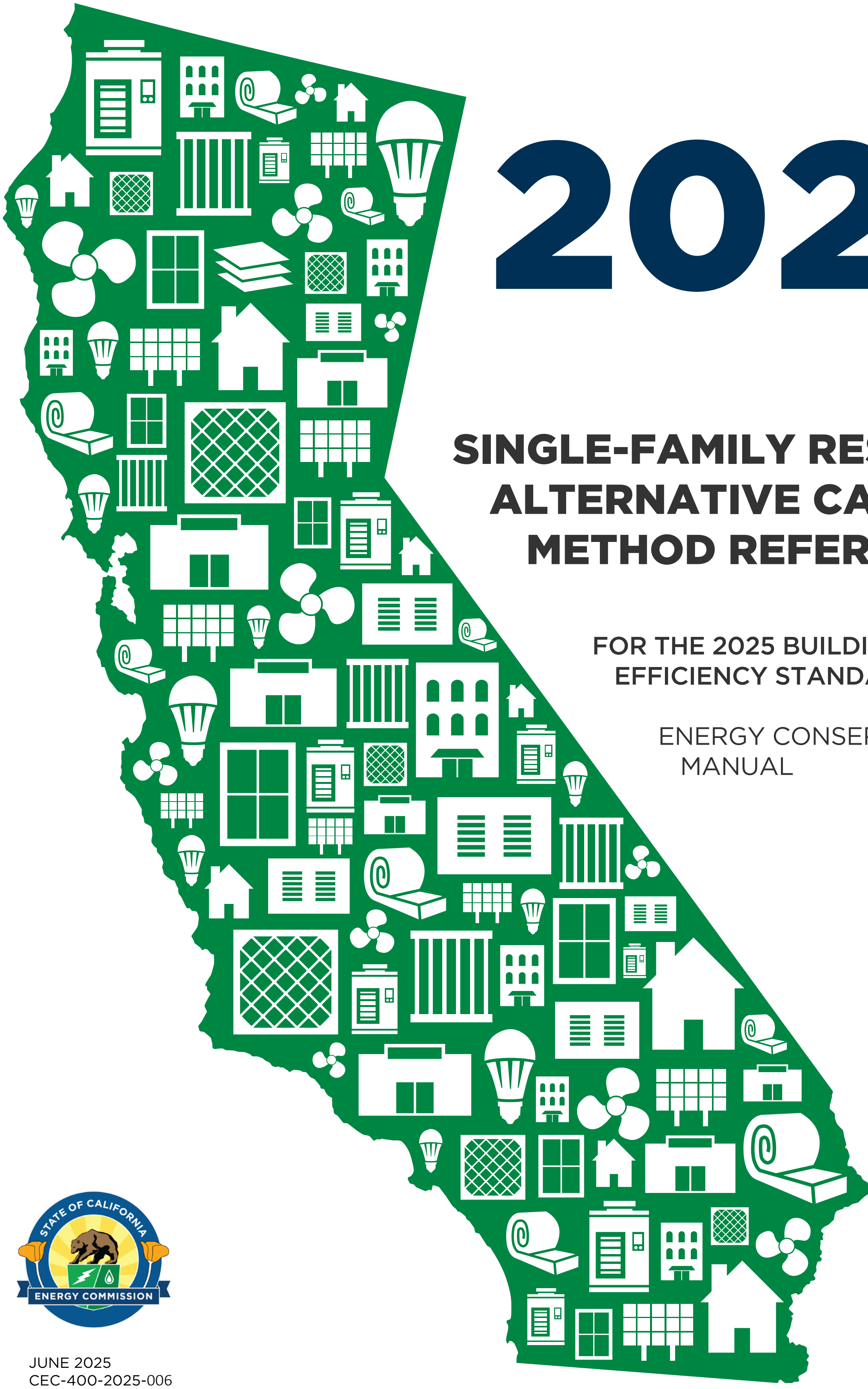

2025

SINGLE-FAMILY RESIDENTIAL ALTERNATIVE CALCULATION METHOD REFERENCE MANUAL

FOR THE 2025 BUILDING ENERGY EFFICIENCY STANDARDS

ENERGY CONSERVATION MANUAL

JUNE 2025
CEC-400-2025-006

CALIFORNIA ENERGY COMMISSION
Gavin Newsom, Governor

CALIFORNIA ENERGY COMMISSION

CALIFORNIA NATURAL RESOURCES AGENCY

California Energy Commission

STAFF REPORT

2025 Single-Family Residential Alternative Calculation Method Reference Manual

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California Energy Commission

Haile Bucaneg
Thao Chau, P.E.
Primary Authors

Haile Bucaneg
Nikhil Kapur
Thao Chau, P.E.
Project Managers

Gypsy Achong
Branch Manager
BUILDING STANDARDS BRANCH

Will Vicent
Deputy Director
EFFICIENCY DIVISION

Michael J. Sokol
Director
EFFICIENCY DIVISION

Drew Bohan
Executive Director

ACKNOWLEDGMENTS

The California Energy Commission (CEC) adopted and put into effect the first Building Energy Efficiency Standards in 1978 and has updated these standards periodically in the intervening years. The Building Energy Efficiency Standards are a unique California asset that has placed the state on the forefront of energy efficiency, sustainability, energy independence, and climate change issues. The standards also have provided a template for national standards within the United States as well as for other countries around the globe. They have benefitted from the conscientious involvement and enduring commitment to the public good of many persons and organizations along the way. The 2025 Building Energy Efficiency Standards for residential and nonresidential buildings development and adoption process continued the 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 2025 Building Energy Efficiency Standards for residential and nonresidential buildings were conceptualized, evaluated, and justified through the work of CEC staff and consultants working under contract to the CEC. Revisions were also supported by the utility-organized Codes and Standards Enhancement Initiative and shaped by the participation of more than 150 stakeholders and the contribution of formal public comments.

CEC Efficiency Division staff would like to acknowledge Commissioner Andrew McAllister and his adviser, Bill Pennington, for their unwavering leadership throughout the standards development; Javier Perez, who served as project manager for the 2025 standards code cycle; Payam Bozorgchami, P.E., who served as the senior engineer and senior technical lead; Gypsy Achong, who served as the Manager for the Buildings Standards Branch; Mikey Shewmaker, who served as the supervisor for the Standards Development Unit; Devin Black, Josephine Crosby, Ana Gonzalez, Michael Murza, Albert Kim, and Isaac Serratos, who provided legal counsel and support; and technical staff contributors of the Building Standards Branch including Haider Alhabibi; Jessica Arroyo; Ronald Balneg; Stephen Becker; Amie Brousseau; Thao Chau, P.E.; Sahar Daemi; Kyle Grewing; Simon Lee, P.E; Elmer Motel; Gagandeep Randhawa; Anushka Raut; Muhammad Saeed; Danny Tam; Trevor Thomas; Bach Tsan; RJ Wichert, P.E.; and Allen Wong, and of the Standards Compliance Branch, including Joe Loyer; and Cheng Moua, P.E. Additional staff input and assistance came from the Energy Hotline staff and the CEC's web team. Administrative support and editing were provided by Corrine Fishman; Tajanee Ford-Whelan; and Michi Mason.

Critical support for the staff in conceptualizing, evaluating, and reviewing this document came from consultants and stakeholders, including Bruce Wilcox, Scott Criswell, Dimitri Contoyannis, Alea German, Eric Martin, Diane Pepetone, Robert Scott, Traci Meyer-Jones, and the Codes and Standards Enhancement Initiative, which is supported by a consortium of California utility providers which includes the Pacific Gas and Electric

Company, Southern California Edison, San Diego Gas & Electric, Sacramento Municipal Utility District, and Los Angeles Department of Water and Power.

ABSTRACT

The California Energy Commission's (CEC) *2025 Building Energy Efficiency Standards* for residential and nonresidential buildings allows compliance by either a prescriptive or a performance method. Performance compliance uses computer-modeling software to trade-off efficiency measures. Performance compliance is the most popular compliance method because of the flexibility it provides in the building design.

Compliance software must be certified by the CEC using the rules established for modeling software. This document establishes the rules for creating a building model, describes how the proposed design (energy use) is defined, explains how the standard design (energy budget) is established, and reports on the Performance Compliance Certificate. This document does not specify the minimum capabilities of vendor-supplied software. The CEC reserves the right to approve vendor software for limited implementations of what is documented in this manual.

This *Single-Family Residential Alternative Calculation Method Reference Manual* explains how the proposed and standard designs are determined. The explanation for multifamily residential building proposed and standard designs are described in the *Nonresidential and Multifamily Alternative Calculation Method Reference Manual.*

The 2022 compliance manager is the simulation and compliance rule implementation software specified by the CEC. The compliance manager, called California Building Energy Code Compliance Residential (CBECC-Res), models all the regulated energy performance features affecting the energy compliance of a building.

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 code, energy use, performance compliance, design, proposed design, standard design

Bucaneg, Haile; Thao Chau, P.E.; and Nikhil Kapur. 2025. *2025 Residential Alternative Calculation Method Reference Manual*. California Energy Commission, Building Standards Branch. CEC-400-2025-006

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1 Introduction

1.1 Purpose

The Warren-Alquist Act created the California Energy Commission's authority to establish and regularly update building efficiency standards codified in Public Resources Code Sections 25402 subdivisions (a)-(b). Public Resources Code, section 25402.1(e) directs the CEC to certify an energy conservation manual for use by designers, builders, and contractors of residential and nonresidential buildings, specifically including instructions for use of a public domain computer program for calculating energy consumption in residential and nonresidential buildings (Public Resources Code, section 25402.1(e)5).

This manual documents the rules used for modeling single-family residential buildings for performance-based compliance under California's *2025 Building Energy Efficiency Standards* (Energy Code) for residential and nonresidential buildings. This document explains how the proposed design and standard design are established for a building and what is reported on the certificate of compliance (CF1R) compliance document.

The 2025 compliance manager is the simulation and compliance rule implementation software specified by the California Energy Commission (CEC).

Documentation of detailed calculation algorithms is contained in the companion volume *Appendix G, 2025 Residential Alternative Calculation Method Algorithms*.

This reference manual documents the compliance analysis modeling rules for all aspects of the CEC's Alternative Calculation Method (ACM) Reference Manual for single-family residential buildings. For modeling rules for multifamily buildings, please refer to the *Nonresidential and Multifamily Alternative Calculation Method Reference Manual*. This document **does not** specify the minimum capabilities of vendor-supplied software. The CEC 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 2025 Energy Code and definitions for terms used in this manual can be found in the 2025 Energy Code. Documents also relied upon include the *Reference Appendices for the 2025 Building Energy Efficiency Standards* (reference appendices) and the *2025 Single-Family Residential Compliance Manual*, *2025 Energy Code Accounting Methodology*.

Detailed modeling information for the software user can be found in the *California Building Energy Code Compliance Residential (CBECC-Res) User Manual*.

1.3 Compliance for Newly Constructed Buildings

Compliance for newly constructed buildings requires calculating the energy use of the proposed design, and comparing it to the energy budget of the standard design. Energy use accounts for regulated energy end uses, including space conditioning, water heating, and mechanical ventilation. There may also be additional calculations to establish the photovoltaics

(PV) requirement of the standard design, and the respective PV requirement of the proposed design.

When the energy use of the proposed design is equal to or less than the energy budget of the standard design, the proposed design complies with the 2025 Energy Code. The compliance margin is the difference between the energy budget of the standard design and the energy use of the proposed design. When the compliance margin is equal to or greater than zero, the project complies with the 2025 Energy Code.

The energy use of the proposed design and the energy budget of the standard design are expressed in units of Source Energy, Long-term System Cost (LSC), and peak cooling energy. The LSC consists of an Efficiency LSC, photovoltaic and battery energy storage system (BESS) LSC and Total LSC. These metrics are described in greater detail in the following sections. The proposed building shall separately comply with Source Energy budget (expressed in British thermal units (Btus)), the Efficiency LSC (expressed in dollars), the Total LSC (expressed in dollars) and peak cooling energy (expressed in kilowatt hours (kWhs)).

1.4 Source Energy

The compliance software shall calculate the long-run marginal, hourly source energy use for both the standard design and the proposed design as described in the equation below.

$$Source\ Energy = \sum \left(Electricity\ Use_i \times SE_{kWh,i}\right) + \sum \left(Gas\ Use_i \times SE_{gas,i}\right)$$

Where:

Electricity Use_i = The electric energy used in the i^{th} hour.

$SE_{kWh,\ i}$ = The source energy factor for electricity in the i^{th} hour.

Gas Use_i = The gas energy used in the i^{th} hour.

$SE_{gas,\ i}$ = The source energy factor for gas in the i^{th} hour.

Hourly source energy is used to determine compliance. To comply through the performance compliance approach, the Source Energy use of the proposed design must be equal to or less than the Source Energy budget of the standard design. This applies to newly constructed buildings.

1.5 Long-term System Cost

The compliance software shall calculate the LSC for both the standard design and the proposed design by multiplying the LSC factor for each hour of the year by the predicted site energy use for that hour. LSC factors have been established by the Energy Commission for residential and nonresidential occupancies, for each of the climate zones, and for each fuel type (electricity, natural gas, and propane). The LSC approach is documented in more detail in Reference Appendices, Joint Appendix JA3. The Total LSC for a single-family residential project combines the LSC for all efficiency measures (Efficiency LSC) and the LSC for all photovoltaic system, battery energy storage systems, lighting, demand flexibility measures, and other plug loads as described in the following equations:

$$Total\ LSC = Efficiency\ LSC + \sum(PV_i \times LSC_{kWh,i}) + \sum(BESS_i \times LSC_{kWh,i}) + \sum(L_{unregulated,i} \times LSC_{kWh,i}) + \sum(DF_i \times LSC_{kWh,i}) + \sum(PL_i \times LSC_{kWh,i})$$

$$Efficiency\ LSC = \sum(SC_{kwh,i} \times LSC_{kWh,i}) + \sum(SC_{gas,i} \times LSC_{gas,i}) + \sum(WH_{kwh,i} \times LSC_{kWh,i}) + \sum(WH_{gas,i} \times LSC_{gas,i}) + \sum(MV_{kwh,i} \times LSC_{kWh,i}) + \sum(MV_{gas,i} \times LSC_{gas,i}) + \sum(SUC_i \times LSC_{kWh,i})$$

Where:

PV_i = The energy generation of the photovoltaic system in the i^{th} hour. Additional informaiton for export considerations are described below.

$LSC_{kWh,\ i}$ = The LSC factor for electricity in the i^{th} hour.

$BESS_i$ = Battery energy storage system energy in the i^{th} hour.

$L_{unregulated,i}$ = Unregulated lighting energy used in the ith hour.

DF_i = The demand flexibility energy in the ith hour.

PL_i = Plug load energy used in the ith hour.

$SC_{kwh,i}$ = The space-conditioning electric energy used in the i^{th} hour.

$SC_{gas,i}$ = The space-conditioning gas energy used in the i^{th} hour.

$LSC_{gas,\ i}$ = The LSC factor for gas in the i^{th} hour.

$WH_{kwh,i}$ = The water heating electric energy used in the i^{th} hour.

$WH_{gas,i}$ = The water heating gas energy used in the i^{th} hour.

$MV_{kwh,i}$ = The mechanical ventilation electric energy used in the i^{th} hour.

$MV_{gas,i}$ = The mechanical ventilation gas energy used in the i^{th} hour.

SUC_i = The energy associated with the self-utilization credit in the i^{th} hour. The LSCs that apply to photovoltaic and BESS systems depend on whether generated energy is used on site or exported to the grid. If energy is used on site the LSC factors are based on the LSC factors as described in Reference Appendices, Joint Appendix JA3. If energy is exported to the grid, the hourly export LSC factors provided by the CEC are used. These export LSC factors account for the LSC costs that are avoided by the exports in each hour.

To comply through the performance compliance approach, the Total LSC, and the Efficiency LSC of the proposed design must be equal to or less than the Total LSC, and the Efficiency LSC of the standard design. This applies to newly constructed buildings, additions to existing buildings, additions plus alterations of existing buildings, and alterations of existing buildings. The hourly LSC factors can be found at the Energy Commission website (https://www.energy.ca.gov/files/2025-energy-code-date-and-hourly-factors).

1.6 Peak Cooling Energy

The compliance software shall calculate peak cooling energy for both the standard design and the proposed design. Peak cooling energy is the total annual mechanical cooling site energy, in kWh, that occurs at peak hours between 4 pm and 9 pm for July to November. Up to a 20% increase in peak cooling energy for a proposed design compared to the minimally code-compliant standard design is allowed when using the performance compliance approach. Peak cooling is applicable in climate zones 4 and 8 through 15.

1.7 Compliance for Additions and Alterations

Compliance for additions and alterations to existing buildings requires calculating the energy use of the proposed design, and the energy budget of the standard design.

When the energy use of the proposed design is equal to or less than the energy budget of the standard design, the addition or alteration or both comply with the 2025 Energy Code. The compliance margin is the difference between the energy use of the standard design and the energy budget of the proposed design. When the compliance margin is zero or greater, the project complies.

The energy use is expressed in units LSC per square foot of conditioned floor area (LSC/ft^2) and accounts for regulated energy end uses, including space heating, space cooling, ventilation, and water heating. Unregulated energy end uses are not included, such as interior lighting, appliances, cooking, plug loads, and exterior lighting. PV generation and demand flexibility measures, such as BESS, have no effect on additions and alterations to existing buildings.

1.8 Self-Utilization Credit

When a PV system is coupled with a BESS, the compliance software allows a portion of the photovoltaic and BESS LSC to be traded against the Efficiency LSC. This modest credit can be used for tradeoffs against building envelope and efficiencies of the equipment installed in the building. More detail is provided in 2.1.5 Self-Utilization Credit.

1.9 Heat Pump Water Heating Load Shifting

Any Reference Appendices, Joint Appendix JA13-compliant HPWH will receive LSC credit for each climate zone according to**Error! Reference source not found.**. The LSC percentage reduction is applied upon the completion of the compliant simulation run. Note that this reduction only applies to the water heating LSC values.

