZn=(zone)

      SURFACE IntWallF(zone) sfType=Wall sfArea=0.25*Intwall(zone)
      sfCon=IntwallFrm; sfAZM=0 sfExCnd=ADJZN sfAdjZn=(zone)

   3. Furniture

      SURFACE Furniture(zone) sfType=wall sfArea= Floor Area * 2.;
      sfCon=FurnCon; sfAZM=0 sfExCnd=ADJZN sfAdjZn=Zone

   4. Interior Floor if \( Int_{Flr}(zone) > 0 \)

      // floor construction for interior mass. Assumes 2x10 @ 16" OC. Both floor and ceiling are in the conditioned zone

      SURFACE IntFlrFrm sfType=Floor sfCon=IntFFrm2x10 sfArea=0.1 * RaisedFlr;
      sfExCnd=ADJZN sfAdjZn=(Zone)

      SURFACE IntFlrCav sfType=Floor sfCon=IntFCav2x10 sfArea=0.9 * RaisedFlr;
      sfExCnd=ADJZN sfAdjZn=(Zone)

   4. Constructions

      CONSTRUCTION FurnCon // 2.5" wood  Revised Layers
      Layer lrMat="SoftWood" lrThk=2.5/12
3.5 Appliances, Miscellaneous Energy Use and Internal Gains

3.5.1 Background

This model is derived from the 2008 HTM (California Energy Commission, HERS Technical Manual, California Energy Commission, High Performance Buildings and Standards Development Office. CEC-400-2008-012). This is a major change from the 2008 RACM in that internal gains are built up from models for refrigerator, people, equipment and lights instead of
the simple constant plus fixed BTU/ft$^2$ used there. The HTM derived model has been used in the 2013 Development Software throughout the 2013 revision process.

This model has another significant change beyond the HTM model with the addition of latent gains required as input for the new CSE air conditioning model. There was no information on latent gains in either the 2008 RACM or the HTM. The latent model here was created by applying the best available information on the latent fraction of internal gains to the HTM gains model.

### 3.5.2 Approach

The approach here is to calculate the Appliances and Miscellaneous Energy Use (AMEU) for the home and use that as the basis for the internal gains. This will facilitate future expansion of the procedure to calculate a HERS Rating.

#### 3.5.2.1 Problems

The procedure here (also used in the 2013 development program) does not work correctly for multifamily buildings unless all of the units are the same (CFA and number of bedrooms). I don't believe this problem was considered in developing the HTM. I believe that the only exactly correct solution involves simulating each unit as a separate zone with a different internal gain. For now we will ignore this problem and assume that average values are OK.

The HTM equations are FUBAR if there is a gas range and electric oven.

The allocation of internal gain to zones is not specified in either the RACM or the HTM. A proposed approach is presented here.

### 3.5.3 Inputs

- **Units**: Number of dwelling units in the building.
- **BRperUnit**: Bedrooms/DwellingUnits rounded to an integer
- **CFA**: Conditioned Floor Area in the building
- **CFAperUnit**: CFA/DwellingUnits

New CBECC input at the building level: an Appliances Input Screen (for a single conditioned zone, most of these default, we are assuming that MF buildings will be done as one zone):

<table>
<thead>
<tr>
<th>Input</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator/Freezer</td>
<td>Efficiency (Choice of Default = 669 kWh/year, no other choices at this time), Location (Choice of zones if multiple conditioned zones). // HTM assumes all Dwelling units have refrigerators. Different for additions and alterations when we get to them.</td>
</tr>
<tr>
<td>Dishwasher</td>
<td>Efficiency (Choice of Default, no other choices at this time), Location (Choice of zones if multiple conditioned zones). // HTM</td>
</tr>
</tbody>
</table>
assumes all Dwelling units have refrigerators. Different for additions and alterations when we get to them.