Table 1: JA13 HPWH Basic Control Credit

Climate Zone	**JA13 Credit (%)**

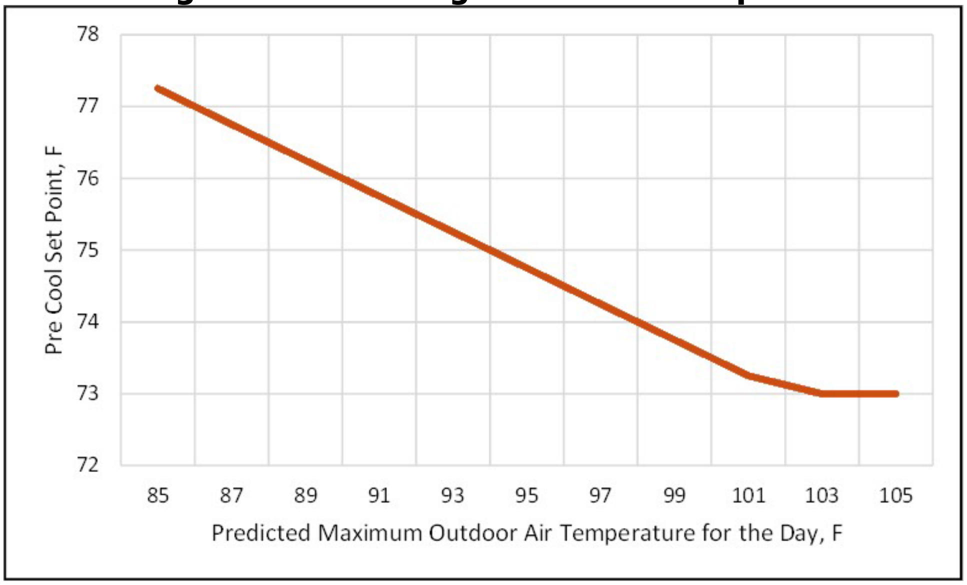
1	6.7
2	3.7
3	7.6
4	4.0
5	8.5
6	6.8
7	8.8
8	4.4
9	4.4
10	4.4
11	4.2
12	4.7
13	8.0
14	3.1
15	8.2
16	22.7

1.10 Precooling

Precooling represents a program where special thermostats in homes receive signals from the local utility that alter the occupant’s normal behavior to reduce air-conditioning energy consumption during peak electricity demand periods. The house is precooled to a lower-than-normal set point in the hours preceding the onset of the peak and then the thermostat is returned to the normal setting for the peak period. The thermal mass of the structure and furnishings absorbs the cooling load as the house warms up, allowing the cooling system to remain off for most, or all, of the highest peak period hours.

CBECC-Res precooling simulations alter the thermostat set points only during daylight hours on days when the average daily outdoor temperature is greater than 78° F, and the peak electricity values are high. On those days, the precooling period thermostat setpoint depends on the predicted outdoor temperature for the day as plotted in Figure 1: Precooling Thermostat Set point.

Figure 1: Precooling Thermostat Set point



Source: California Energy Commission

The compliance credit due to precooling is reduced to 30% of the LSC value of perfect operation to account for unreliable occupant behavior in actual homes.

2 Proposed 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 single-family residential building configuration is defined by the user through entries that include floor areas, wall areas, roof areas, ceiling areas, window areas, skylight areas, and door areas. The user also specifies performance characteristics such as R-values, solar heat gain coefficient (SHGC), solar reflectance, and thermal emittance are required inputs. Information about the orientation and tilt is also required for roofs, and exterior walls. Details about the HVAC and water heating systems, as well as any solar generation systems and BESS, are also defined by the user. The user entries for all building elements should be consistent with the actual building design. If the compliance software models the specific geometry of the building by using a coordinate system or graphic entry technique, the data generated should be consistent with the actual building design.

2.1.2 Standard Design

The standard design building, from which the energy budget is established, is in the same location and has the same geometry as the proposed design, except the wall and window areas are distributed equally among the four cardinal directions (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 energy budget for the residential standard design is the energy that would be used by a building that has all of the same features as the proposed design except the building minimally meets the requirements of the prescriptive standards. The compliance software generates the standard design automatically, based on fixed and restricted inputs and assumptions. Custom energy budget generation shall not be accessible to program users for modification when the program is used for compliance or when the program generates compliance forms.

The basis of the standard design is the prescriptive requirements from the Energy Code Section 150.1(c), Table 150.1-A. Prescriptive requirements vary by climate zone. Reference Appendices, Joint Appendix JA2, Table 2-1, contains the 16 California climate zones and representative cities. The climate zone is based on the zip code for the proposed building, as documented in JA2.1.1.

The following sections present the details of 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 CEC has established alternate modeling assumptions, the standard design features will differ from the proposed design, so the building receives appropriate credit for its efficiency. When measures require verification by a Energy Code Compliance (ECC) rater or are designated as a *special feature,* the specific requirement is listed on the CF1R.

2.1.3Photovoltaics Requirements

The PV system requirements are applicable to newly constructed single-family residential buildings as specified in Section 150.1(c)14. PV system details are based on the publicly available System Advisor Model algorithms developed by the National Renewable Energy Laboratory. See Appendix F for more information.

STANDARD DESIGN

The standard design PV system is sized to meet the requirements of Section 150.1(c)14.

The standard design is based on an azimuth of 170 degrees, standard efficiency for modules, inverter efficiency of 96 percent, fixed tracking, no shading except for horizon shading, roof tilt of 22.61 degrees (5:12 pitch), and annual solar access of 98 percent.

PROPOSED DESIGN

The proposed PV system is input by the user including by user-defined values for:

- Array azimuth of the actual installation, or choosing CFI1 (installation of 150–270 degrees), or CFI2 (installation of 105-300 degrees).
- Module type, including standard (for example, poly- or monocrystalline silicon modules with efficiencies of 14 – 17 percent) and premium (for example, high-efficiency monocrystalline silicon modules with anti-reflective coatings with efficiencies of 18 – 20 percent).
- Inverter efficiency.
- Roof pitch, or choosing CFI1 or CFI2 (installation up to 7:12).
- CFI2 reduces PV production by 10% compared to CFI1. To meet the Total LSC, the difference can be made up by increasing PV size by 10% or increasing energy efficiency features or through battery storage.
- Array tracking type including fixed, single-axis tracking, and two-axis tracking.
- Annual solar access percentage, excluding horizon shading, of the modules.

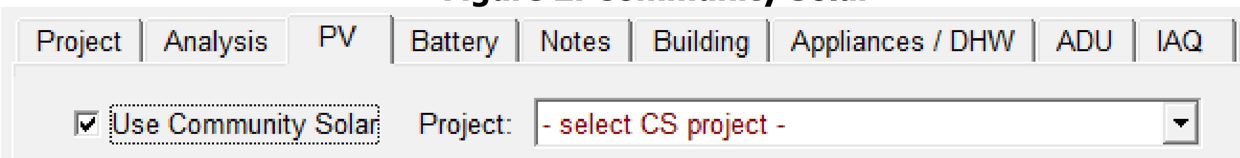
The PV system size is reported in kWdc.

COMMUNITY SOLAR

For projects that use an approved Neighborhood Solar Shares (NSS) program to provide the required PV system, click the “Use Community Solar” checkbox on the PV tab and select the NSS program from the drop-down list. The compliance software will automatically use the

PV characteristics of the NSS program site and system to size the required NSS shares for the building.

Figure 2: Community Solar



Source: California Energy Commission

When the solar electric generation system meets one of the prescriptive exceptions in Section 150.1(c)14, the standard design is modeled with a PV system dictated by the exception limit. The proposed design system size shall exceed the PV size required by the standard design. When the solar electric generation system size is determined based on a limited SARA, the proposed design system size shall not exceed the SARA-determined size.

VERIFICATION AND REPORTING

The PV system details are reported as special features on the CF1R.

2.1.4Battery Energy Storage System

Detailed calculations for PV and BESS are included in Appendices C and D. When a PV system and BESS are included on site, energy generated by the PV system should first prioritize offsetting site energy usage, followed by charging the BESS to be discharged to offset later site energy usage for load shifting, and lastly exporting to the utility grid.

The compliance software provides credit for a BESS, dependent on the compliance cycling capacity as specified in Reference Appendices, Joint Appendix JA12, coupled with a PV system array. If specified, the compliance cycling capacity must be 5 kWh or larger. For Energy Code compliance, the PV system has no effect on energy efficiency requirements or the Efficiency LSC unless a BESS is included, and the self-utilization credit is modeled.

The compliance software includes a checkbox option to allow excess PV system generation credit for above-code programs to the extent that excess generation is allowed by the utility. This option, combined with a BESS, allows any PV system size to impact Total LSC and Source Energy credit.

BATTERY ENERGY STORAGE SYSTEM CONTROLS

The control strategy used for both the standard design is the time-of-use control strategy as described in Referenced Appendices, Joint Appendix JA12. The proposed design control strategy can use either the basic control strategy or the TOU strategy.

The standard design controls for separate BESS is the TOU strategy as described in Reference Appendices, Joint Appendix JA12.

VERIFICATION AND REPORTING

The BESS details are reported as special features on the CF1R.

2.1.5Self-Utilization Credit

The Energy Code does not allow a tradeoff between the Efficiency LSC and the effect of the PV system on the Total LSC unless BESS is provided. When the PV system is coupled with at least a 5 kWh JA12 BESS, the compliance software allows a portion of the photovoltaic and BESS LSC to be traded against the Efficiency LSC. A modest self-utilization credit can be used for tradeoffs against building envelope and efficiencies of the equipment installed in the building. A checkbox is provided in the compliance software to enable this credit.

The magnitude of the credit is equal to the 90 percent of the difference between the 2025 and 2016 Standards envelope requirements.

The following envelope features were used to represent the 2016 Standards:

- Below-deck batt roof insulation value of R-13 for climate zones 4 and 8 – 16.
- Wall U-factor of 0.051 for climate zones 1 – 5 and 8 – 16 and U-factor of 0.065 for climate zones 6 and 7.
- Window U-factor of 0.32 for climate zones 1 – 16.
- Window SHGC of 0.25 for climate zones 2, 4, and 6-16, and not required in climate zones 1, 3, and 5.
- No QII requirements.

The following envelope features were used to represent the 2025 Standards:

- Below-deck batt roof insulation value of R-19 for climate zones 4 and 8-16.
- Wall U-factor of 0.048 for climate zones 1 – 5 and 8 – 16 and U-factor of 0.065 for climate zones 6 and 7.
- Window U-factor of 0.27 for climate zones 1 – 5, 11 – 14 and 16, and U-factor of 0.30 for climate zones 6 – 10 and 15. If the home has 500 square feet or less of conditioned floor area and is in climate zone 5, the U-factor is 0.30.
- Window SHGC of 0.23 in climate zones 2, 4, and 6-14, SHGC of 0.20 for climate zone 15, and not required in climate zones 1, 3, 5, and 16.
- QII required in all climate zones.

Table 2: Self Utilization Credits

Climate Zone	Single-Family
01	10%
02	7%
03	10%
04	9%
05	11%
06	4%

Climate Zone	Single-Family
07	4%
08	10%
09	10%
10	10%
11	10%
12	10%
13	10%
14	10%
15	9%
16	12%

Source: California Energy Commission

Carbon Dioxide Emissions

For every hour of the year, the compliance software calculates all energy end uses in the house, including HVAC, water heating, indoor air quality (IAQ), plug loads, appliances, inside and exterior lighting, and PV system generation. Based on these hourly calculations, the software calculates PV electricity generation that serves the house loads (which reduces the electricity purchased from the grid) and the hourly exports back to the grid. Next, the software applies source energy factors that represent the carbon dioxide (CO_2) generation characteristics of the grid to the hourly kWh balances to calculate the CO_2 generation for each hour of the year. Finally, the software totals the hourly results to yield the annual CO_2 emissions in metric tons per year.

The software reports CO_2 generation for:

1. Total CO_2 generation.
2. CO_2 generation excluding exports to the grid (self-use only).

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 is defined as either part of the attic or part of a cathedral ceiling (also called a *rafter roof*). The software models surfaces separating conditioned space from exterior or unconditioned spaces (such as a garage or storage) as interior surfaces adjacent to the unconditioned zone. Exterior surfaces of an attached garage or storage space are modeled as part of the unconditioned zone.

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

Each surface area is entered along with performance characteristics, including building materials, U-factor, and SHGC. The orientation and tilt (Figure 3: Surface DefinitionsFigure 3: Surface Definitions) are required for envelope elements.

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

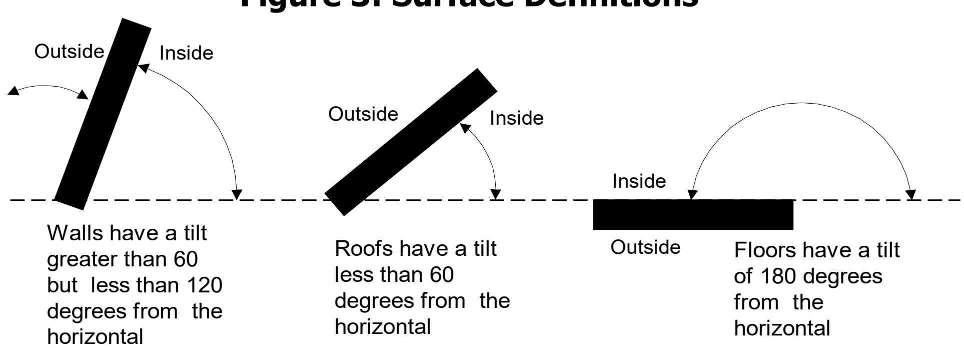
STANDARD DESIGN

To determine the standard design for single-family residential buildings, the compliance software creates a building with the same general characteristics (number of stories, attached garage, climate zone) and with wall and window areas distributed equally among the four cardinal directions. Envelope and HVAC performance inputs are set to the prescriptive requirements in Section 150.1(c) and Table 150.1-A for single-family residential buildings. For additions and alterations, the standard design for existing features in the existing building shall have the same wall and fenestration areas and orientations as the proposed building. The details are below.

VERIFICATION AND REPORTING

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

Figure 3: Surface Definitions



Source: California Energy Commission

2.2.1 Climate and Weather

PROPOSED DESIGN

The user specifies the climate zone based on the zip code of the proposed building. Compliance requirements, weather, design temperatures, and LSC 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 summer and winter.

STANDARD DESIGN

The standard design climate zone is the same as the proposed design.

Verification and Reporting

The zip code and climate zone of the proposed design are reported on the CF1R for verification.

2.2.2 Standards Version

This input determines the appropriate federal appliance efficiency requirements for the standard design to compare with the proposed design.

Proposed Design

The user inputs Compliance 2026.

Standard Design

The standard design cooling and heating equipment efficiency is based on the federal requirements where applicable. A minimum SEER2, EER2, HSPF2, Annual Fuel Utilization Efficiency (AFUE) (as applicable) that meet the current standard for the type of equipment are modeled.

For heat pumps less than 45,000 BTU the EER2 in the standard design is based on the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is below 11.7, then the EER2 in the standard design is equal to the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is 11.7 or greater, then the EER2 of the standard design is 11.7. Consequently, the maximum EER2 of heat pump equipment for cooling in the standard design is 11.7.

For heat pumps 45,000 BTU or larger, the EER2 in the standard design is based on the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is below 11.2, then the EER2 in the standard design is equal to the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is 11.2 or greater, then the EER2 of the standard design is 11.2. Consequently, the maximum EER2 of heat pump equipment for cooling in the standard design is 11.2.

Verification and Reporting

Compliance version is reported on the CF1R.

2.2.3 Existing Condition Verified

These inputs are used for additions and alterations. The standard design for existing conditions varies based on whether the existing conditions are verified by an ECC rater before construction. See 2.10.5 Existing + Addition + Alteration Approach for more information.

Proposed Design

The user inputs either yes or no. “Yes” indicates that the existing building conditions has been, or will be, verified by a ECC Rater. The default assumption is “no.”

STANDARD DESIGN

The standard design assumption is based on the Energy Code Section150.2(b), Table 150.2-G. If the user input is "no," the standard design for the existing component is based on the value in the second column (Standard Design Without Third Party Verification of Existing Conditions Shall be Based On). If the proposed design response is "yes," the standard design value for the existing components is the value in the third column (Standard Design With Third Party Verification of Existing Conditions Shall be Based On).

VERIFICATION AND REPORTING

Verification of existing conditions is a special feature and is reported in the ECC-required verification listings on the CF1R.

2.2.4Air 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 airflows between the conditioned zones, unconditioned zones, and outside.

Building Air Leakage and Infiltration (ACH50)

The airflow through a blower door at 50 pascals (Pa) of pressure measured in cubic feet per minute is called CFM50. CFM50 multiplied by 60 minutes, divided by the volume of conditioned space, is the air changes per hour at 50 Pa, called ACH50.

Specific data on ACH50 may be entered if the single-family home or townhouse will have verified building air leakage testing.

PROPOSED DESIGN

ACH50 defaults to 5 for newly constructed buildings in single-family houses and townhomes and 7 for all other buildings that have heating and cooling system ducts, or both, outside conditioned space, and for buildings with no cooling system. In single-family homes and townhomes with no ducts in unconditioned space, the default ACH50 is 4.4 and 6.2 for all other buildings.

Specific data on ACH50 may be entered if the single-family home or townhouse will have verified building air leakage testing. User input of an ACH50 that is less than the default value becomes a special feature requiring ECC verification.

STANDARD DESIGN

The standard design shall have five ACH50 for single-family homes and seven 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 details and target values modeled in the proposed design, is reported in the ECC-required verification listing on the CF1R.

Air Leakage Distribution

Air leakage is distributed by the compliance software across the envelope surfaces according to the factors in Table 3: Air Leakage Distribution
(Percentage of Total Leakage by Surface). For buildings modeled with multiple conditioned zones, either a 20-square-foot open door or 30-square-foot open stairwell (in a multistory building) is assumed between any two conditioned zones.

Table 3: Air Leakage Distribution (Percentage of Total Leakage by Surface)

Building Configuration	Ceilings	Floors	Exterior Walls	House to Garage
Slab on Grade	50	0	N/A	N/A
Raised Floor	40	10	N/A	N/A
No Garage	N/A	N/A	50	0
Attached Garage	N/A	N/A	40	10

Source: California Energy Commission

2.2.5 Quality Insulation Installation

The compliance software user may specify quality insulation installation (QII) for the proposed design as "yes" or "no." The effective R-value of cavity insulation is reduced, as shown in Table 4: Modeling Rules for Unverified Insulation Installation Quality in buildings with no QII. When set to "no," framed walls, ceilings, and floors are modeled with added winter heat flow between the conditioned zone and attic to represent construction cavities open to the attic. QII does not affect the performance of continuous sheathing in any construction.

PROPOSED DESIGN

The compliance software user may specify compliance with QII. The default is "no" for QII.

STANDARD DESIGN

The standard design is modeled with "yes" for verified QII for newly constructed single-family residential buildings and additions greater than 700 square feet in all climate zones.