<table>
<thead>
<tr>
<th>Appliances, Miscellaneous Energy Use and Internal Gains</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Clothes Dryer</strong> Location (Choice of zones if multiple zones, No Dryer space or hookup provided) Dryer power (Choice Electric, Gas or other) //Assuming gas for now</td>
</tr>
<tr>
<td><strong>Clothes Washer</strong> Location (Choice of zones if multiple zones), No Washer space or hookup provided</td>
</tr>
<tr>
<td><strong>Range/Oven</strong> Location (Choice of zones if multiple conditioned zones, No Range/Oven space and hookup provided) Range/Oven power (Choice Electric, Gas or other) Assumes gas for now</td>
</tr>
</tbody>
</table>

Assumes CSE Meters are set up elsewhere:

- Mtr_Elec
- Mtr_NatGas
- Mtr_Othewr //PropaNE

Write Constants to the CSE input:

```plaintext
#redefine Intgain_mo choose1($month,
1.19,1.11,1.02,0.93,0.84,0.8,0.82,0.88,0.98,1.07,1.16,1.21) //The monthly internal gain multiplier (same as 2008 RACM).

#redefine Lights_hr
hourval(0.023,0.019,0.015,0.017,0.021,0.031,0.042,0.041,0.034,0.029,0.027,0.025,\n0.021,0.021,0.021,0.026,0.031,0.044,0.084,0.118,0.113,0.096,0.063,0.038) // Changed 0.117 to 0.118 to add to 1

#redefine OutdoorLights_hr hourval(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0) //

#redefine People_hr
hourval(0.035,0.035,0.035,0.035,0.035,0.059,0.082,0.055,0.027,0.014,0.014,0.014,\n0.014,0.019,0.027,0.041,0.055,0.068,0.082,0.082,0.070,0.053,0.035)

#redefine Equipment_hr
hourval(0.037,0.035,0.034,0.034,0.032,0.036,0.042,0.044,0.037,0.032,0.033,0.033,\n0.032,0.033,0.035,0.037,0.044,0.053,0.058,0.060,0.062,0.060,0.052,0.045)
```
1. Setup the gains that are distributed across the zones per CFA of the zone and write to CSE input: Calculations are generally more complicated in future for HERS
   a. //Lights Returns Btu/day-CFA - based on ElectricityInteriorLights = (214 + 0.601xCFA) × (FractPortable + (1-FractPortable)×PAMInterior ) //HTM Eqn 11, p. 30
      #define FractPortable .22 //fixed for now, variable later for HERS
      #define Paminterior 0.625 //fixed for now, variable later for HERS
      #Redefine LightsGainperCFA (((214. + 0.601 * CFAperUnit) * (FractPortable + (1-FractPortable) * Paminterior ) * 3413. / 365) * DwellingUnits /CFA)
   b. People Returns BTU/day-CFA - 100% is internal gain 57.3% sensible, 42.7% latent
      Based on HTM and BA existing bldgs Sensible 220, Latent 164 BTU
      #redefine PeopleperUnit (1.75 + 0.4 * BRperUnit)
      #Redefine PeopleGainperCFA ((3900/0.573) * PeopleperUnit * DwellingUnits / CFA)
   c. Misc Electricity Returns BTU/day-CFA - 100% is internal gain
      #Redefine MiscGainperCFA ((723. + (0.706 * CFAperUnit))* DwellingUnits * 3413. / 365.)/CFA

2. Setup the gains that are point sources located in a particular zone and write to CSE input. Calculations are generally more complicated in future for HERS
   a. Refrigerator. In the HTM all Standard Design refrigerators use the same amount of electricity (669 kWh/year) regardless of the size of dwelling unit or number of bedrooms. The proposed use is based on the energy label of the actual refrigerator installed or if that is not available the default. For existing home HERS calculations the default is (775 kWh/year). Refrigerators run at a constant power 24 hours per day, regardless of the interior air temperature or number of times the door is opened.
      Returns BTU/day - 100% is internal gain. Installed refrigerator rating is input for proposed in HERS later
      #Redefine RefrigeratorGain (DwellingUnits * 669. * (3413. / 365.))
   b. Dishwasher. 0 based choose returns BTU/day // uses Table based in INTEGER bedrooms per dwelling.
      #Redefine DishwasherGain (choose (BRperUnit,90,90,126,126,126,145,145,174,174,174,default 203) * DwellingUnits * 3413. / 365.)
   c. Stove and Oven – Assumes both are gas with electronic igniter Returns BTU/day - Full Energy Use, 90% is internal Gain
define CookGain (((31. + (.008 * CFAperUnit)) * 0.43 * 0.9) * DwellingUnits * 100000. / 365.) //Added the 0.43 for the electronic ignition 12/4 BAW

d. Clothes Washer - // Returns BTU/day

#define WasherGain ((-64 + 0.108 * CFAperUnit) * DwellingUnits * 3413. / 365.)

e. Clothes Dryer - Assumes gas with electronic igniter Returns BTU/day - Full energy Use, 30% is internal gain

define DryerGain (13. + (.01 * CFAperUnit)) * DwellingUnits * 100000. / 365. //Added the 0.43 for the electronic ignition //120831

f. Exterior Lights Returns Btu/day - based on HTM Eqn 14

#define PamExterior 0.49 //fixed for now, variable later for HERS

#define ExtLightGain ((-81 + 0.152 * CFA) × PAMExterior * 3413. / 365)

3. For each conditioned zone: //Write GAIN objects inside each conditioned zone

GAIN Lights(zone) gnPower= LightsGainperCFA*CFA(Zone)*Lights_hr*Intgain_mo gnFrRad=0.4 gnEndUse=Lit gnMeter= Mtr_Elec

GAIN People(zone) gnPower= PeopleGainperCFA*CFA(Zone)*People_hr*Intgain_mo gnFrRad=0.3 gnFrLat=0.427 // Free Energy so not metered

GAIN Misc(zone) gnPower= MiscGainperCFA*CFA(Zone)*Equipment_hr*Intgain_mo gnFrRad=0.3 gnFrLat=0.03 gnEndUse=Rcp gnMeter= Mtr_Elec

Write any of the following if the source is located in this zone:

GAIN Refrigerator gnPower= RefrigeratorGain/24 gnFrRad=0 gnEndUse=Refr gnMeter= Mtr_Elec // No *Intgain_mo, change fro 2013 DevProg

GAIN Dishwasher gnPower= DishwasherGain*Equipment_hr*Intgain_mo gnFrRad=0.25 gnEndUse=Dish gnMeter= Mtr_Elec //

GAIN Cooking gnPower= CookGain*Equipment_hr*Intgain_mo gnFrRad=0.67 gnEndUse=Cook gnMeter= Mtr_NatGas gnFrZn=.9 //

GAIN Washer gnPower= WasherGain*Equipment_hr*Intgain_mo gnFrRad=0 gnEndUse=Wash gnMeter= Mtr_Elec //

GAIN Dryer gnPower= DryerGain*Equipment_hr*Intgain_mo gnFrRad=0 gnFrLat=0.5 gnEndUse=Dry gnMeter= Mtr_NatGas gnFrZn=.3 //

Write the following to the 1st zone only (one gain per building):

GAIN ExtLights gnPower= ExtLightGain*OutdoorLights_hr gnFrZn=.0 gnEndUse=Ext gnMeter= Mtr_Elec // outside lights, no internal gain
4. For each unconditioned zone write the following if the source is located in this zone:
   //Garage or Basement Maybe 2nd refrigerator in garage later?

   GAIN Washer
gnPower= WasherGain*Equipment_hr*Intgain_mo gnFrRad=0
gnEndUse=Wash gnMeter= Mtr_Elec   //

   GAIN Dryer
gnPower= DryerGain*Equipment_hr*Intgain_mo gnFrRad=0
gnFrLat=0.5 gnEndUse=Dry gnMeter= Mtr_NatGas gnFrZn=.3  //

3.6 Seasonal Algorithm

These are constant control rules. You could substitute values for defined terms in some cases like Winter_Vent Winter_Cool Summer_heat and Sumr_Vent_Temp

   //Thermostats and associated controls

   //Heat Mode

   #redefine SZ_Heat_hr

   #redefine Liv_Heat_hr

   #redefine Slp_Heat_hr

   #redefine Winter_Vent 77

   #redefine Winter_Cool 78

   //Cool Mode

   #redefine SZ_Cool_hr

   #redefine Liv_Cool_hr

   #redefine Slp_Cool_hr

   #redefine Summer_Heat 60

   #redefine Sumr_Vent_Temp 68   //

   // Summer Winter mode switch based on 7 day average temp. Winter<=60>Summer
#redefine Coolmode select(@weather.taDbAvg07>60., 1,default 0)

#redefine HeatSet select(@weather.taDbAvg07>60., Summer_Heat, default SZ_Heat_hr )

#redefine CoolSet select(@weather.taDbAvg07>60., SZ_Cool_hr, default Winter_Cool )

#redefine Tdesired select(@weather.taDbAvg07>60., Sumr_Vent.Temp, default Winter_Vent )

// Window interior shade closure

#define SCnight 0.8    // when the sun is down.  80%

#define SCday 0.5   // when the sun is up  50%

#define SCcool 0.5 // when cooling was on previous hour.  50%?
Appendix A. Derivation of Duct Loss Equations Using Heat Exchanger Effectiveness and Y-Delta Transformations

This derivation is for one zone only, and the nomenclature is specific to this appendix alone.