VERIFICATION AND REPORTING

The presence of QII is reported in the ECC-required verification listings on the CF1R. Verified QII is certified by the installer and field verified to comply with RA3.5. Credit for verified QII applies to ceilings/attics, knee walls, exterior walls, and exterior floors.

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

Table 4: Modeling Rules for Unverified Insulation Installation Quality

Component	Modification
Walls, Floors, Attic Roofs, Cathedral Ceilings	Multiply the cavity insulation R-value/inch by 0.7.
Ceilings Below Attic	Multiply the blown and batt insulation R-value/inch by 0.96-0.00347*R.
Ceilings Below Attic	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.

Source: California Energy Commission

2.2.6Number of Bedrooms

PROPOSED DESIGN

The number of bedrooms in a building is used to establish the IAQ mechanical ventilation requirements and determine if a building qualifies as a compact building for incentive programs. The number of bedrooms has a direct effect on water heating use.

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.

2.2.7Front Orientation

The input for the building front orientation is the actual azimuth of the front of the building. This azimuth will generally be the side of the building facing the street or where the front door is located. The orientations 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.

For homes that may be built in any orientation, such as a subdivision, multiple orientation compliance can be selected for newly constructed buildings only. When selected the software will model the building using the four cardinal directions (north, east, south, and west).

PROPOSED DESIGN

The user specifies whether compliance is for multiple orientations or a site-specific orientation. For site-specific orientation, the user inputs the actual azimuth of the front in degrees from true north.

STANDARD DESIGN

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

VERIFICATION AND REPORTING

A typical reported value would be "290 degrees." This value would indicate that the front of the building faces north 70° west in surveyors' terms. When compliance is shown for multiple orientations, "all orientations" or "cardinal" is reported as on the CF1R, and the energy use results are reported for four orientations including north, east, south, and west.

2.2.8 Fuel Type

For newly constructed single-family residential buildings, the user specifies natural gas if available (see Energy Code, Section 100.1(b) for definition of Natural Gas Availability), or propane, if natural gas is not available. The user also identifies the fuel type for cooking appliances, clothes dryer, heating equipment, and water-heating equipment. This specification is to establish the LSC values from Reference Appendices, Joint Appendix JA3 used by the compliance software to determine standard and proposed design energy use.

For projects with a run scope of "addition alone," natural gas is available if a gas service line can be connected to the site without a gas main extension. Natural gas is considered available for additions or alteration projects or both if a gas service line is connected to the existing building.

PROPOSED DESIGN

The user specifies either natural gas, or propane.

Standard Design

The standard design assumptions for space heating are as defined in 2.4.1 Heating Subsystems, and those for water heating are defined in 2.9 Domestic Hot Water (DHW).

2.2.9 Attached Garage

The user specifies whether there is an attached garage. The garage zone is modeled as an unconditioned zone (2.8 Garage/Storage).

PROPOSED DESIGN

The user specifies whether there is an attached unconditioned space or garage.

STANDARD DESIGN

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

VERIFICATION AND REPORTING

Features of an attached unconditioned space that affect compliance are reported on the CF1R.

2.2.10 Lighting

The details of the calculation assumptions for lighting loads included in Appendix E are based on the Codes and Standards Enhancement (CASE) report on plug loads and lighting (Rubin 2016, see Appendix F).

PROPOSED DESIGN

Fraction of portable lighting, power adjustment multiplier, and the exterior lighting power adjustment multiplier (watts/ft^2 — watts per square foot) are fixed assumptions.

STANDARD DESIGN

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

VERIFICATION AND REPORTING

No lighting information is reported on the CF1R for compliance with the Energy Code.

2.2.11 Appliances

The details of the calculation assumptions for appliances and plug loads contained in Appendix E are based on the Codes and Standards Enhancement (CASE) report on plug loads and lighting (Rubin 2016, see Appendix F).

PROPOSED DESIGN

All buildings with kitchens are assumed to have a refrigerator, dishwasher, and cooking appliance. Optionally, buildings can have a clothes washer and clothes dryer in the conditioned space. The user can select fuel type as gas or electric for the clothes dryer and cooking appliance.

STANDARD DESIGN

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

VERIFICATION AND REPORTING

No information for the appliance types listed above is reported on the CF1R for compliance with the Energy Code.

2.3 Building Materials and Construction

2.3.1 Materials

Only materials approved by the CEC may be used in defining constructions. Additional materials may be added to the compliance manager through an exceptional method application, as outlined in Section 10-109(e) and Section 10-110.

Table 5: Materials Listshows a partial list of the materials available for construction assemblies.

MATERIAL NAME

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

THICKNESS

Some materials, such as three-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 construction of the building.

CONDUCTIVITY

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

Table 5: Materials List

Material Name	Thickness (in.)	Conductivity (Btu/h-°F-ft)	Coefficient for Temperature Adjustment of Conductivity (°F (-1))	Specific Heat (Btu/lb-°F)	Density (lb/ft^3)	R-Value per Inch (°F-ft^2-h/ Btu-in)
Gypsum Board	0.5	0.09167	0.00122	0.27	40	0.9091
Wood Layer	Varies	0.06127	0.0012	0.45	41	1.36
Synthetic Stucco	0.375	0.2	N/A	0.2	58	0.2
3 Coat Stucco	0.875	0.4167	N/A	0.2	116	0.2
All other siding	N/A	N/A	N/A	N/A	N/A	0.21
Carpet	0.5	0.02	N/A	0.34	12.3	4.1667
Light Roof	0.2	1	N/A	0.2	120	0.0833
5 PSF Roof	0.5	1	N/A	0.2	120	0.0833
10 PSF Roof	1	1	N/A	0.2	120	0.0833
15 PSF Roof	1.5	1	N/A	0.2	120	0.0833
25 PSF Roof	2.5	1	N/A	0.2	120	0.0833
TileGap	0.75	0.07353	N/A	0.24	0.075	1.1333
SlabOnGrade	3.5	1	N/A	0.2	144	0.0833
Earth	N/A	1	N/A	0.2	115	0.0833

Material Name	Thickness (in.)	Conductivity (Btu/h-°F-ft)	Coefficient for Temperature Adjustment of Conductivity (°F (-1))	Specific Heat (Btu/lb-°F)	Density (lb/ft^3)	R-Value per Inch (°F-ft^2-h/ Btu-in)
SoftWood	N/A	0.08167	0.0012	0.39	35	1.0204
Concrete	N/A	1	N/A	0.2	144	0.0833
Foam Sheathing	Varies	Varies	0.00175	0.35	1.5	Varies
Ceiling Insulation	Varies	Varies	0.00418	0.2	1.5	Varies
Cavity Insulation	Varies	Varies	0.00325	0.2	1.5	Varies
Vertical Wall Cavity	3.5	0.314	0.00397	0.24	0.075	N/A
GHR Tile	1.21	0.026	0.00175	0.2	38	N/A
ENSOPRO	0.66	0.03	0.00175	0.35	2	N/A
ENSOPRO Plus	1.36	0.025	0.00175	0.35	2	N/A
Door	N/A	N/A	N/A	N/A	N/A	5

Source: California Energy Commission

COEFFICIENT FOR TEMPERATURE ADJUSTMENT OF CONDUCTIVITY

The conductivity of some materials varies with temperature according to the coefficient listed. Materials that have a coefficient of zero do not vary with temperature.

SPECIFIC HEAT

The specific heat is the amount of heat in British thermal units (Btu) it takes to raise the temperature of 1 pound of the material 1 degree Fahrenheit (Btu/lb-°F).

DENSITY

The density of the material is the weight of the material in pounds per cubic foot (lb/ft^3).

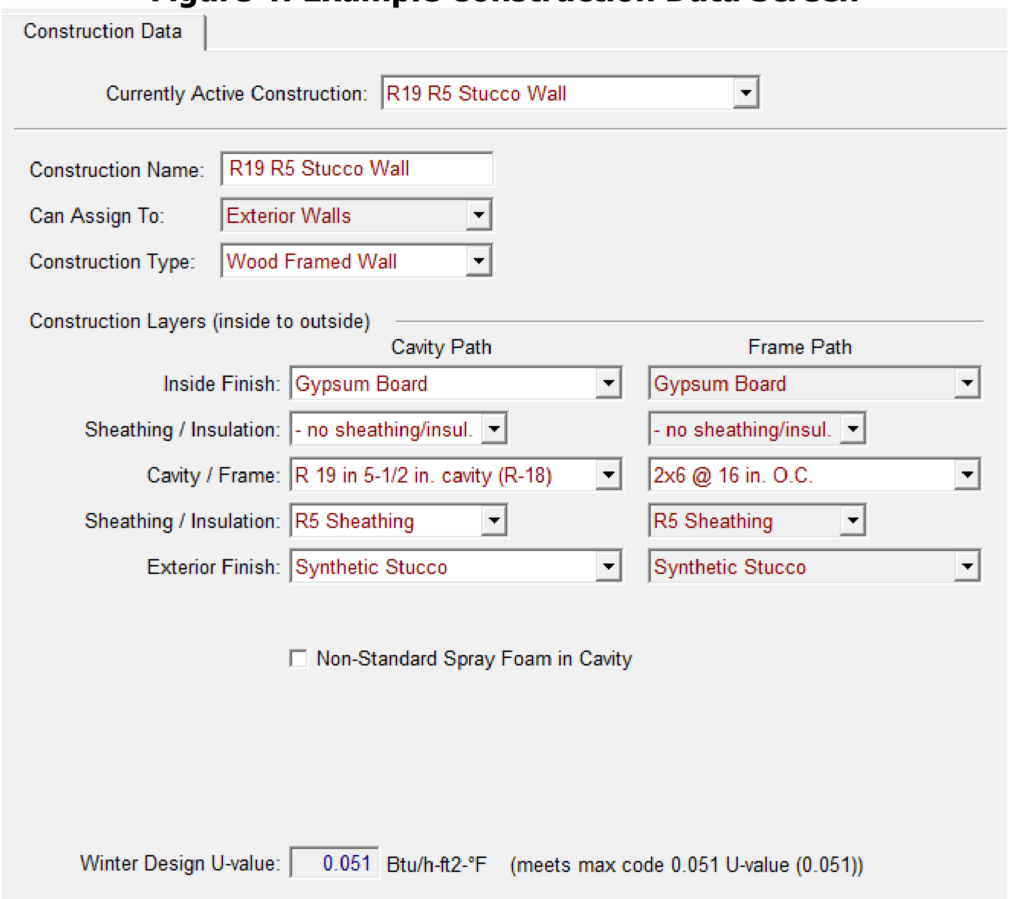
R-VALUE PER INCH

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

2.3.2Construction Assemblies

“Constructions” are defined by the compliance software user to characterize the envelope performance of the building. The user assembles a construction from one or more layers of materials, as shown in. 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 that 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 layer and framing rather than the U-factor.

Figure 4: Example Construction Data Screen



Source: California Energy Commission

Assembly Types

The types of assemblies are:

- Exterior wall.
- Interior wall.
- Underground wall.
- Attic roof.
- Cathedral roof.
- Ceiling below attic.

Interior ceiling.

Interior floor.

Exterior floor (over unconditioned space or exterior).

Floor over crawl space.

Construction Type

The types of construction are:

Ceiling below attic (the roof structure is not defined here, but is part of the attic), wood-framed. In a residence with a truss roof, the ceiling is where the insulation is located, while the structure above the ceiling is encompassed by the term "attic" or "roof." The attic or roof consists of (from inside to outside) the radiant barrier, below-deck insulation, framing, above-deck insulation, and the roofing product, such as asphalt or tile roofing. See more in 2.6.2 Ceiling Below Attic.

Cathedral ceiling (with the roof defined as part of the assembly), wood-framed. Since there is no attic, the roof structure is connected to the insulated assembly at this point.

Roof, structurally insulated panels (SIP).

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

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

Party surfaces separate conditioned space included in the analysis from conditioned space not included in the analysis. Party surfaces for spaces not included in the analysis include spaces joining an addition alone to the existing dwelling. Interior walls, ceilings, or floors can be party surfaces.

Construction Layers

All assemblies have a cavity path and a frame path.

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-rated properties rounded to the nearest whole R-value. 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 an interior or demising floor. The exterior walls, floor, and 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. Nonstandard framing (for example, 24" on center wall framing, advanced wall framing) is reported as a special feature.

2.3.3Spray-Foam Insulation

The R-values for spray-applied polyurethane foam (SPF) insulation differ depending on whether the product is open cell or closed cell. Spray-foam insulation R-values are calculated based on the nominal thickness of the insulation multiplied by the default thermal resistivity per inch, or the total R-value may be calculated based on the thickness of the insulation multiplied by the tested R-value per inch as certified by the Department of Consumer Affairs, Bureau of Household Goods and Services. (See 2.3.3 Spray-Foam Insulation and Reference Appendices, Residential Appendix RA3.5.) Additional documentation and verification requirements for a value other than the default values shown in are required. (See details in Reference Appendices, Residential Appendix RA3.5.6.)

Table 6: Required Thickness Spray-Foam Insulation (in inches)

Equivalent R-values for SPF Insulation	**11**	**13**	**15**	**19**	**21**	**22**	**25**	**30**	**38**
Required thickness closed cell @ R5.8/inch	2.00	2.25	2.75	3.50	3.75	4.00	4.50	5.25	6.75
Required thickness open cell @ R3.6/inch	3.0	3.5	4.2	5.3	5.8	6.1	6.9	8.3	10.6

Source: California Energy Commission

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 2.5 pounds per cubic foot.

Low-Density Open-Cell SPF Insulation

The default R-value for spray-foam insulation with an open cellular structure is calculated as R-3.6 per inch, 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.

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 Reference Appendices, Joint Appendix JA4.1.7. Furthermore, a ECC verification requirement for the installation of spray-foam insulation using higher-than-default values is included on the CF1R.

2.4 Building Mechanical Systems

A space-conditioning system (also referred to as "HVAC system") is made up of the heating subsystem (also referred to as "heating unit," "heating equipment," or "heating system"); cooling subsystem (also referred to as "cooling unit," "cooling equipment," or "cooling system"); the distribution subsystem (if any); and fan subsystem (if any). Ventilation cooling systems and indoor air-quality-ventilation systems are defined at the building level for single-family residential buildings. (See also 2.4.8 Indoor Air Quality Ventilation and 2.4.9 Ventilation Cooling System)

2.4.1 Heating Subsystems

The heating subsystem describes the equipment that supplies heat to a space-conditioning system. Heating systems are subdivided into two subsystems, which are categorized according to the types shown in Table 7: Other HVAC Heating Equipment Types. A conversion factor is used to convert heating seasonal performance factor (HSPF2) to HSPF ratings for modeling. For split-system, small-duct high-velocity, and space-constrained equipment, the conversion factor is 1/0.85 to convert HSPF2 to HSPF. For single-package equipment, the conversion factor is 1/0.84 to convert HSPF2 to HSPF.

Furnace capacity is determined by the compliance software as 200 percent of the heating load at the heating design temperature. Heat pump compressor size is determined by the compliance software as the larger of the compressor size calculated to meet 110 percent of the cooling load at the cooling design temperature, or the compressor size calculated to meet 110 percent of the heating load at the heating design temperature. Supplemental heat is disabled for homes greater than 500 square feet located in Climate Zones 1-6, 8-14, and 16 when the outdoor air temperature is above 40°F. Supplemental heat is provided by electric resistance in the standard design. In the proposed design, supplemental heat is provided by electric resistance except in the case of dual fuel heat pumps where supplemental heat is provided by gas. The dual fuel heat pump will be disabled when the outside air temperature is below 40°F.

If the heat pump heating capacity is insufficient to meet load during any hour, and supplemental heating is provided by electric resistance, the unmet portion of the load is met by supplemental heating.

A parasitic load for the heat pump crankcase heater (CCH) is modeled as 10 watts per ton of rated cooling capacity. The CCH operates whenever the outdoor dry bulb temperature is below 50°F and the compressor is not operating.

Defrost for the heat pump occurs below 40°F outdoor.

PROPOSED DESIGN

The user selects the type of heating subsystem and supplies required inputs for the heating subsystem, including the rated heating efficiency. The rated heating capacity is not used by the compliance software to size the standard design system.

When the proposed space-conditioning system is a heat pump, the user specifies the rated heating capacity at 47°F and 17°F for the heat-pump compressor. These capacities are used to calculate supplemental heat in the simulation. The specified capacities are listed on the CF1R for verification by a ECC Rater.

STANDARD DESIGN

When calculating the standard design efficiency LSC and source energy, the standard design heating subsystem is an electric split-system heat pump with default ducts in the attic and a heating seasonal performance factor (HSPF2) meeting the minimum efficiency for heat pumps as defined in the *Appliance Efficiency Regulations*.

When calculating the PV LSC standard design, the space heating system is dependent on the fuel type of the proposed system. If the proposed system is gas fueled, the standard design is a gas furnace with default ducts in the attic and an annual AFUE meeting the *Appliance Efficiency Regulations* minimum efficiency for central systems. If the proposed system is electric, the standard design is a heat pump as described for the standard design Efficiency LSC.

VERIFICATION AND REPORTING

The proposed heating subsystem type and rated efficiency are reported in the compliance document, CF1R. Measures requiring verification are listed in Table 10: Summary of Space Conditioning Measures Requiring Verification, and are also listed in the ECC verification section on the CF1R.

Table 7: Other HVAC Heating Equipment Types

Name	Heating Equipment Description
CntrlFurnace	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=80% when manufactured before December 18, 2028 and 95% minimum AFUE when manufactured on or after December 18, 2028. Distribution can be gravity flow or use any of the ducted systems.
PkgGasFurnace	The furnace side of a packaged air-conditioning system. Packaged gas or propane furnaces have a minimum AFUE=81%. Distribution can be any of the ducted systems.
WallFurnace Gravity	Noncentral gas- or oil-fired wall furnace, gravity flow. Equipment has varying efficiency requirements by capacity. Distribution is ductless.
WallFurnace Fan	Noncentral gas- or oil-fired wall furnace, fan-forced. Equipment has varying efficiency requirements by capacity. Distribution is ductless.
FloorFurnace	Noncentral gas- or oil-fired floor furnace. Equipment has varying efficiency requirements by capacity. Distribution is ductless.
RoomHeater	Noncentral gas- or oil-fired room heaters. Noncentral gas- or oil-fired wall furnace, gravity flow. Equipment has varying efficiency requirements by capacity. Distribution is ductless.
WoodHeat	Wood-fired stove. In areas with no natural gas available, a wood-heating system with any supplemental heating system is allowed to be installed if exceptional method criteria described in the *Residential Compliance Manual* are met.
Boiler	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.
Electric	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.
CombHydro	Water-heating system can be any gas water heater. 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).