Heat transfer through the duct walls can be illustrated in the electrical analogy in Figure A-1. The first node on the left represents the temperature of the air in the duct (Td) and is connected to the temperate on the surface of the duct (Ts) by the conductance through the duct wall (Ud). The convective heat transfer coefficient (hc) connects the surface temperature to the duct zone air temperature (Ta). The radiation heat transfer coefficient (hr) connects the surface temperature to the duct zone radiant temperature (Tr).

Figure A-1: Electrical Analogy of Heat Transfer through a Duct Wall

The temperatures of the duct zone are assumed to be constant; the duct surface temperature is not. The duct surface temperature can be removed from the analysis by using a Y-Δ transform. Figure A-2 shows the result of this transformation with direct connections between the duct air temperature, the duct zone radiant and air temperatures through combined coefficients defined in Equation A-1.

\[
U_r = \frac{U_d h_r}{D} \quad U_c = \frac{U_d h_c}{D} \quad U_x = \frac{h_c h_r}{D}
\]

Equation A-1

where

\[
D = U_d + h_c + h_r
\]
Figure A-2: Heat Transfer through a Duct Wall with Surface Temperature Removed

Using an energy balance, the rate of change of heat flow along the length \((x)\) of duct must equal the heat flow through the duct wall, or

\[-mc_p \frac{dT_d(x)}{dx} = U_c P(T'_d(x) - T_a) + U_r P(T_d(x) - T_r)\]

(Equation A-2)

where

\(mc_p\) = capacitance flow rate of the air in the duct

\(T_d\) = temperature of air in the duct

\(U_c\) = equivalent heat transfer coefficient (see Equation A-1)

\(P\) = perimeter of duct

\(T_a\) = temperature of air in duct zone

\(U_r\) = equivalent heat transfer coefficient (see Equation A-1)

\(T_r\) = radiant temperature in duct zone

Regrouping by temperature terms

\[mc_p \frac{dT_d(x)}{dx} = -(U_c P + U_r P)T_d(x) + U_c P T_a + U_r P T_r\]

(Equation A-3)

and dividing through by the quantity \((U_c P + U_r P)\) gives
\[
\frac{mc_p}{(U_c P + U_r P)} \frac{dT_d(x)}{dx} = -T_d(x) + T_{amb}
\]

*Equation A-4*

where

\[
T_{amb} = \frac{U_c P}{(U_c P + U_r P)} T_a + \frac{U_r P}{(U_c P + U_r P)} T_r
\]

*Equation A-5*

Let \( y(x) \) be

\[
y(x) = T_{amb} - T_d(x)
\]

*Equation A-6*

The derivative of which is

\[
dy = -dT_d
\]

*Equation A-7*

Substituting Equation A-6 and Equation A-7 into Equation A-4 gives

\[
-\frac{mc_p}{(U_c + U_r)P} \frac{dy}{dx} = y(x)
\]

*Equation A-8*

Rearranging

\[
\frac{1}{y(x)} dy = -\frac{(U_c + U_r)P}{mc_p} dx
\]

*Equation A-9*

and integrating from entrance \((x = 0)\) to exit \((x = L)\)

\[
\int_0^L \frac{1}{y(x)} dy = \int_0^L -\frac{(U_c + U_r)P}{mc_p} dx
\]

*Equation A-10*

gives

\[
\ln y(L) - \ln y(0) = -\frac{(U_c + U_r)PL}{mc_p}
\]
Recalling the definition in Equation A-6 and replacing the product of the perimeter and length with the surface area \( A \) of the duct, and a bit of manipulation yields the following relationships

\[
\frac{y(L)}{y(0)} = \frac{T_d(L) - T_{amb}}{T_d(0) - T_{amb}} = \exp\left(-\frac{(U_c + U_r)A}{mc_p}\right)
\]

Equation A-11

Let

\[
\beta = \exp\left(-\frac{(U_c + U_r)A}{mc_p}\right)
\]

Equation A-12

Then

\[
\frac{T_d(L) - T_{amb}}{T_d(0) - T_{amb}} = \beta
\]

Equation A-13

Solving for the exit temperature gives

\[
T_d(L) = \beta(T_d(0) - T_{amb}) + T_{amb}
\]

Equation A-14

The temperature change in length \( L \) of duct is

\[
T_d(0) - T_d(L) = -\beta(T_d(0) - T_{amb}) - T_{amb} + T_d(0)
\]

Equation A-15

This can be rewritten as

\[
T_d(0) - T_d(L) = (1 - \beta)(T_d(0) - T_{amb})
\]

Equation A-16

Let \( \varepsilon \) be the sensible heat exchanger effectiveness

\[
\varepsilon = (1 - \beta)
\]

Equation A-17

Then the conduction loss from the duct to the duct zone can then be written as
\[ Q_{\text{loss}} = mc_p (T_d (0) - T_d (L)) = \varepsilon mc_p (T_d (0) - T_{\text{amb}}) \]

Equation A-19
Appendix B. Screen Pressure Drop

The following algorithms are not currently implemented in the code, but are here for future code use, and in the interim are useful to manually determine the effects of screens on window ventilation flow pressure drop.

The references cited are a few of the papers reviewed to ascertain state of the art regarding screen pressure drop. In one of the more recent papers, Bailey et al. (2003) give the pressure drop through a screen as:

$$\Delta p = K \frac{\rho w^2}{2g_c} = K \frac{m^2}{2g_c \rho A^2}$$

*Equation B-1*

where,

$$K = \left( \frac{1}{\beta^2} - 1 \right) \left[ \frac{18}{Re} + \frac{0.75}{\log(Re + 1.25)} + 0.055 \log(Re) \right]$$

*Equation B-2*

and,

$$\beta = \text{screen porosity} = \text{open area/total area perpendicular to flow direction.}$$

$$\beta = \left( 1 - \frac{d}{t_1} \right) \left( 1 - \frac{d}{t_2} \right)$$

$$Re = \frac{wd}{\nu} = \frac{md}{\rho A \nu} = \text{Renolds number.}$$

$$w = \text{face velocity} = \frac{m}{\rho A} \text{ ft/sec.}$$

$$m = \text{mass flow rate, lbm/sec.}$$
$d =$ wire diameter, ft.

$v =$ viscosity $\approx 1.25E-4 + 5.54E-07T(\text{degF})$; ft$^2$/sec. $= 1/6100$ ft$^2$/sec at 70-F.

$\rho =$ air density, lb$\text{m}/\text{ft}^3$.

$g_c =$ 32.2 lb$\text{m}$/ft-lb$\text{sec}^2$.

The first term, intended for portraying $Re < 1$ pressure drops, is the dominate term. The third term, intended for $Re > 200$, is relatively negligible, and the second term is a bridge between the first and third terms.

The Reynolds number for the screen flow $Re = \frac{wd}{v}$ is roughly 5 times the face velocity in ft/sec. For a velocity of 1 ft/sec, $Re \sim 5$. For the expected range of wind speeds of concern for ventilation (see note #1), and with the motive of making the partial derivatives simple (see below), Equation B-2 is approximated as

$$K = \left(\frac{1}{\beta^2 - 1}\right)\frac{25}{Re}$$

*Equation B-3*

[note #1: California CZ12 ave yearly Vmet $\approx 11$ ft/sec. Correcting for height and shielding gives $V_{\text{local}} = 11*0.5*0.32 \approx 1.8$ ft/sec. For max flow case of windows on windward and leeward walls, with typical wall wind pressure coefficients, $w \approx 0.5*V_{\text{local}}$. Thus, the maximum window velocity expected for the annual average wind velocity of 11 ft/sec is $w \approx 0.5*1.8 = 0.9$ ft/sec. In a building with windows in multiple directions, the average $w$ is expected to be much lower, perhaps 0.5 ft/sec. *Stack Effect:* Using old ASHRAE equation, $w(fpm) = 9\sqrt{H[ft](\Delta T[\text{F}])} = 9*\frac{\sqrt{10+10}}{60} = 1.5$ ft/sec. Together, the wind and stack may be on the order of 1-ft/sec].