Source: California Energy Commission

2.4.2Heat Pump Subsystems

PROPOSED DESIGN

When the proposed space-conditioning system is a heat pump, the user specifies the rated heating capacity at 47°F and 17°F for the heat-pump compressor. These capacities are used to determine the effect of supplemental electric resistance heat in the simulation. The specified capacities are listed on the CF1R for verification by a HERS Rater.

The following are HP systems that are simulated directly based on user's inputs, and therefore the performance specified by the user impacts the compliance result:

SplitHeatPump
PkgTermHeatPump
SglPkgVertHeatPump
PkgHeatPump
LrgPkgHeatPump
SDHVSplitHeatPump
AirToWaterHeatPump
HeatPumpDHWCombo
VCHP

The following are system types for which the user can select and enter performance data, but the analysis uses the standard design system type, i.e., a split HP, in both proposed and standard designs, which results in a neutral compliance result, and only reports the user-entered performance data:

DuctlessMiniSplitHeatPump
DuctlessMultiSplitHeatPump
DuctlessVRFHeatPump
DuctedMiniSplitHeatPump
DuctedMultiSplitHeatPump
Ducted+DuctlessMultiSplitHeatPump
RoomHeatPump
GroundSourceHeatPump

See Table 8: Heat Pump Equipment Types for the list of all available heat pump equipment currently in the software.

Table 8: Heat Pump Equipment Types

Name	Heat Pump Equipment Description
SplitHeatPump	Central split heat pump system. Distribution system is one of the ducted systems.

Name	**Heat Pump Equipment Description**
SDHVSplitHeatPump	Small-duct, high-velocity, central 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 capacity and uses high-velocity room outlets generally greater than 1,000 feet per minute that have less than 6.0 square inches of free area.
DuctlessMiniSplitHeatPump	A heat pump system that has an outdoor section and one or more ductless indoor sections. The indoor section(s) cycle on and off in unison in response to an indoor thermostat.
DuctlessMultiSplit HeatPump	A heat pump system that has an 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.
DuctlessVRF HeatPump	A variable-refrigerant-flow 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.
PkgHeatPump	Central packaged heat pump systems. A central packaged heat pump is a heat pump in which the blower, coils, and compressor are contained in a single package, powered by single-phase electric current, air-cooled, and rated below 65,000 Btu/h. The distribution system is one of the ducted systems.
LrgPkgHeatPump	Large central packaged heat pump systems, rated above 65,000 Btu/h.
RoomHeatPump	Noncentral room air-conditioning systems. These include packaged terminal (commonly called "through-the-wall") units and any other ductless heat pump systems.
SglPkgVertHeatPump	Single-package vertical heat pump. This is a package air-conditioner that uses reverse cycle refrigeration as the prime heat source and may include secondary supplemental heating by means of electrical resistance.
PkgTermHeatPump	Packaged terminal heat pump. This is a package terminal air-conditioner that uses reverse cycle refrigeration as the prime heat source; has a supplementary heating source available, with the choice of electric resistant heat; and is industrial equipment.

Name	Heat Pump Equipment Description
DuctedMiniSplitHeatPump	Ducted mini-split heat pump is a system that has an outdoor section and one or more ducted indoor sections. The indoor section(s) cycle on and off in unison in response to an indoor thermostat.
DuctedMultiSplitHeatPump	Ducted multi-split heat pump is a system that has a single outdoor section, and two or more ducted indoor sections. The indoor sections operate independently and can be used to condition multiple zones in response to multiple indoor thermostats.
Ducted+DuctlessMulti SplitHeatPump	Multi-split heat pump system with a combination of ducted and ductless indoor units.
AirToWaterHeatPump	An indoor conditioning coil, a compressor, and a refrigerant-to-water heat exchanger that provides heating and cooling functions. May also have the ability to heat domestic hot water.
GroundSourceHeatPump	An indoor conditioning coil with air-moving means, a compressor, and a refrigerant-to-ground heat exchanger that provides heating, cooling, or heating and cooling functions. May also have the ability to heat domestic hot water.
VCHP	Variable Capacity Heat Pump (VCHP) with the ability to change the speed of compressor and ancillary components to vary capacity from the nominal rated capacity.
SinglezoneDualFuelHeatPump	Single-zone dual fuel heat pump system with constant volume fan, direct expansion heat pump cooling and heating, and gas supplemental heating.
HeatPumpDHWCombo	Combined space heating and domestic water heating system.

Source: California Energy Commission

Air Source Heat Pumps

The compliance software shall represent air source heat pump performance at different outdoor dry bulb temperatures, compressor speeds, and entering air conditions, such that the modeled performance is consistent with the rated capacities and efficiencies input by the user. For performance at outdoor dry bulb temperatures and compressor speeds where user input is not provided, the compliance software shall use statistically representative normalized relationships of capacity and efficiency based on performance data of relevant products. For variable capacity heat pumps, these relationships shall enable the calculation of performance at both minimum and maximum capacity compressor operation. Air source heat pump equipment is simulated based on the RESNET Guidelines for Simulating Unitary Air-conditioning and Air-source Heat Pump Equipment, March 28, 2025. This document can be found at https://www.resnet.us/about/standards/publications/.

Ground-Source Heat Pump

A ground-source heat pump system, which uses the earth as a source of energy for heating and as a heat sink for energy when cooling, is simulated as a minimum efficiency split-system equivalent to the standard design with default duct conditions in place of the proposed system. The mandatory efficiencies for ground-source heat pumps are a minimum coefficient of performance (COP) for heating and EER/EER2 for cooling. A conversion factor is used to convert EER to EER2 ratings for modeling. For all air conditioners the conversion factor is 0.96 to convert EER to EER2.

Air-to-Water Heat Pumps

Air-to-water heat pumps (AWHPs) must be listed in the Title 20 MAEDbS database. For the proposed design, fixed compressor speed AWHPs would be modeled equivalent to the prescriptive air source heat pump in heating and cooling operation. Variable-compressor-speed AWHPs are modeled with a two percent reduction in hourly heating energy use and an eight percent reduction in hourly cooling energy use relative to the prescriptive air source heat pump.

2.4.3Combined Hydronic Space/Water Heating

Combined hydronic space/water heating (HeatPumpDHWCombo) is a system where a water heater is used to provide space heating and water heating. Dedicated hydronic space-heating systems are also a modeling capability. Space-heating terminals may include fan coils, baseboards, and radiant floors.

For combined hydronic systems, the water-heating portion is modeled based on the water heating efficiency of the system. For space heating, an effective AFUE is calculated for gas water heaters. For electric water heaters, an effective HSPF2 is calculated. The procedures for calculating the effective AFUE or HSPF2 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 Appendix G.

If a large fan coil is used and air-distribution ducts are in the attic, crawl space, or other unconditioned space, the efficiency of the air-distribution system must be determined using methods consistent with those described in 2.4.5 Distribution Subsystems. Duct efficiency is accounted for when the distribution type is ducted.

Commercial or Consumer Storage Gas Water Heater

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

$$AFUE_{eff} = RE - \frac{PL}{RI} \quad \textbf{Equation 1}$$

Where:

$AFUE_{eff}$ = The effective AFUE of the gas water heater in satisfying the space heating load.

RE = The recovery efficiency (or thermal efficiency) of the gas storage water heater. A default value of 0.70 may be assumed if the recovery efficiency is unknown. This value is generally available from the CEC 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 in unconditioned space.

RI = The rated input of the gas water heater (kBtu/h) available from the CEC appliance directory.

Instantaneous Gas Water Heater

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

$$AFUE_{eff} = UEF \quad \textbf{Equation 2}$$

Where:

$AFUE_{eff}$ = The effective AFUE of the gas water heater in satisfying the space heating load.

UEF = The rated uniform energy factor of the instantaneous gas water heater.

Storage Electric Water Heater

The effective HSPF2 of the storage electric water heaters used for space heating in a combined hydronic system is given by the following equations.

$$HSPF2_{eff} = 3.413\left(1 - \frac{PL}{3.413 \times kWi}\right) \quad \textbf{Equation 3}$$

Where:

$HSPF2_{eff}$ = The effective HSPF2 of the storage electric water heater in satisfying the space-heating load.

PL = Pipe losses (kBtu/h). Assumed zero when less than 10 feet of piping between the water heater storage tank and the fan coil or other heating elements are in unconditioned space.

kW_i = The kilowatts of input to the water heater available from the CEC’s appliance directory.

STANDARD DESIGN

When a hydronic system used for heating is proposed to use electricity, the heating equipment for the standard design is an electric split-system heat pump with an HSPF2 meeting the *Appliance Efficiency Regulations* requirements for split-systems. The standard design heat pump compressor size is determined by the compliance 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 AFUE meeting the *Appliance Efficiency Regulations* minimum efficiency for central systems. When a proposed design uses electric and non-electric heat, the standard design is a gas furnace.

2.4.4Cooling Subsystems

The cooling subsystem describes the equipment that supplies cooling to a space-conditioning system.

Air-conditioner compressor size is determined by the compliance software as 110 percent of the cooling load at the cooling design temperature. For heat pumps the compressor size is 110 percent of the heating load or 110 percent of the cooling load, whichever is larger.

A parasitic load for the air-conditioner crankcase heater (CCH) is modeled as 10 watts per ton of rated cooling capacity. The CCH operates whenever the outdoor dry bulb temperature is below 50°F and the compressor is not operating.

The compliance software shall represent unitary air conditioner performance at different outdoor dry bulb temperatures, compressor speeds, and entering air conditions, such that the modeled performance is consistent with the rated capacities and efficiencies input by the user. For performance at outdoor dry bulb temperatures and compressor speeds where user input is not provided, the compliance software shall use statistically representative normalized relationships of capacity and efficiency based on performance data of relevant products. Unitary air conditioning equipment is simulated based on the Resnet Guidelines for Simulating Unitary Air-conditioning and Air-source Heat Pump Equipment, March 28, 2025.

PROPOSED DESIGN

Cooling subsystems are categorized according to the types shown in Table 9: HVAC Cooling Equipment Types (Other Than Heat Pumps) and in Table 8: Heat Pump Equipment Types. The user selects the type of cooling equipment and supplies required inputs for the cooling subsystem, including the rated cooling efficiency. The cooling equipment type and additional information is based on the equipment type and zoning, such as the SEER2 and

EER2. A conversion factor is used to convert EER2 to EER ratings for modeling. For all air-conditioners the conversion factor is 1/0.96 to convert EER2 to EER. A conversion factor is used to convert SEER2 to SEER ratings for modeling. For split-system equipment, the conversion factor is 1/0.95; for single-package equipment, the conversion factor is 1/0.96; for small-duct high-velocity equipment, the conversion factor is 1.00; and for space-constrained equipment, the conversion factor is 1/0.99 to convert SEER2 to SEER. For some types of equipment, the user may also specify through checkboxes if the equipment has a multispeed compressor and if the system is zoned or not. For ducted cooling systems, the cooling airflow from the conditioned zone through the cooling coil is input as CFM per ton. The rated cooling capacity is not a compliance variable.

See sections below for the details of specific inputs.

STANDARD DESIGN

The cooling subsystem for the standard design building is a single zone heat pump for cooling system meeting the minimum requirements of the *Appliance Efficiency Regulations*.

For heat pumps less than 45,000 BTU the EER2 in the standard design is based on the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is below 11.7, then the EER2 in the standard design is equal to the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is 11.7 or greater, then the EER2 of the standard design is 11.7. Consequently, the maximum EER2 of heat pump equipment for cooling in the standard design is 11.7.

For heat pumps 45,000 BTU or larger, the EER2 in the standard design is based on the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is below 11.2, then the EER2 in the standard design is equal to the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is 11.2 or greater, then the EER2 of the standard design is 11.2. Consequently, the maximum EER2 of heat pump equipment for cooling in the standard design is 11.2.

Fan efficacy meeting the 2025 Energy Code’s mandatory requirements is assumed in all climate zones.

Table 9: HVAC Cooling Equipment Types (Other Than Heat Pumps)

Name	Cooling Equipment Description
NoCooling	Entered when the proposed building is not cooled or when cooling is optional (to be installed at some future date). Both the standard design and the proposed design use the same default. (Refer to 2.4.7 No Cooling)
SplitAirCond	Split air-conditioning systems. Distribution system is one of the ducted systems. (Efficiency metric: SEER2 and EER2)

Name	Cooling Equipment Description
PkgAirCond	Central packaged air-conditioning systems less than 65,000 Btu/h cooling capacity. Distribution system is one of the ducted systems. (Efficiency metric: SEER2 and EER2)
LrgPkgAirCond	Large, packaged air-conditioning systems rated at or above 65,000 Btu/h cooling capacity. Distribution system is one of the ducted systems.
SDHVSplitAirCond	Small-duct, high-velocity, split air-conditioning system.
DuctlessMiniSplitAirCond	Ductless minisplit air-conditioning system having an outdoor section and one or more indoor sections. The indoor sections cycle on and off in unison in response to an indoor thermostat.
DuctlessMultiSplitAirCond	Ductless multisplit air-conditioning system having an outdoor section and two or more indoor sections. The indoor sections operate independently and can be used to condition multiple zones in response to multiple indoor thermostats.
DuctlessVRFAirCond	Ductless variable refrigerant flow (VRF) air-conditioning system.

Name	Cooling Equipment Description
SglPkgVertAirCond	Single-packaged vertical air-conditioning is a self-contained cooling system that is factory-assembled, is arranged vertically, can be mounted on the exterior or interior of a space, and can be installed through the wall. These units can be ducted or ductless.
PkgTermAirCond	Packaged terminal air-conditioning (PTAC) is a self-contained cooling system that is installed through the wall. These systems do not use ducts.
DuctedMiniSplitAirCond	Ducted minisplit air-conditioning system having an outdoor section and one or more indoor sections. The indoor sections cycle on and off in unison in response to an indoor thermostat.
DuctedMultiSplitAirCond	Ducted multisplit air-conditioning system having an outdoor section and two or more indoor sections. The indoor sections operate independently and can be used to condition multiple zones in response to multiple indoor thermostats.
Ducted+DuctlessMulti SplitAirCond	Combination of ducted and ductless multisplit air-conditioning system have an outdoor section and two or more indoor sections. The indoor sections operate independently and can be used to condition multiple zones in response to multiple indoor thermostats.
RoomAirCond	Room air-conditioner is a self-contained cooling system other than a packaged terminal air conditioner that is installed through the wall for the purpose of providing delivery of conditioned air to an enclosed space. These systems do not use ducts. Same as DuctlessSplitAirCond except that cooling is not supplied to each habitable space in the dwelling unit.
EvapCondenser	Evaporatively cooled condensers. A split mechanical system with a water-cooled condenser coil. This system must conform with RA4.3.2.

Source: California Energy Commission

Verification and Reporting

Information shown on the CF1R includes cooling equipment type and cooling efficiency (SEER2 or EER2 or both). Measures requiring verification are listed in Table 10: Summary of

Space Conditioning Measures Requiring Verification, and in the ECC verification section on the CF1R.

Verified Refrigerant Charge

Proper refrigerant charge is necessary for electrically driven compressor air-conditioning and heating systems to operate at full capacity and efficiency. For cooling, compliance software calculations set the cooling compressor efficiency multiplier to 0.90 to account for the effect of improper refrigerant charge or 0.96 for proper charge. For heating, compliance software calculations set the heating compressor efficiency multiplier to 0.92 to account for the effect of improper refrigerant charge or 0.96 for proper charge.

PROPOSED DESIGN

The compliance software allows the user to indicate if systems will have diagnostically tested refrigerant charge. This allowance applies only to ducted split-systems, packaged air-conditioners, and heat pumps. Refrigerant charge verification is required by Section 150.1(c) and Table 150.1-A for the proposed cooling system type.

STANDARD DESIGN

The standard design building is modeled with a diagnostically tested refrigerant charge in Climate Zones 2 and 8–15 for air-conditioners in all homes. For heat pumps diagnostically tested, refrigerant charge is modeled in all climate zones except for homes.

VERIFICATION AND REPORTING

Refrigerant charge require field verification or diagnostic testing and is reported in the ECC-required verification listings on the CF1R. Details on refrigerant charge measurement are discussed in Reference Appendices, Residential Appendix RA3.2.

Table 10: Summary of Space Conditioning Measures Requiring Verification

Measure	Description	Procedures
Verified Refrigerant Charge	Air-cooled air conditioners, and air-source heat pumps must be tested diagnostically to verify that the system has the correct refrigerant charge and meets the system airflow requirement.	RA1.2, RA3.2
Verified System Airflow	System airflow must be verified to be greater than or equal to a specified criterion.	RA3.3
Verified Air-Handling Unit Fan Efficacy	Fan efficacy (watt/CFM) must be verified to be equal to or less than a specified criterion.	RA3.3
Verified HSPF2, SEER2 or EER2	Efficiency of installed air-conditioner or heat-pump models modeled for compliance credit must be verified.	RA3.4.4.1

Measure	Description	Procedures
Verified Heat Pump Capacity	Optional verification of heat-pump system capacity.	RA3.4.4.2
Evaporatively Cooled Condensers	Verification of duct leakage, refrigerant charge, and EER2 is required for compliance credit.	RA3.1.4.3, RA3.2, RA3.4.3, RA3.4.4.1
Whole-House Fan	When verification of the whole-house fan is selected or required, airflow, watt draw, and capacity are verified.	RA3.9
Central Fan Ventilation Cooling System	When compliance includes central fan ventilation cooling, airflow and fan efficacy are verified.	RA3.3.4

Source: California Energy Commission

Verified System Airflow

Adequate airflow to the conditioned space is required for ducted air-conditioning systems to operate at full efficiency and capacity. Air-distribution system efficiency is achieved by increasing the efficiency of motors or by designing and installing air distribution systems with less resistance to airflow. Compliance software calculations account for the effect of airflow on sensible heat ratio and compressor efficiency.

Section 150.0(m)13 requires verification that the central air-handling unit airflow rate is greater than or equal to 350 CFM/ton for systems other than small-duct, high-velocity types or 250 CFM/ton for small-duct, high-velocity systems. Compliance credit is calculated for systems with airflow rates higher than the required CFM/ton, and the airflow rates must be verified by diagnostic testing using procedures in Reference Appendices, Residential Appendix RA3.3.