The constant 25 in this approximate formula was determined by forcing Equation B-2 and Equation B-3 to match when the window air velocity is at the characteristic value $w_c = 21\psi v C_d^2$, defined below. As discussed there, at this velocity the pressure drop through the screen is equal to that through the window orifice.
Equation B-3 can be written as

\[ K = \frac{25\psi \nu}{w}, \text{ or alternately } \frac{25\psi \rho A v}{m} \]

Equation B-4

where, as a result of the approximation Equation B-3, the screen inputs can be combined into one characteristic screen parameter \(\psi\) (of dimension \(ft^{-1}\)):

\[ \psi = \frac{1}{d} \left( \frac{1}{\beta^2} - 1 \right) \]

Equation B-5

\(\psi\) encapsulates all that needs to be known about the screen for pressure drop purposes. This is only true when \(K\) varies in the form assumed by Equation B-3.

The flow rate through a screenless window is modeled by Airnet as a sharp edged orifice of opening area \(A\).

\[ m = c_d A (2\rho g_c \Delta p)^{\frac{1}{2}} \]

Equation B-6

[Idelchik says this is valid for \(Re > 10^4\)].

At the equal pressure point the window orifice Reynolds number is \(Re_{wdw} = (D_h/d)25\psi d C_d^2\).
\[ w_c = 1.89 \text{ ft/sec} \quad \text{for std 14x18x0.011 screen \& \text{Cd}=0.6; 14\&18 \text{ are wires/inch}.} \]

\[ \text{Re}_c = 10.6 \quad \text{for std 14x18x0.011 screen \& \text{Cd}=0.6} \]

\[ \text{Re}_{wdw} = (-1.5*12/0.011)^*10.6 = 1,7345 > 10^4. \]

Thus Re is not > 10^4 when \( w < -1 \text{ ft/sec.} \) But this is when the pressure drop starts to be dominated by the screen, so the orifice drop accuracy is not so important.

Solving for \( \Delta p, \)

\[ \Delta p = \frac{1}{\text{Cd}^2} \frac{\rho w^2}{2g_e} = \frac{1}{\text{Cd}^2} \frac{m^2}{2g_e \rho A^2} \]

*Equation B-7*

Adding Equation B-1 and Equation B-7 gives the total pressure drop for a window and screen in series:

\[ \Delta p = \left( K + \frac{1}{\text{Cd}^2} \right) \frac{m^2}{2g_e \rho A^2} \]

*Equation B-8*

Solving for mass flow rate,

\[ m = AC_d \left( \frac{1}{1 + \text{Cd}^2 K} \right)^{\frac{1}{2}} \left( 2 \rho g_e \Delta p \right)^{\frac{1}{2}} \]

*Equation B-9*

or,

\[ m = AC_d S (2 \rho g_e \Delta p)^{\frac{1}{2}} \]

*Equation B-10*

where \( S \) is the ratio of the flow with a screen to the flow rate without a screen, as a function of velocity \( w, \) viscosity, and screen and window orifice parameters.

\[ S = \left( \frac{1}{1 + \text{Cd}^2 K} \right)^{\frac{1}{2}} = \left( \frac{1}{1 + \text{Cd}^2 \frac{25 \rho \nu}{w}} \right)^{\frac{1}{2}} \]

*Equation B-11*

Equating Equation B-1 and Equation B-7 shows that the velocity when the screen and window pressure drops are equal is given by:

\[ w_c = 25 \rho \nu \text{Cd}^2 \]
The corresponding Reynolds number is $Re_c = 25\psi d C_d^2$.

Substituting Equation B-12 into Equation B-11 shows that for this condition,

$$S_c = \frac{1}{\sqrt{2}} = 0.707$$

Equation B-13

Equation B-12 and Equation B-13 show that $w_c$, which, besides viscosity, only depends on the screen constant $\psi$ and window-orifice coefficient $C_d$, can be considered a "characteristic" velocity, the velocity at which the flow is reduced by $(1 - 0.707) \approx 29.3\%$ by the addition of a screen to the window.

Figure B-2 shows that the typical $\Delta p$ vs. flow curves for a screen and an orifice separately, not in series. The curves cross at velocity $w_c$. To the left of $w_c$, the laminar flow pressure drop dominates the window orifice pressure drop; to the right the orifice pressure drop progressively dominates. Screens give a greater flow reduction at low wind speeds than at high wind speeds.

**Figure B-2: Pressure vs. Flow Characteristics**

In Figure B-2, to the left of $w_c$ the laminar-flow screen pressure drop is higher, and to the right the orifice pressure drop dominates.

Figure B-3 shows $S$ as a function of air velocity $w$ for two common screen sizes. For the Standard screen, $w_c$ is 1.9-ft/sec. [At $w = \sim 1$-ft/sec taken as typical according to note #1, $S = 0.6$, corresponding to a 40% reduction in flow].
Partial Derivatives for use in Airnet:

From Equation B-4 and Equation B-8,

$$\Delta p = \left( \frac{25\psi \rho v}{m} + \frac{1}{C_d^2} \right) \frac{m^2}{2g_c \rho A^2}$$

Equation B-14

This can be written in the quadratic form for m:

$$m^2 + bm - a\Delta p = 0$$

Equation B-15

Where,

$$a = 2g_c \rho C_d^2 A^2$$

$$b = 25\psi \rho v C_d^2 A$$

The single real root of the quadratic Equation B-15 gives the mass flow rate through a screen in series with a window-orifice as a function of screen and window properties and overall pressure drop:
If $\Delta p$ is taken as $\Delta p = P_1 - P_2$, then the partial derivative of $m$ with respect to $P_1$ is

$$\frac{\partial m}{\partial P_1} = \frac{a}{b\sqrt{1 + \frac{4a\Delta p}{b^2}}}$$

*Equation B-17*

$$\frac{\partial m}{\partial P_2} = -\frac{\partial m}{\partial P_1}$$

*Equation B-18*

These derivatives are needed in the Newton-Raphson procedure. The derivatives Equation B-17 and Equation B-18 do not become unbounded when $\Delta p = 0$, as does the orifice Equation B-6, so that no special treatment is needed near $\Delta p = 0$.

But the derivatives do become a little peculiar near zero $\Delta p$ as shown in Figure B-4 and Figure B-5. The value of $a/b \approx 25$, and $\frac{4a}{b^2} \approx 88$ for these plots for the standard screen of Figure B-3. It is possible this could cause problems in the N-R method, but testing AirNet with this type of element is the easiest way to find out.
Figure B-4: For Small $\Delta p$

Figure B-5: For Large $\Delta p$
Appendix C. Exact Longwave Radiation Model

Figure C-1 shows the standard Heat Transfer Engineering method of determining the long wavelength radiation exchange between black-body surfaces at uniform temperatures (Oppenheim(1956), Mills(1992)). The areas need not be equal, or symmetrically disposed, but are drawn that way for simplicity. The surfaces are assumed to be isothermal, and each surfaces temperature node is connected to all other surface temperature nodes via conductances $h_b A_i F_{ij}$.

The following methodology is referred to as the “exact” solution in the discussions of Section 2.6. However, it is recognized that it still is an idealization. For instance, surfaces are generally not isothermal. Although the heat transfer $q_{ij}$ [Btu/hr], of Equation C-2 is accurate if surfaces $i$ and $j$ are isothermal, the local surface heat transfer $q'_{ij}$ [Btu/hr-ft$^2$] on the surfaces is nonuniform because the local view factors are different than the integrated value $F_{ij}$. For example, if the two surfaces are connected along a common edge, then near the edge $q'_{ij}$ will be higher than the average $q_{ij}/A_i$, which will tend to change the temperatures of each wall near the edge faster than away from the edge. For the same reason, the radiation intensities are also non-uniform over a surface, which affects the accuracy of the treatment of the emissivity effects by the Oppenheim surface conductance term, which assumes uniform irradiation.

From the Stefan-Boltzmann equation, the net heat transfer rate between surfaces $i$ and $j$ is:

$$q_{ij} = h_b A_i F_{ij} (T_i - T_j)$$

where,

$$h_b = 4\sigma \bar{T}^3 = \text{black body radiation coefficient; Btu/(hr-ft}^2\text{-F}).$$

$$\sigma = 0.1714x10^{-8} \text{ Btu/hr-ft}^2\text{-R}^4, \text{ the Stefan-Boltzmann constant.}$$

$$\bar{T}^3 \approx \frac{T_i + T_j}{2}, \text{ degrees R.}$$

The $F_{ij}$ term is the standard view factor, equal to the fraction of radiation leaving surface $i$ that is intercepted by surface $j$. $F_{ij}$ depends on the size, shape, separation, and orientation of the surfaces, and at worst requires a double integration. Reciprocity requires that $A_i F_{ij} = A_j F_{ji}$.