For single-zone systems:

- As an alternative to verification of 350 CFM/ton for systems other than small-duct, high-velocity types or 250 CFM/ton for small-duct, high-velocity systems, ECC verification of a return duct design that conforms to the specification given in Table 150.0-B or C may be used to demonstrate compliance.
- The return duct design alternative is not an input to the compliance software but must be documented on the certificate of installation CF2R.
- If airflow rates greater than 350 CFM/ton for systems other than small-duct, high-velocity types or greater than 250 CFM/ton for small-duct, high-velocity systems is modeled for compliance credit, the alternative return duct design method using Table 150.0-B or C is not allowed for demonstrating compliance.

- Variable-capacity systems, including multispeed and variable-speed compressor systems must verify airflow rate (CFM/ton) for system operation at the maximum compressor speed and the maximum air handler fan speed.

For zonally controlled systems:

- The alternative return duct design method using Table 150.0-B or C is not allowed for zonally controlled systems.
- Variable-capacity systems including multispeed, variable-speed, and single-speed compressor systems must all verify airflow rate (CFM/ton) by operating the system at maximum compressor capacity and maximum system fan speed in every zonal control mode with all zones calling for conditioning.

PROPOSED DESIGN

The default cooling airflow rate is 350 CFM/ton. Users may model a higher-than-default airflow for these systems and receive credit in the compliance calculation if greater-than-default system airflow is diagnostically tested using the procedures in Reference Appendices, Residential Appendix RA3.3.

STANDARD DESIGN

The standard design shall assume a system that complies with the mandatory (Section 150.0) and prescriptive (Section 150.1) requirements for the applicable climate zone.

VERIFICATION AND REPORTING

The airflow rate verification compliance target (CFM or CFM/ton) is reported in the ECC-required verification listings of the CF1R. When there is no cooling system, the verified airflow rate is reported on the CF1R as a special feature.

Verified Air-Handling Unit Fan Efficacy

The mandatory requirement for minimum air-handling unit fan efficacy is 0.45 watts/CFM for gas furnace air-handling units, 0.58 watts/CFM for air-handling units that are not gas furnaces, and 0.62 watts/CFM for small-duct, high-velocity systems as verified by an ECC Rater, see Section 150.0(m)13. Users may model a lower fan efficacy (watts/CFM) and receive credit in the compliance calculation if the proposed fan efficacy value is diagnostically tested using the procedures in Reference Appendices, Residential Appendix RA3.3.

For single-zone systems:

- Installers may elect to use an alternative to ECC verification of the watts/CFM required by Section 150.0(m)13: ECC verification of a return duct design that conforms to the specification given in Table 150.0-B or C.
- The return duct design alternative is not an input to the compliance software but must be documented on the certificate of installation.

- If a value less than the watts/CFM required by Section 150.0(m)13 is modeled by the software user for compliance credit, the alternative return duct design method using Table 150.0-B or C is not allowed for demonstrating compliance.
- Multispeed or variable-speed compressor systems must verify fan efficacy (watts/CFM) for system operation at the maximum compressor speed and the maximum air handler fan speed.

For zonally controlled systems:

- The alternative return duct design method using Table 150.0-B or C is not allowed for zonally controlled systems.
- Variable-capacity systems including multispeed, variable-speed, and single-speed compressor systems must all verify fan efficacy (watts/CFM) by operating the system at maximum compressor capacity and maximum system fan speed with all zones calling for conditioning.
- Single-speed compressor systems must verify fan efficacy in every zonal control mode.

PROPOSED DESIGN

The compliance software shall allow the user to enter the fan efficacy. The default mandatory value is 0.45, 0.58, or 0.62 watts/CFM, depending on the applicable system type, as described above. 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, a default value of 0.45 watts/CFM is assumed.

STANDARD DESIGN

The standard design shall assume a verified fan efficacy equal to or less than the following:

- 0.45 watts/CFM for gas furnace air-handling units, as well as air-handling units that are not gas furnaces and have a cooling capacity less than 54,000 BTU/h.
- 0.58 watts/CFM for air-handling units that are not gas furnaces and have a cooling capacity greater than or equal to 54,000 BTU/h.
- 0.62 watts/CFM for small duct high velocity forced air systems.

VERIFICATION AND REPORTING

For user inputs lower than the default mandatory requirement, fan efficacy is reported in the ECC-required verification listings of the CF1R.

For default mandatory 0.45, 0.58, or 0.62 watts/cfm, the choice of either fan efficacy or alternative return duct design according to Table 150.0-B or C is reported in the ECC-required verification listings of the CF1R.

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

Verified Energy Efficiency Ratio (EER2)

Proposed Design

The compliance software shall allow the user the option to enter an EER2 rating for central cooling equipment. For equipment that is rated only with an EER2, the user will enter the EER2. EER2 is an ECC-verified measure. A conversion factor is used to convert EER2 to EER ratings for modeling. For all cooling equipment, the conversion factor is 1/0.96 to convert EER2 to EER. A conversion factor is used to convert SEER2 to SEER ratings for modeling. For split-system equipment the conversion factor is 1/0.95; for single-package equipment the conversion factor is 1/0.96; for small-duct high-velocity equipment the conversion factor is 1.00; and for space-constrained equipment the conversion factor is 1/0.99 to convert SEER2 to SEER.

Standard Design

The standard design is based on minimum efficiency EER2 for the type of cooling equipment modeled in the proposed design, based on the applicable *Appliance Efficiency Regulations*.

For heat pumps less than 45,000 BTU the EER2 in the standard design is based on the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is below 11.7, then the EER2 in the standard design is equal to the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is 11.7 or greater, then the EER2 of the standard design is 11.7. Consequently, the maximum EER2 of heat pump equipment for cooling in the standard design is 11.7.

For heat pumps 45,000 BTU or larger, the EER2 in the standard design is based on the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is below 11.2, then the EER2 in the standard design is equal to the EER2 of the equipment in the proposed design. When the EER2 of the equipment in the proposed design is 11.2 or greater, then the EER2 of the standard design is 11.2. Consequently, the maximum EER2 of heat pump equipment for cooling in the standard design is 11.2.

Verification and Reporting

If an EER2 is modeled in the compliance software, the EER2 requires field verification. The EER2 rating is verified using rating data from the AHRI Directory of Certified Product Performance website or another directory of certified product performance ratings approved by the CEC for determining compliance. Verified EER2 is reported in the ECC-required verification listings on the CF1R.

Verified Seasonal Energy Efficiency Ratio (SEER2)

Proposed Design

The compliance software allows the user to specify the SEER2 value. A conversion factor is used to convert SEER to SEER2 ratings for modeling. For split-system equipment the conversion factor is 0.95; for single-package equipment the conversion factor is 0.96; for small-duct high-velocity equipment the conversion factor is 1.00; and for space-constrained equipment the conversion factor is 0.99 to convert SEER to SEER2.

Standard Design

The standard design is based on the default minimum efficiency SEER2 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 is 13.8 SEER2.

Verification and Reporting

If a SEER2 higher than the default minimum efficiency is modeled in the compliance software, the SEER2 requires field verification. The higher-than-minimum SEER2 rating is verified using rating data from AHRI Directory of Certified Product Performance website or another directory of certified product performance ratings approved by the CEC for determining compliance. Verified SEER2 is reported in the ECC-required verification listings on the CF1R.

Verified Evaporatively Cooled Condensers

Proposed Design

Compliance software shall allow users to specify an evaporatively cooled condensing unit. The installation must comply with the requirements of Reference Appendices, Residential Appendix RA4.3.2 to ensure the predicted energy savings are achieved. This credit must be combined with verified refrigerant charge, EER2, and duct leakage.

Standard Design

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

Verification and Reporting

An evaporatively cooled condensing unit, verified EER2, and duct leakage testing are reported in the ECC-required verification listings on the CF1R.

Evaporative Cooling

Evaporative cooling technology is best suited for dry climates where indirect, or indirect-direct cooling of the supply air stream can occur without compromising indoor comfort. Evaporative coolers must comply with RA4.3.2:

- Be indirect or indirect-direct evaporative cooling; direct evaporative cooling is not allowed to be used for compliance
- Listed under Title 20 Appliance Standards
- Certified to the Commission that water use does not exceed 7.5 gallons per ton hour based on Title 20 Appliance Standards testing criteria
- Permanently installed

- Provide automatic relief of supply air from the house with maximum air velocity through relief dampers not exceeding 800 feet per minute
- Bleed systems not allowed
- A water quality management system (either "pump out" or conductivity sensor) is required

PROPOSED DESIGN

Compliance software shall allow users to specify one of three types of evaporative cooling: (1) indirect; or (2) indirect-direct. Product specifications and other modeling details are found in the CEC appliance directory for evaporative cooling. For indirect or indirect-direct, select the appropriate type from the CEC appliance directory and input a 13 EER as well as the airflow and media saturation effectiveness or cooling effectiveness from the CEC appliance directory.

STANDARD DESIGN

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

VERIFICATION AND REPORTING

When indirect or indirect-direct evaporative cooling is modeled, the EER2 verification is shown in the ECC verification section on the CF1R, along with the system type, airflow, and system effectiveness.

2.4.5 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 and modeled as one large system. If the systems are aggregated, they must be the same type, and all meet the same minimum specifications.

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

Distribution Type

Fan-powered, ducted distribution systems 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 and duct location are specified when a ducted system is specified.

PROPOSED DESIGN

The compliance software shall allow the user to select from the basic types of HVAC distribution systems and locations listed in Table 11: HVAC Distribution Type and Location Descriptors. For ducted systems, the default location of the HVAC ducts and the air handler are in the attic.

Table 11: HVAC Distribution Type and Location Descriptors

Name	HVAC Distribution Type and Location Description
Ducts located in attic (ventilated and unventilated)	Ducts located overhead in the attic space.
Ducts located in a crawl space	Ducts located under floor in the crawl space.
Ducts located in a garage	Ducts located in an unconditioned garage space.
Ducts located within the conditioned space (except < 12 linear ft)	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.
Ducts located entirely in conditioned space	HVAC unit or systems with all HVAC ducts (supply and return) within the conditioned floor space. Location of ducts in conditioned space eliminates conduction losses but does not change losses due to leakage. Leakage either from ducts that are not tested for leakage or from sealed ducts is modeled as leakage to outside the conditioned space.
Distribution system without ducts (none)	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.
Ducts located in outdoor locations	Ducts in exposed locations outdoors.
Verified low-leakage ducts located entirely in conditioned space	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 RA3.1.4.3.8.
Ducts located in multiple places	Ducts with different supply and return duct locations.

Source: California Energy Commission

Table 12: Summary of Verified Distribution Systems

Measure	**Description**	**Procedures**
Verified Duct Sealing	Mandatory measures require that space-conditioning ducts be sealed. Field verification and diagnostic testing are required to verify that approved duct system materials are used, and that duct leakage meets the specified criteria.	RA3.1.4.3
Verified Duct Location, Reduced Surface Area and R-value	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.[1] For buried duct measures, verified QII is required, as well as duct sealing.	RA3.1.4.1, 3.1.4.1.1
Low-Leakage Ducts in Conditioned Space	When the standards specify use of the procedures in Reference Appendices, Residential Appendix RA3.1.4.3.8 to determine if the space-conditioning system ducts are 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 RA3.1.4.3.8. Field verification for ducts in conditioned space is required. Duct sealing is required.	RA3.1.4.3.8
Hydronic Delivery in Conditioned Space	Compliance credit can be taken for hydronic delivery systems with no ducting or piping in unconditioned space. For radiant ceiling panels, the verifications in Reference Appendices, Residential Appendix RA3.4.5 must be completed to qualify.	RA3.4.5
Low-Leakage Air-Handling Units	Compliance credit can be taken for installing a factory-sealed air-handling unit tested by the manufacturer and certified to the CEC to have met the requirements for a low-leakage air-handling unit. Field verification of the air handler model number is required. Duct sealing is required.	RA3.1.4.3.9

Measure	Description	Procedures
Verified Return Duct Design	Verification to confirm that the return duct design conforms to the criteria given in Table 150.0-B or Table 150.0-C. as an alternative to meeting 0.45 or 0.58 watts/CFM fan efficacy of Section150.0(m)13.	RA3.1.4.4
Verified Bypass Duct Condition	Verification to determine if system is zonally controlled and confirm that bypass ducts condition modeled matches installation.	RA3.1.4

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. If these conditions are met, ECC Rater verification is not required.

Source: California Energy Commission

The compliance 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 (Table 12: Summary of Verified Distribution Systems), including duct leakage target, R-value, supply and return duct area, diameter, and location.

STANDARD DESIGN

The standard heating and cooling system for central systems is modeled with default duct assumptions and locations as described in Table 13: Summary of Standard Design Duct Location, and with duct leakage as specified in Table 21: Duct/Air Handler Leakage. The standard design duct insulation is determined by Table 150.1-A (assuming attic Option B) as R-6 in Climate Zones 3 and 5–7, and R-8 in Climate Zones 1, 2, 4, and 8–16. The standard design building is assumed to have the same number of stories as the proposed design for determining the duct efficiency.

Table 13: Summary of Standard Design Duct Location

Configuration of the Proposed Design	Standard Design Duct Location	Detailed Specifications
Attic over the dwelling unit	Ducts and air handler located in the attic	Ducts sealed (mandatory requirement) No credit for verified R-value, location, or duct design
No attic but crawl space or basement	Ducts and air handler located in the crawl space or basement	Ducts sealed (mandatory requirement) No credit for verified R-value, location, or duct design
Buildings with no attic, crawl space or basement	Ducts and air handler located indoors	*Ducts tested to meet verified low leakage ducts in conditioned space requirements.* No credit for verified R-value, location or duct design

This table is applicable only when the standard design system has air-distribution ducts

Source: California Energy Commission

Verification and Reporting

Distribution type, location, R-value, and the determination of whether tested and sealed will be shown on the CF1R. If there are no ducts, the absence of ducts is shown as a special feature on the CF1R. Any duct location other than attic (for example, crawl space) is shown as a special feature on the CF1R. Ducts in crawl space or the basement shall include a special feature note if supply registers are within 2 feet of the floor. Measures that require ECC verification will be shown in the ECC-required verification section of the CF1R.

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 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 the surface area. If the supply or return duct system is 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 14: Location of Default Duct Surface Area 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 (Table 13).

VERIFICATION AND REPORTING

Duct location is reported on the CF1R. Ducts entirely in conditioned space and verified low-leakage ducts entirely in conditioned space are reported in the ECC-required verification listing on the CF1R.

Default duct locations are shown in Table 14: Location of Default Duct Surface Area. 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 two or more stories, 35 percent of the default duct area may be assumed to be in conditioned space, as shown in Table 14: Location of Default Duct Surface Area.

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

Table 14: Location of Default Duct Surface Area

Supply Duct Location	One story	Two or more stories
All in crawl space	100% crawl space	65% crawl space, 35% conditioned space
All in basement	100% basement	65% basement, 35% conditioned space
Other	100% attic	65% attic, 35% conditioned space

Source: California Energy Commission

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.

Default Return Duct Surface Area

Default return duct surface area is calculated using:

$$A_{r,out} = K_r \times A_{floor} \quad \textbf{Equation 4}$$

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

Default Supply Duct Surface Area

Standard Design

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

$$A_{s,out} = 0.27 \times A_{floor} \times K_s \qquad \textbf{Equation 5}$$

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

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

Proposed Design

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

$$A_{s,out} = 0.027 \times A_{floor} \qquad \textbf{Equation 6}$$

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 shall be calculated based on the associated 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. The software assumes the user input duct system area is 85 percent of the total duct system area. The other 15 percent is assumed to be air handler, plenum, and connectors. Because of this, the total duct system area used in the building simulation is:

Simulated Duct System Area = 1.1765 multiplied by the total user entered duct system area

Bypass Duct

Section 150.1(c)13 prohibits use of bypass ducts unless a bypass duct is otherwise specified on the certificate of compliance. A bypass duct may be needed for some single-speed outdoor condensing unit systems. The software allows users to specify a bypass duct for the system. Selection of a bypass duct does not trigger changes in the ACM modeling defaults, but verification by a ECC Rater is required to use the procedure in Reference Appendices, Residential Appendix RA3.1.4.6.

Specification of a zonally controlled system with a single-speed condensing unit will trigger a default airflow rate value of 150 CFM/ton for the calculations. User input less than 350 CFM/ton reduces the compliance margin compared to systems that model 350 CFM/ton as described in 2.4.4 Verified System Airflow.

PROPOSED DESIGN

Software shall allow users to specify whether a bypass duct is 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 Section150.1(c) and Table 150.1-A. The system is not a zonally controlled system.

VERIFICATION AND REPORTING

An HVAC system with zonal control, and the determination of whether the system is assumed to have a bypass duct or have no bypass duct, is reported in the ECC-required verification listings on the CF1R.

Duct System Insulation

For conduction calculations in the standard and proposed designs, 85 percent of the supply and return duct surface is assumed duct material at the related specified R-value, and 15 percent is assumed 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 7, including each segment of the duct system that has a different R-value.

$$R_{eff} = \frac{(A_1 + A_2 ... + A_N)}{\left(\frac{A_1}{R_1} + \frac{A_2}{R_2} ... + \frac{A_N}{R_N}\right)} \qquad \textbf{Equation 7}$$

Where:

R_{eff} = Area weighted effective R-value of duct system for use in calculating duct efficiency, (h-ft²-°F/Btu)

A_N = Area of duct segment n, square feet

R_N = R-value of duct segment n including film resistance (duct insulation rated R + 0.7) (h-ft²-°F/Btu)

PROPOSED DESIGN

The software user inputs the R-value of the proposed duct insulation and details. The default duct thermal resistance is based on Table 150.1-A, attic option B, which is R-6 in Climate Zones 3 and 5–7, R-8 in Zones 1, 2, 4, and 8–16.

Duct location and duct R-value are reported on the CF1R. Credits for systems with mixed insulation levels, nonstandard supply and return duct surface areas, or ducts buried in the attic require the compliance and diagnostic procedures in Reference Appendices, Residential Appendix RA3.1.4.1.

If verified duct design is selected, the user must enter the duct design into the software. For each duct segment entered, the user must specify Type (supply/return), Buried (yes/no, as specified by 2.4.5 Buried Attic Ducts), Diameter (inside/nominal), Length, and Duct Insulation R-value. User-entered duct design must be verified by a ECC Rater according to the procedures in Reference Appendices, Residential Appendix RA3.1.4.1.1. User-entered duct design and duct location are reported on the CF1R when nonstandard values are specified.

STANDARD DESIGN

The required duct insulation R-value for attic Option B is from Table 150.1-A for the applicable climate zone used in the standard design.

VERIFICATION AND REPORTING

Duct type (supply/return), nominal diameter, length, R-value, and location, and supply and return areas are reported on the CF1R. Verified duct design is reported in the ECC-required verification listing on the CF1R.

Buried Attic Ducts

Ducts partly, fully, or deeply buried in blown attic insulation in dwelling units meeting the requirements for verified QII may take credit for increased effective duct insulation. To qualify for buried duct credit, ducts must meet mandatory insulation levels (R-6) before burial, be directly or within 3.5 inches of ceiling gypsum board, and be surrounded by at least R-30 attic insulation. Moreover, credit is available only for duct runs where the ceiling is level, there is at least 6 inches of space between the duct outer jacket and the roof sheathing, and the attic insulation has uniform depth. Existing ducts are not required to meet mandatory minimum insulation levels, but to qualify for buried duct credit, they must have greater than R-4.2 insulation before burial.

In addition to the above requirements, deeply buried ducts must be buried by at least 3.5 inches of insulation above the top of the duct insulation jacket and located within a lowered area of the ceiling, a deeply buried containment system, or buried by at least 3.5 inches of uniformly level insulation. Mounding insulation to achieve the 3.5-inch burial level is not allowed.

Deeply buried duct containment systems must be installed such that the walls of the system are at least 7 inches wider than the duct diameter (3.5 inches on each side of duct), the walls extend at least 3.5 inches above the duct outer jacket, and the containment area surrounding the duct must be completely filled with blown insulation.

The duct design shall identify the segments of the duct that meet the requirements for being buried, and these are input into the software separately from nonburied ducts. For each buried duct, the user must enter the duct size, R-value, length, and determination of whether the duct qualifies as deeply buried. The user must also indicate if a duct uses a deeply buried containment system. The software calculates the weighted average effective duct system R-value based on the user-entered duct information, blown insulation type (cellulose or fiberglass), and R-value.

Duct-effective R-values are broken into three categories: partially, fully, and deeply, with each having different burial levels and requirements. Partially buried ducts have less than 3.5 inches of exposed duct depth, fully buried ducts have insulation depth at least level with the duct jacket, and deeply buried ducts have at least 3.5 inches of insulation above the duct jacket in addition to the above requirements. Effective duct R-values used by the software are listed in Table 15: Buried Duct Effective R-Values:
R-8 Ducts With Blown Fiberglass Attic Insulation through Table 20: Buried Duct Effective R-Values:
R-4.2 Ducts with Blown Cellulose Attic Insulation.

PROPOSED DESIGN

The software calculates the effective R-value of buried ducts based on user-entered duct size, R-value, and length; attic insulation level and type; and determination of whether the duct meets the requirements of a deeply buried duct by using a lowered ceiling chase or a containment system. This feature must be combined with verified QII, verified duct location, reduced surface area and R-value, and verified minimum airflow. The software will allow any combination of duct runs and the associated buried condition, and the overall duct system effective R-value will be a weighted average of the combination. 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 ECC-required verification listing on the CF1R.

Table 15: Buried Duct Effective R-Values:
R-8 Ducts With Blown Fiberglass Attic Insulation

Duct Diameter	R-30 Ceiling	R-38 Ceiling	R-40 Ceiling	R-43 Ceiling	R-49 Ceiling	R-60 Ceiling
3"	R-18	R-26	R-26	R-26	R-26	R-26
4"	R-13	R-18	R-26	R-26	R-26	R-26
5"	R-13	R-18	R-18	R-26	R-26	R-26
6"	R-13	R-18	R-18	R-18	R-26	R-26

Duct Diameter	R-30 Ceiling	R-38 Ceiling	R-40 Ceiling	R-43 Ceiling	R-49 Ceiling	R-60 Ceiling
7"	R-13	R-13	R-18	R-18	R-26	R-26
8"	R-8	R-13	R-13	R-18	R-18	R-26
9"	R-8	R-13	R-13	R-13	R-18	R-26
10"	R-8	R-13	R-13	R-13	R-18	R-26
12"	R-8	R-8	R-8	R-13	R-13	R-26
14"	R-8	R-8	R-8	R-8	R-13	R-18
16"	R-8	R-8	R-8	R-8	R-8	R-13
18"	R-8	R-8	R-8	R-8	R-8	R-13
20"	R-8	R-8	R-8	R-8	R-8	R-8
22"	R-8	R-8	R-8	R-8	R-8	R-8
24"	R-8	R-8	R-8	R-8	R-8	R-8

Source: California Energy Commission

Table 16: Buried Duct Effective R-Values: R-8 Ducts with Blown Cellulose Attic Insulation

Duct Diameter	R-30 Ceiling	R-38 Ceiling	R-40 Ceiling	R-43 Ceiling	R-49 Ceiling	R-60 Ceiling
3"	R-14	R-20	R-20	R-20	R-32	R-32
4"	R-14	R-14	R-20	R-20	R-20	R-32
5"	R-8	R-14	R-14	R-20	R-20	R-32
6"	R-8	R-14	R-14	R-14	R-20	R-32
7"	R-8	R-14	R-14	R-14	R-20	R-20
8"	R-8	R-8	R-8	R-14	R-14	R-20
9"	R-8	R-8	R-8	R-8	R-14	R-20
10"	R-8	R-8	R-8	R-8	R-14	R-20
12"	R-8	R-8	R-8	R-8	R-8	R-14
14"	R-8	R-8	R-8	R-8	R-8	R-8
16"	R-8	R-8	R-8	R-8	R-8	R-8
18"	R-8	R-8	R-8	R-8	R-8	R-8
20"	R-8	R-8	R-8	R-8	R-8	R-8
22"	R-8	R-8	R-8	R-8	R-8	R-8
24"	R-8	R-8	R-8	R-8	R-8	R-8

Source: California Energy Commission

Table 17: Buried Duct Effective R-Values:
R-6 Ducts with Blown Fiberglass Attic Insulation

Duct Diameter	R-30 Ceiling	R-38 Ceiling	R-40 Ceiling	R-43 Ceiling	R-49 Ceiling	R-60 Ceiling
3"	R-15	R-24	R-24	R-24	R-24	R-24
4"	R-15	R-24	R-24	R-24	R-24	R-24
5"	R-11	R-15	R-24	R-24	R-24	R-24
6"	R-11	R-15	R-15	R-24	R-24	R-24
7"	R-11	R-15	R-15	R-15	R-24	R-24
8"	R-11	R-15	R-15	R-15	R-24	R-24
9"	R-6	R-11	R-11	R-15	R-24	R-24
10"	R-6	R-11	R-11	R-15	R-15	R-24
12"	R-6	R-6	R-11	R-11	R-15	R-24
14"	R-6	R-6	R-6	R-6	R-11	R-15
16"	R-6	R-6	R-6	R-6	R-11	R-15
18"	R-6	R-6	R-6	R-6	R-6	R-11
20"	R-6	R-6	R-6	R-6	R-6	R-11
22"	R-6	R-6	R-6	R-6	R-6	R-6
24"	R-6	R-6	R-6	R-6	R-6	R-6

Source: California Energy Commission

Table 18: Buried Duct Effective R-Values:
R-6 Ducts with Blown Cellulose Attic Insulation

Duct Diameter	R-30 Ceiling	R-38 Ceiling	R-40 Ceiling	R-43 Ceiling	R-49 Ceiling	R-60 Ceiling
3"	R-12	R-18	R-18	R-18	R-31	R-31
4"	R-12	R-18	R-18	R-18	R-31	R-31
5"	R-12	R-12	R-18	R-18	R-18	R-31
6"	R-6	R-12	R-12	R-18	R-18	R-31
7"	R-6	R-12	R-12	R-12	R-18	R-31
8"	R-6	R-12	R-12	R-12	R-18	R-31
9"	R-6	R-6	R-6	R-12	R-12	R-18
10"	R-6	R-6	R-6	R-6	R-12	R-18
12"	R-6	R-6	R-6	R-6	R-6	R-12
14"	R-6	R-6	R-6	R-6	R-6	R-12

Duct Diameter	R-30 Ceiling	R-38 Ceiling	R-40 Ceiling	R-43 Ceiling	R-49 Ceiling	R-60 Ceiling
16"	R-6	R-6	R-6	R-6	R-6	R-6
18"	R-6	R-6	R-6	R-6	R-6	R-6
20"	R-6	R-6	R-6	R-6	R-6	R-6
22"	R-6	R-6	R-6	R-6	R-6	R-6
24"	R-6	R-6	R-6	R-6	R-6	R-6

Source: California Energy Commission

Table 19: Buried Duct Effective R-Values: R-4.2 Ducts With Blown Fiberglass Attic Insulation

Duct Diameter	R-30 Ceiling	R-38 Ceiling	R-40 Ceiling	R-43 Ceiling	R-49 Ceiling	R-60 Ceiling
3"	R-13	R-22	R-22	R-22	R-22	R-22
4"	R-13	R-22	R-22	R-22	R-22	R-22
5"	R-13	R-22	R-22	R-22	R-22	R-22
6"	R-13	R-13	R-22	R-22	R-22	R-22
7"	R-9	R-13	R-13	R-22	R-22	R-22
8"	R-9	R-13	R-13	R-13	R-22	R-22
9"	R-9	R-13	R-13	R-13	R-22	R-22
10"	R-4.2	R-9	R-13	R-13	R-13	R-22
12"	R-4.2	R-9	R-9	R-9	R-9	R-22
14"	R-4.2	R-4.2	R-4.2	R-9	R-9	R-22
16"	R-4.2	R-4.2	R-4.2	R-4.2	R-9	R-13
18"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-9
20"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-9
22"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2
24"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2

Source: California Energy Commission

Table 20: Buried Duct Effective R-Values: R-4.2 Ducts with Blown Cellulose Attic Insulation

Duct Diameter	R-30 Ceiling	R-38 Ceiling	R-40 Ceiling	R-43 Ceiling	R-49 Ceiling	R-60 Ceiling
3"	R-15	R-15	R-29	R-29	R-29	R-29
4"	R-9	R-15	R-15	R-15	R-29	R-29

Duct Diameter	R-30 Ceiling	R-38 Ceiling	R-40 Ceiling	R-43 Ceiling	R-49 Ceiling	R-60 Ceiling
5"	R-9	R-15	R-15	R-15	R-29	R-29
6"	R-9	R-9	R-15	R-15	R-15	R-29
7"	R-4.2	R-9	R-9	R-15	R-15	R-29
8"	R-4.2	R-9	R-9	R-9	R-15	R-29
9"	R-4.2	R-9	R-9	R-9	R-15	R-15
10"	R-4.2	R-4.2	R-9	R-9	R-9	R-15
12"	R-4.2	R-4.2	R-4.2	R-4.2	R-9	R-15
14"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-9
16"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-9
18"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2
20"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2
22"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2
24"	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2	R-4.2

Source: California Energy Commission

Duct/Air Handler Leakage

The total duct/air handler leakage shown in Table 21: Duct/Air Handler Leakage is used in simulating the duct system. The supply duct leakage for each case is the table value multiplied by 0.585. The return leakage is the table value multiplied by 0.415.

Proposed Design

For each ducted system, the software user specifies one of the duct/air handler leakage cases shown in Table 21: Duct/Air Handler Leakage.

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 ECC verification section on the CF1R. Duct leakage is measured in accordance with procedures and values specified in Reference Appendices, Residential Appendix RA3.

Low-Leakage Air Handlers

A low-leakage air handler may be specified as well as a lower duct leakage value. (See 2.4.5 Duct/Air Handler Leakage.) Installation requires installing one of the list of approved low-leakage air handling units published by the CEC. The manufacturer certifies that the appliance complies with the requirements of Reference Appendices, Joint Appendices JA9.2.1, 9.2.2, 9.2.3, and 9.2.4.

Table 21: Duct/Air Handler Leakage

Case	Duct Leakage	Air Handler Leakage	Total Duct/Air Handler Leakage
Duct systems in existing single-family houses	10%	Included in duct leakage	10%
Sealed and tested new or altered duct systems in unconditioned or conditioned space in a townhome or single-family home	5%	2%	7%
Verified low-leakage ducts in conditioned space	0%	0%	0%
Low-leakage air handlers in combination with sealed and tested new duct systems	5% or as measured	0%	5% or as measured

Source: California Energy Commission

PROPOSED DESIGN

Credit can be taken for installing a factory-sealed air-handling unit tested by the manufacturer and certified to the CEC to meet the requirements for a low-leakage air-handler. Field verification of the air handler 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.

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 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.

2.4.6Space-Conditioning Fan Subsystems

Fan systems move air for air-conditioning, heating, and ventilation systems. The software allows the user to define the fans to be used for space-conditioning, IAQ, and ventilation cooling. IAQ and ventilation cooling are discussed in 2.4.8 Indoor Air Quality Ventilation and 2.4.9 Ventilation Cooling System.

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 cooling and heating systems, the fan efficacy default is the mandatory minimum verified efficacy of 0.45, 0.58, or 0.62 watts/CFM, depending on applicable system type (also assumed when there is no cooling system).

STANDARD DESIGN

The standard design shall assume a verified fan efficacy complying with the mandatory requirement of equal to or less than the following:

0.45 watts/CFM for gas furnace air-handling units, as well as air-handling unit that are not gas furnaces and have a capacity less than 54,000 BTU/h

0.58 watts/CFM for air-handling units that are not gas furnaces and have a capacity greater than or equal to 54,000 BTU/h

0.62 watts/CFM for small duct high velocity forced air systems

VERIFICATION AND REPORTING

Minimum verified fan efficacy is mandatory for all ducted cooling systems. Fan efficacy is reported in the ECC-required verification listings on the CF1R.

2.4.7Space-Conditioning Systems

This section describes the general procedures for heating and cooling systems in single-family 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 and modeled as one large system. If the systems are aggregated, they must be the same type, and all meet the same minimum specifications.

Multiple System Types Within a Building

Proposed Design

For proposed designs using more than one heating system type, equipment type, or fuel type, if the types do not serve the same floor area, then 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.

Multiple Systems Serving Same Area

If a space or a zone is served by more than one heating system, compliance is demonstrated with the most LSC energy-consuming system serving the space or zone. For spaces or zones that are served by electric resistance heat in addition to other heating systems, the electric resistance heat is deemed the most LSC energy-consuming system unless the supplemental heating meets the exception to Section 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 satisfy the cooling load are modeled.

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 Section 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 specified in Section 150.1(c) and Table 150.1-A for the applicable climate zone.

Verification and Reporting

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

Zonally Controlled Forced-Air Cooling Systems

Zonally controlled central forced-air cooling systems must be able to deliver, in every zonal control mode, an airflow to the dwelling of > 350 CFM per ton of nominal cooling capacity and operating at an air-handling unit fan efficacy of < 0.45 or 0.58 watts/CFM depending on the applicable system type. This is a ECC-verified measure, complying with Reference Appendices, Residential Appendix RA3.3.

An exception allows multispeed or variable-speed compressor systems or single-speed compressor systems to meet the mandatory airflow (CFM/ton) and fan efficacy (watt/CFM) requirements by operating the system at maximum compressor capacity, and system fan speed with all zones calling for conditioning, rather than in every zonal control mode.

PROPOSED DESIGN

The user selects zonally controlled as a cooling system input.

STANDARD DESIGN

The standard design building does not have a zonally controlled cooling system.

VERIFICATION AND REPORTING

Zonally controlled forced-air cooling systems are required to have the system bypass duct status verified by a ECC Rater according to the procedures in Reference Appendices, Residential Appendix RA3.1.4.6, and the fan efficacy and airflow rate are required to be verified according to the procedures in Reference Appendices, Residential Appendix RA3.3.

2.4.8Indoor Air Quality Ventilation

The Energy Code requires that all newly constructed buildings with dwelling units and additions to existing dwelling units greater than 1,000 ft^2 to meet the requirements of ASHRAE Standard 62.2 with California amendments as specified in Section150.0(o). IAQ ventilation is not required for spaces that are not dwelling units. Providing acceptable IAQ by mechanical ventilation is one of the requirements of Standard 62.2. For single-family homes, the required mechanical ventilation rate is equal to the total required ventilation rate for the dwelling minus the calculated annually averaged infiltration rate.

The total required ventilation rate for the dwelling unit is calculated using Energy Code, Equation 150.0-B.

Equation 8 (Equation 150.0-B)

$$\boldsymbol{Q_{total} = 0.03 \times A_{floor} + 7.5 \times (N_{br} + 1)}$$

Where:

Q_{total} = Total required ventilation rate (CFM)

A_{floor} = Conditioned floor area in square feet (ft^2)

N_{br} = Number of bedrooms (not fewer than one)

The effective infiltration rate of the dwelling is calculated using Equation 150.0-C or 150.0-D of the Energy Code.

Equation 9 (Equation 150.0-C & D)

$$Q_{50} = \frac{V_{du} \times ACH_{50}}{60\ min}$$

Where:

Q_{50} =Leakage rate at 50 Pa

V_{du} =Dwelling unit conditioned volume (ft^3)

ACH_{50} = Air changes per hour at 50 Pa (0.2 inch water).

The software uses a default of 2 ACH_{50}. The user may input dwelling unit leakage less than 2 ACH_{50}, if the leakage rate is verified by the procedures specified in Reference Appendices, Residential Appendix RA 3.8.

The effective annual average infiltration rate is calculated using Energy Code, Equation 150.0-E.

Equation 10 (Equation 150.0-E)

$$Q_{inf} = 0.052 \times Q_{50} \times wsf \times \left(\frac{H}{H_r}\right)^{Z}$$

Where:

Q_{inf} = Effective annual infiltration rate (CFM) (L/s)

Q_{50} = Leakage rate at 50 Pa (from equation 150.0-C or 150.0-D)

wsf = Weather and shielding factor from Table 150.0-D (based on a Climate Zone representative city)

H = Vertical distance between the lowest and highest above-grade points within the pressure boundary (ft)

H_r = Reference height, 8.2 ft

Z =0.4 for calculating the effective annual average infiltration rate

For single-family and horizontally attached dwelling units, the required mechanical ventilation rate is calculated using Equation 150.0-F of the Energy Code.