Equation (C-1) is in the linearized form of the Stefan-Boltzmann equation, where for small temperature differences, $(T_i^4 - T_j^4)$ is approximated by $4\bar{T}^3 (T_i - T_j)$.
Figure C-2 shows the Figure C-1 black surface case extended to handle diffuse gray surfaces ($\varepsilon = \alpha = \text{constant over temperature range of interest}$) with emissivities $\varepsilon_i$, by adding the Oppenheim radiant surface conductances $\frac{A_i \varepsilon_i}{1 - \varepsilon_i}$ between the surface temperature nodes and the black body network. (Figure C-2 also represents the un-linearized Stefan-Boltzmann circuit if the surface temperatures are replaced by the emissive power of the surfaces. In this case the surface radiosities are the potentials at the floating nodes.)
Figure C-2: View-Factor Method’s Network for Grey Surfaces

By dissolving the radiosity nodes using Y-delta transformations, Figure C-2 converts into Figure C-3 showing the same circuit form as the black surface circuit of Figure C-1. The transformation provides the conductances $A_iF_{ij}$ implicit in the conductances of Figure C-2.
$F'_{ij}$ are the ‘radiant interchange factors’. As with the black surfaces view factors, reciprocity holds: $A_iF'_{ij} = A_jF'_{ji}$. The net heat transfer between surface $i$ and $j$ (both directly and via reflections from other surfaces) is given by:

$$q_{ij} = h_b A_i F'_{ij} (T_i - T_j)$$

*Equation C-2*

The total net heat transfer from surface $i$ (i.e., the radiosity minus the irradiation for the un-linearized circuit) is given by summing Equation C-2 for all the surfaces seen by surface $i$, $j \neq i$:

$$q_i = \sum_{j=1}^{n} h_b A_i F'_{ij} (T_i - T_j)$$

*Equation C-3*

The above methodology is referred to as the “exact” solution in the discussion of Section 2.6.1. However, as discussed by Carroll, it is recognized that it is still an idealization. For instance, surfaces are generally not isothermal. Although the heat transfer, $q_{ij}$ [Btu/hr], of Equation C-2 is accurate if surfaces $i$ and $j$ are isothermal, the local surface heat transfer $q'_{ij}$ [Btu/hr-ft$^2$] on the surfaces is nonuniform because the local view factors are different than the integrated value $F_{ij}$. For example, if the two surfaces are connected along a common edge, then near the edge $q_{ij}'$ will be higher than the average $q_{ij}/A_i$, which will tend to change the temperatures of each
wall near the edge faster than away from the edge. For the same reason, the radiation intensities are also non-uniform over a surface, which affects the accuracy of the treatment of the emissivity effects by the Oppenheim surface conductance term, which assumes uniform irradiation.

Appendix D. Determining the Form of the Self-weighting Term \( F_1 \)

Consider a flat black surface of area \( A_1 \) and temperature \( T_1 \) viewing the rest of the room of area \( A_s \) and surface temperature \( T_s \), with the view factor \( F_{1s} = 1 \). By Equation C-1 of Appendix C, the net \( q \) from surface \( A_1 \) is given by:

\[
q_1 = h_b A_1 F_{1s}(T_1 - T_s) = h_b A_1 (T_1 - T_s)
\]

Equation D-1

With Carroll’s model applied to this geometry,

\[
q_1 = h_b A_1 F_1 (T_1 - T_r)
\]

Equation D-2

where

\[
T_r = \frac{A_1 F_1 T_1 + A_s F_s T_s}{A_1 F_1 + A_s F_s}
\]

Equation D-3

Equating Equation D-1 and Equation D-2 and solving for \( F_1 \) gives:

\[
F_1 = \frac{1}{1 - \frac{A_1 F_1}{A_1 F_1 + A_s F_s}}
\]

Equation D-4

The net heat transfer rate from surface 1 is \( q_1 = h_b A_1 F_1 (T_1 - T_r) \), with similar expressions for \( F_s \) and \( q_s \). This is then generalized to the form of Equation 78 of Section 2.6.1.
REFERENCES


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McAdams eq. (7-8 ) for horizontal plates with heat transfer down from a cold plate, or up from a hot plate, for the turbulent case: 
\[
\text{Nu} = 0.14 Ra^{1/3} \quad (2 \times 10^7 < Ra < 3 \times 10^{10})
\]


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