Equation 11 (Equation 150.0-F)

$$Q_{fan} = Q_{total} - \emptyset \times \left(Q_{inf} \times A_{ext}\right)$$

Where:

Q_{fan} = Fan flow rate in cubic feet per minute (CFM)

Q_{total} = Total required ventilation rate (CFM)

Q_{inf} = Effective annual average infiltration rate, CFM from Equation 150.0-E

A_{ext} = Reduction factor accounting for leaks from adjacent dwelling units; 1 for single-family detached homes, or the ratio of exterior envelope surface area that is not attached to garages or other dwelling units to the total envelope surface area for attached dwelling units not sharing ceilings or floor with other dwelling units, occupiable spaces, public garages, or commercial spaces

$\emptyset$ = 1 for balanced ventilation systems and Q_{inf}/Q_{total} otherwise

For estimating the energy impact of this requirement in compliance software, the minimum ventilation rate is met by either a stand-alone IAQ fan system or a central air handler fan system that can introduce outdoor air.

The simplest IAQ fan system is an exhaust fan/bathroom fan that meets the criteria in ASHRAE Standard 62.2 for air delivery and minimal noise. More advanced IAQ fan systems that have a supply or both supply and exhaust fans are possible. To calculate the energy use of stand-alone 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 from 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.

PROPOSED DESIGN

The proposed design shall incorporate a mechanical ventilation system meeting the above mandatory measures. The compliance software allows the user to specify the IAQ ventilation type (see), CFM of outdoor ventilation air equal to or greater than what is required by the Energy Code, and watts/CFM. The user must also indicate whether the dwelling unit is attached or detached and the vertical distance between the lowest and highest above-grade points.

The default minimum IAQ fan is a stand-alone unbalanced exhaust system meeting the above airflow requirements.

For balanced systems, the software allows the user to specify the Sensible Recovery Efficiency (SRE) and Adjusted Sensible Recovery Efficiency (ASRE) if the system has energy or heat recovery. If SRE and ASRE are not available at the ventilation CFM that is input for the dwelling unit, the user can enter HVI-listed ratings for an airflow less than the ventilation CFM and greater than the ventilation CFM. The software will interpolate the values at the ventilation CFM. The watts/CFM for balanced fan systems should be calculated based on the fan power for both fans and the outdoor ventilation rate.

Systems with supply ducts (balanced and supply-only) are simulated with increased fan wattage and reduced SRE and ASRE to account for maintenance and installation factors affecting system efficacy. For these systems, fan wattage is increased by a factor of 1.10 (10 percent increase in wattage), and SRE and ASRE are reduced by a factor of 0.90 (10 percent decrease in recovery efficiencies). For IAQ systems with fault indicator displays

(FID) meeting the specifications provided in Reference Appendices, JA17, Qualification Requirements for Ventilation Systems Fault Indication Displays, these factors don't apply.

Standard Design

For single-family residential buildings, the standard design mechanical ventilation system type (balanced, supply, or exhaust) is the same as the proposed. Fan efficacy is 0.35 watts/CFM for exhaust or supply systems and 0.70 watts/CFM for balanced systems. Airflow rate is equal to the proposed design value or 1.25 times the CFM required by the Energy Code, whichever is smaller.

If the proposed IAQ system uses the central air handler fan, the standard design IAQ fan efficacy is equal to:

- 0.45 watts/CFM for gas furnace air-handling units, as well as air-handling unit that are not gas furnaces and have a capacity less than 54,000 BTU/h.
- 0.58 watts/CFM for air-handling units that are not gas furnaces and have a capacity greater than or equal to 54,000 BTU/h.
- 0.62 watts/CFM for small-duct high-velocity forced air systems.

The standard design is assumed to meet the accessibility criteria in the Energy Code Section 150.0(o)1Civ and incorporates an FID meeting the requirements in Reference Appendices, JA17, Qualification Requirements for Ventilation Systems Fault Indication Displays.

Verification and Reporting

The required ventilation rate to comply with the Energy Code and the means to achieve compliance are indicated on the CF1R. The IAQ system characteristics are reported in the ECC-required verification listing on the CF1R. The diagnostic testing procedures are in Reference Appendices, Residential Appendix RA3.7.

Special features are reported on the CF1R when the proposed system has heat or energy recovery or when the proposed fan efficacy is less than (that is, more efficient than) 0.35 watts/CFM for single-family residential buildings.

Table 22: IAQ Fans

Type	Description	Inputs
Stand-alone IAQ Fan (exhaust, supply, or balanced)	Dedicated fan system that provides IAQ ventilation to meet or exceed the requirements of Energy Code Section 150.0(o).	CFM, watts/CFM, and SRE and ASRE for balanced systems
Central Fan Integrated (CFI) (variable- or fixed-speed)	Automatic operation of the air handler for IAQ ventilation. Ventilation type uses a special damper to induce outdoor IAQ ventilation air and distribute it through the HVAC duct system. Mixing type distributes	CFM, watts/CFM

Type	Description	Inputs
	and mixes IAQ ventilation air supplied by a separate stand-alone IAQ fan system.	

Source: California Energy Commission

2.4.9Ventilation Cooling System

Ventilation cooling systems operate at the dwelling-unit level using fans to bring in outside air to cool the house when the air can reduce cooling loads and save cooling energy. System operation is limited to single-family dwellings and operate according to the schedule and set points shown in. Whole-house fans require either window operation and attic venting or ducting to exhaust hot air. Central fan ventilation cooling systems (fixed and variable-speed) use the HVAC duct system to distribute outside air and require attic venting. Whole-house fans, which exhaust air through the attic, require at least 1 ft^2 of free attic ventilation area per 750 CFM of rated capacity for relief or, if greater, the manufacturer specifications. (See Section150.1[c]12 of the Energy Code.)

Proposed Design

Software allows the user to specify whether a ventilation cooling system (*Table 24* for system types) is included in conditioned and living zones. The user can specify the airflow and watts/CFM (ECC verification required) or a default prescriptive whole-house fan with a capacity of 1.5 CFM/ft^2 of conditioned floor area. When the default capacity is selected, the user can select ECC verification of the airflow and watts to receive full credit for the system capacity. When ECC verification is not selected, the fan capacity is reduced by a factor of 0.67 (33 percent reduction). Ventilation cooling airflow is limited to 3.5 CFM/ft^2 of conditioned area.

Standard Design

The standard design building for a newly constructed single-family residential building or for an addition greater than 1,000 ft^2 to a single-family residential building has a whole-house fan in Climate Zones 8–14, and no ventilation cooling in other climate zones. (See Section150.1[c] and Table 150.1-A.) The whole-house fan has 1.5 CFM/ft^2 of conditioned floor area, 0.14 watts/CFM, with 1 ft^2 of attic vent free area for each 750 CFM of rated whole-house fan airflow CFM.

Verification and Reporting

A ventilation cooling system is either a special feature or a ECC verification requirement, the size and type of which are reported on the CF1R (Table 23: Ventilation Cooling Fans).

Table 23: Ventilation Cooling Fans

Measure	Description	ECC Verification
Whole-House Fan	Traditional whole-house fan mounted in the ceiling to exhaust air from the house to the	Optional RA3.9

Measure	Description	ECC Verification
	attic, inducing outside air in through open windows. Whole-house fans are assumed to operate between dawn and 11 p.m. only at 33 percent of rated CFM to reflect manual operation of fan and windows by occupant. Fans must be listed in the CEC's Whole House Fan directory. If multiple fans are used, enter the total CFM.	
Central Fan Ventilation Cooling Variable- or fixed-speed	Central fan ventilation cooling system. Ventilation type uses a special damper to induce outdoor air and distribute it through the HVAC duct system.	Required RA3.3.4

Source: California Energy Commission

2.5 Conditioned Zones

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

2.5.1Zone Type

Proposed Design

The zone is defined as conditioned, living, or sleeping. Other zone types include garage, attic, and crawl space.

Standard Design

The standard design is conditioned.

VERIFICATION AND REPORTING

When the zone type is living or sleeping, this is reported as a special feature on the CF1R.

Heating Zonal Control Credit

With the heating zonal control credit, 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 ft^2. Other eligibility criteria for this measure are presented in the Residential Compliance Manual, Chapter 4.

PROPOSED DESIGN

The user selects zonal control as a building level input with separate living and sleeping zones.

STANDARD DESIGN

The standard design building is not zoned for living and sleeping separately.

VERIFICATION AND REPORTING

Zonal control is reported as a special feature on the CF1R.

2.5.2Conditioned 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 surface of exterior walls. Stairs are included in conditioned floor area as the area beneath the stairs and the tread of the stairs.

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.

2.5.3Number of Stories

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.

Ceiling Height

PROPOSED DESIGN

The average ceiling height of the proposed design is used to calculate the conditioned volume of the building envelope. The volume (in cubic feet) 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.

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.

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 is the same as the proposed design.

Zone Elevations

The elevation of the top and bottom of each zone is required to set up the airflow 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).

Underground zones are indicated with the number of feet below grade (for example, -8).

Standard Design

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

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 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 Section150.1(c) and Table 150.1-A for the applicable climate zone.

Natural Ventilation

Natural ventilation (from windows) is available during cooling mode when needed and available, as shown in Table 24: Hourly Thermostat Set Points. 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 set point. 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," when the outside temperature is below the estimated zone temperature, and when the estimated zone temperature is above the natural cooling set point temperature. Only the amount of ventilation required to reduce the zone temperature to the natural ventilation set point temperature is used, and the natural ventilation set point temperature is constrained by the compliance software to be greater than the heating setpoint temperature.

Table 24: Hourly Thermostat Set Points

Hour	Cooling	Venting	Heat Pump Heating	Standard Gas Heating Single-Zone	Zonal Control Gas Heating Living	Zonal Control Gas Heating Sleeping
1	78	Off	68	65	65	65
2	78	Off	68	65	65	65
3	78	Off	68	65	65	65
4	78	Off	68	65	65	65
5	78	Off	68	65	65	65
6	78	68*	68	65	65	65
7	78	68	68	65	65	65
8	78	68	68	68	68	68
9	78	68	68	68	68	68
10	78	68	68	68	68	65
11	78	68	68	68	68	65
12	78	68	68	68	68	65
13	78	68	68	68	68	65
14	78	68	68	68	68	65
15	78	68	68	68	68	65
16	78	68	68	68	68	65
17	78	68	68	68	68	68
18	78	68	68	68	68	68
19	78	68	68	68	68	68
20	78	68	68	68	68	68
21	78	68	68	68	68	68
22	78	68	68	68	68	68
23	78	68	68	68	68	68
24	78	Off	68	65	65	65

**Venting starts in the hour the sun comes up.*

Source: California Energy Commission

2.5.4Conditioned Zone Assumptions

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 25: Conditioned Zone Thermal Mass Objects shows the standard interior conditioned zone thermal mass objects and the calculation of the simulation inputs that represent them.

Table 25: Conditioned Zone Thermal Mass Objects

Item	Description	Simulation Object
Interior walls	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 percent 2x4 wood framing and sheetrock on both sides.	Wall exposed to the zone on both sides
Interior floors	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. on-center with miscellaneous bridging, electrical, and plumbing, and a sheetrock ceiling below.	Floor/ceiling surface exposed to the zone on both sides
Furniture and heavy contents	Contents of the conditioned zone with significant heat storage capacity and delayed thermal response, for example heavy furniture, bottled drinks, canned goods, contents of dressers, 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.	Horizontal wood slab exposed to the zone on both sides
Light and thin contents	Contents of the conditioned zone that have a large surface area compared to weight, for example, clothing on hangers, curtains, pots,	Air heat capacity (C_{air}) = CFA * 2

Item	Description	Simulation Object
	and pans. These are assumed to be 2 Btu per square foot of conditioned floor area.	

Source: California Energy Commission

PROPOSED DESIGN

The proposed design has standard conditioned zone thermal mass objects (such as gypsum board in walls, cabinets, sinks, and tubs) that 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 Section 2.5.6 Exterior Thermal Mass.

STANDARD DESIGN

The standard design has standard conditioned zone thermal mass objects.

Thermostats and Schedules

Thermostat settings are shown in Table 24: Hourly Thermostat Set Points. 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.

Heat pumps equipped with supplementary electric resistance heating are assumed to meet mandatory control requirements specified in Section110.2(b) and (c).

Systems with no setback required by Section110.2(c) (gravity gas wall heaters, gravity floor heaters, gravity room heaters, noncentral electric heaters, fireplaces or decorative gas appliances, wood stoves, room air-conditioners, and heat pumps) are assumed to have a constant heating set point of 68 degrees Fahrenheit. The cooling set point from Table 24: Hourly Thermostat Set Points is assumed in both the proposed and standard designs.

PROPOSED DESIGN

The proposed design assumes a mandatory setback thermostat meeting the requirements of Section110.2(c). Systems that are not required to have 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 that is not required to have a setback thermostat, the standard design has no setback thermostat capabilities.

Determining Heating Mode vs. Cooling Mode

When the building is in the heating mode, the heating set points for each hour are set to the “heating” values in Table 24: Hourly Thermostat Set Points, the cooling set point is a constant 78 degrees Fahrenheit (°F), and the ventilation set point is set to a constant 77°F. When the building is in the cooling mode, the heating set point is a constant 60°F, and the cooling and venting set points are set to the values in Table 24: Hourly Thermostat Set Points.

The mode depends upon the outdoor temperature averaged over hours 1 through 24 of eight days prior to the current day through two days prior to the current day. (For example, 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.

2.5.5Internal Gains

Internal gains assumptions are included in Appendix E and consistent with the CASE report on plug loads and lighting (Rubin 2016, see Appendix F).

Proposed Design

Plug loads and lighting are fixed assumptions that very based on the time of day, day of the week (for example, weekday vs. weekend), and season.

Standard Design

The standard design internal gains are the same as the proposed design.

2.5.6Exterior 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.

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 attic, enter the area, and select a construction assembly for each.

The compliance software will verify that the area-weighted average U-factor for ceiling and rafter roof assemblies meets the mandatory maximum U-factor of 0.043. The software will also verify that the area-weighted average U-factor for roof assemblies that are above conditioned space in climate zones 4, and 8-16 meets the mandatory maximum U-factor of 0.184, unless duct systems meet one of the following:

- Ducts located within the conditioned space (except < 12 linear ft)

- Ducts located entirely in conditioned space below the ceiling separating the occupiable space from the attic
- Distribution system without ducts (none)
- Ducts buried within attic insulation that complies using Section 150.1(b) and verified according to RA3.1.4.1

If the mandatory requirements are not met, the user will receive an error message and the simulation will not proceed.

STANDARD DESIGN

The standard design for newly constructed buildings has the same ceiling-below-attic area as the proposed design. The standard design is a high-performance attic with a ceiling constructed with 2x4 framed trusses and insulated with the R-values specified in Section150.1(c) and Table 150.1-A for the applicable climate zone, assuming Option B. The roof surface is a 10 lbs/ft^2 tile roof with an air space when the proposed roof is steep slope or a lightweight roof when the proposed roof is low slope.

Single-family dwelling units: Below-roof-deck insulation has R-0 in climate zones 1–3 and 5–7 and R-19 in climate zones 4 and 8–16. Insulation on the ceiling has R-38 in climate zones 1, 2, 4, and 8–16 and R-30 insulation in climate zones 3 and 5–7. Climate zones 2, 3, and 5–7 have a radiant barrier, and climate zones 1, 4, and 8–16 have no radiant barrier.

VERIFICATION AND REPORTING

Ceiling below attic area and constructions are reported on the CF1R. SIP assemblies are reported as a special feature on the CF1R.

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, enter the area, and select a construction assembly for each. The user also enters the roof characteristics of the surface.

STANDARD DESIGN

The standard design has the same area as the proposed design cathedral ceiling modeled as a cathedral ceiling with the features of Option C from Section150.1(c) and Table 150.1-A for the applicable climate zone. The total cathedral ceiling area is equally divided among the four main compass points – north, east, south, and west.

The standard design roof surfaces are modeled with the same aged solar reflectance, and thermal emittance characteristics as Section150.1(c), Table 150.1-A for the applicable roof slope and climate zone.

VERIFICATION AND REPORTING

Non-attic ceiling/roof area and constructions are reported on the CF1R. SIP assemblies are reported as a special feature on the CF1R.

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 zero 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. Underground mass walls are defined with inside and outside insulation and the number of feet below grade. 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 specified as attic, garage, or another zone, and the compliance manager treats that wall as a demising wall. An attached unconditioned space is modeled as an unconditioned zone.

The compliance software will verify that the wall assembly entered by the user meets the mandatory U-factor or insulation requirements as listed in Section 150.0(c). If it does not, the user will receive an error message and the simulation will not proceed.

STANDARD DESIGN

The standard design building has high-performance walls modeled with the same area of framed walls as in the proposed design separating conditioned space and the exterior, with a U-factor equivalent to that as specified in Section150.1(c)1.B and Table 150.1-A for the applicable climate zone.

Single-family dwellings: Above-grade framed walls in Climate Zones 1–5 and 8–16 have 2x6 16-in. on center wood framing with R-21 insulation between framing and R-5 continuous insulation (0.048 U-factor). Climate Zones 6 and 7 above-grade walls have 2x4 16-in. on center wood framing with R-15 insulation between framing and R-4 continuous insulation (0.065 U-factor). Walls adjacent to unconditioned space, such as garage walls, are treated the same as exterior walls, except there is no continuous insulation.

Above-grade mass walls are 6-inch concrete with R-13 interior insulation in 3.5-inch wood furring in Climate Zones 1–15 and R-17 in Climate Zone 16. Below-grade mass walls in Climate Zones 1–15 have R-13, and Climate Zone 16 has R-15 interior insulation in 3.5-inch wood furring. When the proposed design is a wall type such as SIP, straw bale, or other construction type not specifically mentioned above, the standard design wall is a wood-framed wall meeting the requirements of Section150.1(c) Table 150.1-A.

The total gross exterior wall area in the standard design is equal to the total gross exterior wall area of the proposed design for each wall type. The gross exterior wall area of framed walls in the standard design (excluding demising walls) is equally divided among the four main compass points – north, east, south, and west. The gross exterior wall area of mass walls in the standard design (excluding demising walls and below-grade walls) is equally divided among these four main compass points. Window and door areas are subtracted from the gross wall area to determine the net wall area in each orientation.

VERIFICATION AND REPORTING

Exterior wall area and construction details are reported on the CF1R. Metal-framed and SIP assemblies are reported as a special feature on the CF1R.

Exterior Thermal Mass

Constructions for standard exterior mass are 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 2.5.4 Internal Thermal Mass.)

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 areas modeled as separate covered and exposed mass surfaces. Exposed mass surfaces covered with flooring material that is in direct contact with the slab can be modeled as exposed mass. Examples of such materials are tile, stone, vinyl, linoleum, and hard-wood.

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 2.5.4 Internal Thermal Mass 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/ft^{3}-° F, and a conductivity of 0.98 Btu-in/hr-ft^{2}-° F. The exposed portion shall have a surface conductance of 1.3 Btu/h-ft^{2}-° F (no thermal resistance on the surface), and the covered portion shall have a surface conductance of 0.50 Btu/h-ft^{2}-° F, typical of a carpet and pad.

- The "exposed" portion of the conditioned nonslab floor area shall have a thickness of 2.0 inches, a volumetric heat capacity of 28 Btu/ft^3-° F, a conductivity of 0.98 Btu-in/hr- ft^2-°F; and a surface conductance of 1.3 Btu/h- ft^2-° F (no added thermal resistance on the surface). These thermal mass properties apply to the "exposed" portion of nonslab floors for both the proposed design and standard design. The covered portion of nonslab 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 are reported as a special feature on the CF1R.

Doors

Doors are defined as an opening in a building envelope. If the rough opening of a door includes fenestration equal to 25 percent or more of glass or fenestration, it is fenestration. (See 2.5.6 Fenestration.) Doors with less than 25 percent fenestration are considered an opaque door.

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 25 percent glass area, the U-factor shall come from Reference Appendices, Joint Appendix JA4, Table 4.5.1 (default U-factor 0.20) or from NFRC certification data for the entire door. For unrated doors, the glass area of the door, calculated as the sum of all glass surfaces plus 2 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 25 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 among the four main compass points – north, east, south, and west. The U-factor for the standard design is taken from Section150.1(c) and Table 150.1-A. All swinging opaque doors are assumed to have a U-factor of 0.20. The net opaque wall area is reduced by the door area in the standard design.

VERIFICATION AND REPORTING

Door area and U-factor are reported on the CF1R.

Fenestration

Fenestration is modeled with a U-factor and SHGC. Acceptable sources of these values are NFRC, default tables from Section110.6 of the Energy Code, and Reference Appendices, Nonresidential Appendix NA6.

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

There is no detailed model of chromogenic fenestration available. As allowed by Exception 3 to Section 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 nonchromogenic fenestration.

PROPOSED DESIGN

The compliance software allows users to enter individual skylights and fenestration types, the U-factor, SHGC, area, orientation, and tilt.

Performance data (U-factors and SHGC) are from NFRC values or from the CEC default tables from Section110.6 of the Energy Code. In spaces other than sunspaces, solar gains from windows or skylights use the California Simulation Engine (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.

The compliance software will check that the area weighted window U-factor for all fenestration meets the mandatory U-factor for window requirements as listed in Section 150.0(q). If it does not, the user will receive an error message and the simulation will not proceed.

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 among 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 façade. The U-factor and SHGC performance factors for the standard design are taken from Section150.1(c) and Table 150.1-A, which is 0. 27- U-factor except in the following instances. Homes with greater than 500 square feet of conditioned floor area in climate zone 6-10 and 15 have a 0.30 U-factor. Homes with 500 square feet or less of conditioned floor area in climate zones 5-10 and 15 have a 0.30 U-factor. SHGC is 0.23 in climate zones

2, 4, and 6–14 and SHGC is 0.20 in climate zone 15. Where there is no prescriptive requirement (climate zones 1, 3, 5, and 16), the SHGC is set to 0.35.

VERIFICATION AND REPORTING

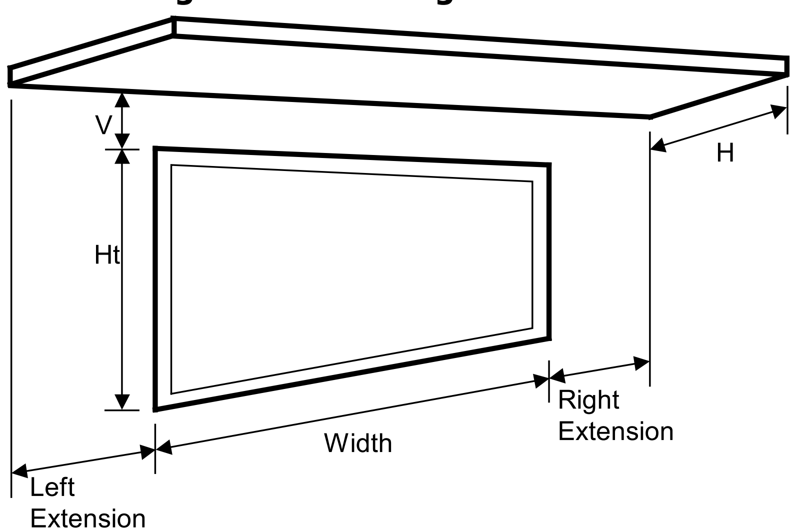
Fenestration area, U-factor, SHGC, orientation, and tilt are reported on the CF1R. SHGC is reported on the CF1R as an allowable maximum and minimum for each window calculated as the SHGC entered by the user plus or minus 0.01.

Overhangs and Sidefins

PROPOSED DESIGN

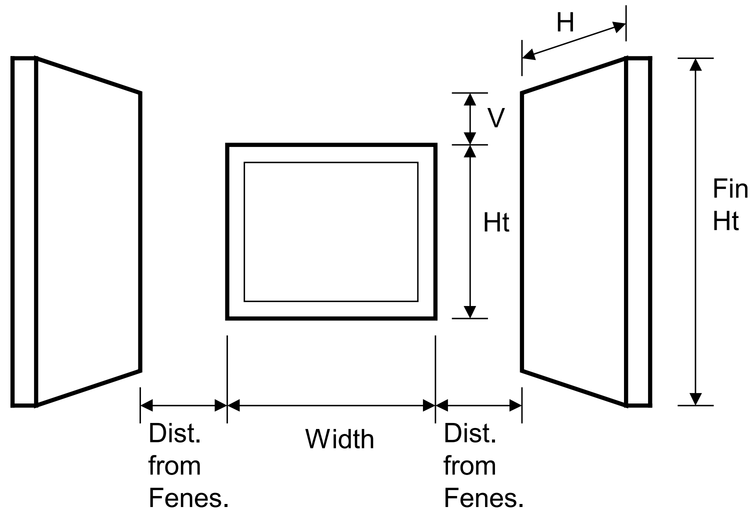
Software users enter a set of basic parameters for a description of an overhang and sidefin for each fenestration or window area entry. The basic parameters include fenestration height, overhang/sidefin length, and overhang/sidefin height. Compliance software user entries for overhangs may also include 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.

Figure 5: Overhang Dimensions



Source: California Energy Commission

Figure 6: Sidefin Dimensions



Source: California Energy Commission

STANDARD DESIGN

The standard design does not have overhangs or sidefins.

VERIFICATION AND REPORTING

Overhang and fin dimensions are reported on the CF1R.

Interior Shading Devices

For both the proposed and standard designs, 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.

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 ASHRAE Window Attachment (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.

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, and with or without slab-edge insulation. Perimeter is the length of wall between conditioned space and the exterior, but it 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 (Section110.8(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.

Underground Floors

Proposed Design

The software allows users to enter areas and depth below grade of slab floors occurring below grade. Unlike slab-on-grade floors, there is no perimeter length associated with underground floors.

Standard Design

The standard design underground floor areas are the same as the proposed design.

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), and concrete raised floors. The proposed floor area and constructions are consistent with the actual building design.

STANDARD DESIGN

The standard design has the same area and type of construction as the proposed design. The thermal characteristics meet Section150.1(c) and Table 150.1-A. For floor areas that are framed construction, the standard design floor has R-19 in 2x6 wood framing, 16-in. on center (0.037 U-factor). For floor areas that are concrete raised floors, the standard design floor is 6 inches of normal-weight concrete with R-8 continuous insulation in climate zones 1, 2, 11, 13, 14, 16; climate zones 12 and 15 have R-4; climate zones 3–10 have R-0.

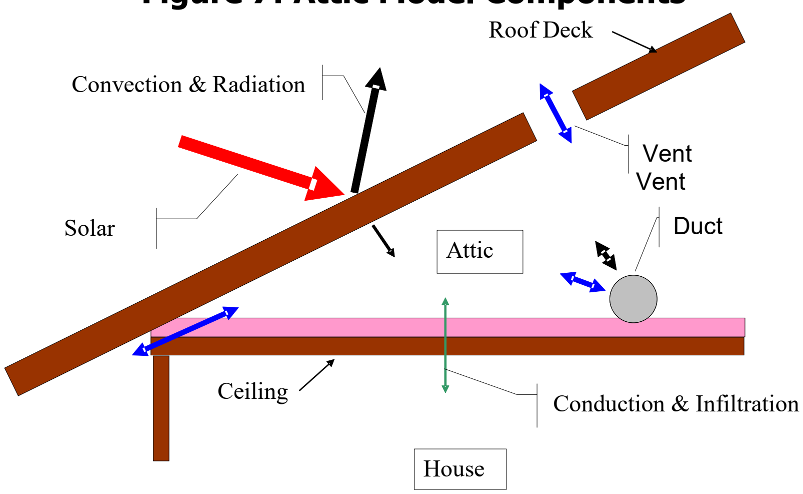
VERIFICATION AND REPORTING

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 7: Attic Model Components.

Figure 7: Attic Model Components



Source: California Energy Commission

2.6.1Attic Components

Roof Rise

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

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 set equal to attic floor area divided by 300.

Fraction High

This is 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. The default value is zero for attics with standard ventilation. Attics with radiant barriers are required to have a vent high fraction of at least 0.3.

Roof Deck/Surface Construction

Typical roof construction types are concrete or clay tile, metal tile, gravel, ballast, or other steep- or low-sloped roofing types.

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 on the certificate of compliance. Roof construction with a roof membrane mass of at least 25 lbs/ft^2, or a roof area that has integrated solar collectors, is assumed to meet the minimum solar reflectance.

Thermal Emittance

Thermal emittance is the certified aged thermal emittance (or emissivity) of the roofing material, or a default value. Unless a default value is modeled, the installed value must be equal to or greater than the value modeled. The default value is 0.85 if the certified aged thermal emittance value is not available from the Cool Roof Rating Council. Roof construction with a roof membrane mass of at least 25 lbs/ft^2 or roof area incorporated integrated solar collectors is assumed to meet the default thermal emittance.

PROPOSED DESIGN

The conditioning is either ventilated or unventilated. Each characteristic of the roof is modeled to reflect the proposed construction. Values for solar reflectance and thermal emittance shall be default or from the CRRC.

Roofs with solar collectors or with thermal mass over the roof membrane with a weight of at least 25 lbs/ft^2 may model the prescriptive values for solar reflectance and thermal 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 less than 2 feet in 12) in climate zones 13 and 15 will have a standard design of solar reflectance index (SRI) 75 modeled using an aged solar reflectance of 0.63 and a thermal emittance of 0.85.

Steep-sloped roofs in climate zones 10–15 will have a standard design roof of SRI 16 modeled using an aged solar reflectance of 0.20 and a minimum thermal emittance of 0.85.

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

Verification and Reporting

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 nonstandard 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 with a floor area equal to the sum of the areas of all 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-value. For simulation, all ceiling below attic insulation is assumed to have nominal properties of R-2.6 per inch, a density of 0.5 lb/ft^3, 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 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 are reported on the CF1R.

2.6.3 Attic Roof Surface and Pitch

Proposed Design

The roof pitch is the ratio of rise to run, (for example, 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 an 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 inches 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.

2.6.4Attic Conditioning

Attics may be ventilated or unventilated. Insulation in a ventilated attic must be installed at the ceiling level. Unventilated attics usually have insulation at the roof deck and sometimes on the ceiling (Section 150.0[a]).

In an unventilated attic, the roof system becomes part of the insulated building enclosure. Local building jurisdictions may impose additional requirements.

PROPOSED DESIGN

A conventional attic is modeled as ventilated. When an attic will not be vented, attic conditioning is modeled as unventilated.

STANDARD DESIGN

Attic ventilation is set to ventilated for the standard design.

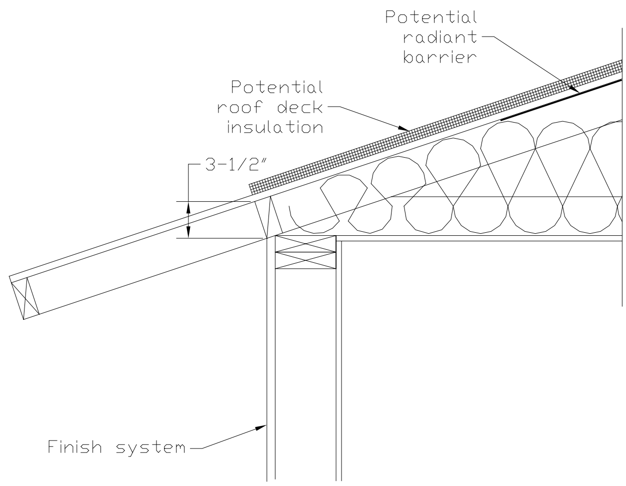
VERIFICATION AND REPORTING

The attic conditioning (ventilated or unventilated) is reported on the CF1R.

2.6.5Attic Edge

With a standard roof truss (Figure 8: Section at Attic Edge with Standard Truss), 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.

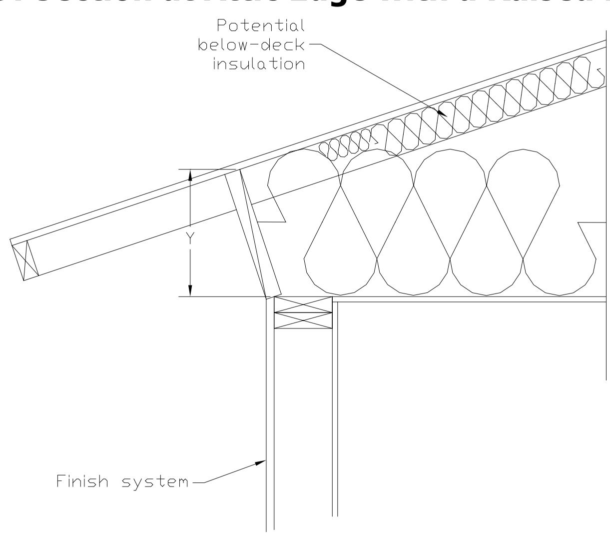
Figure 8: Section at Attic Edge with Standard Truss



Source: California Energy Commission

A raised heel truss (Figure 9: Section at Attic Edge with a Raised Heel Truss) 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 the associated thermal effect.

Figure 9: Section at Attic Edge with a Raised Heel Truss



Source: California Energy Commission

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 Appendix G. 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 8: Section at Attic Edge with Standard Truss. 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 9: Section at Attic Edge with a Raised Heel Truss).

STANDARD DESIGN

The standard design shall have a standard truss with the default vertical distance of 3.5 inches between wall top plate and roof deck.

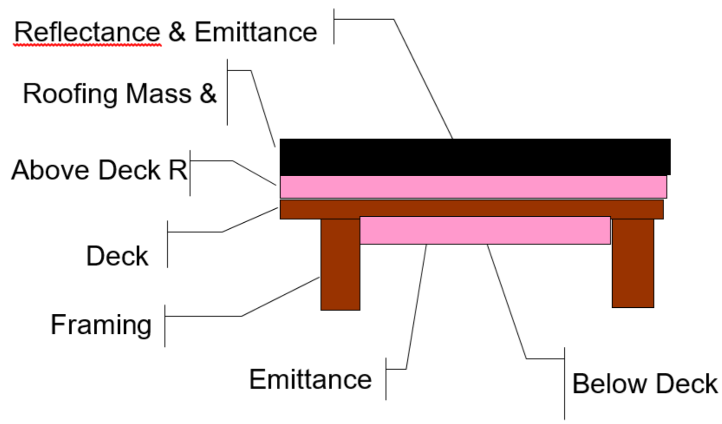
VERIFICATION AND REPORTING

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

2.6.6The 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 10: Components of the Attic Through Roof Deck, which shows a detailed section through the roof deck.

Figure 10: Components of the Attic Through Roof Deck



Source: California Energy Commission

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 the proposed design has:

A radiant Barrier.

No Radiant Barrier.

STANDARD DESIGN

The standard design shall have a radiant barrier if required by the prescriptive Energy Code (Section 150.1[c] and Table 150.1-A) for the applicable climate zone with Option B.

VERIFICATION AND REPORTING

Radiant barriers are reported as a special feature on the CF1R.

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 an uninsulated roof deck.

The compliance software will verify that the wall assembly entered by the user meets the mandatory U-factor or insulation requirements. If it does not, the user will receive an error message and the simulation will not proceed.

STANDARD DESIGN

The standard design has below-deck insulation as specified in 2.5.6 Ceilings Below Attics.

VERIFICATION AND REPORTING

The R-value of any below-deck insulation is reported as a special feature on the CF1R.

Roof Deck and Framing

The roof deck is the structural surface that 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. on center. 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. on center.

VERIFICATION AND REPORTING

Nonstandard roof deck framing or spacing is reported as a special feature on the CF1R.

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.

Standard Design

The standard design accounts for the air gap based on roofing type but has no additional above-deck insulation.

Verification and Reporting

Above-deck insulation R-value is reported as a special feature on the CF1R.

Roofing Type and Mass

Proposed Design

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.** Both types have significant thermal mass and an air gap between the deck and the tiles.
>
> **Metal tile or wood shakes.** These are lightweight with an air gap between the tiles or shakes and the deck. Tapered cedar shingles do not qualify and are treated as a conventional roof surface.
>
> **Other steep-sloped roofing types.** These include asphalt and composite shingles and tapered cedar shingles. These products have no air gap between the shingles and the structural roof deck.
>
> **Low-sloped membranes.** These are basically flat roofs with a slope of less than 2:12.
>
> **Above-deck mass**. The above-deck mass depends on the roofing type. The mass is 10 lbs/ft^2 for concrete and clay tile and 5 lbs/ft^2 for metal tile, wood shakes, or other steep-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 equal to or less than the weight of the material being installed above the roof deck:

No mass (asphalt)

5 lbs/ft²

10 lbs/ft²

15 lbs/ft²

25 lbs/ft²

STANDARD DESIGN

The roof slope shall match the proposed design. The roof type for a steep slope roof is 10 lbs/ft^2 tile. The roof type for low-slope roof is lightweight roof.

VERIFICATION AND REPORTING

The roof type is reported on the CF1R.

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 product 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 CRRC. The installed value must be equal to or higher than the value specified in the software. Roof construction with a roof membrane mass of at least 25 lbs/ft^2 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 nonstandard roof reflectance value.

2.7 Crawl Spaces

PROPOSED DESIGN

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

STANDARD DESIGN

The standard design has a typical vented crawl space when a crawl space is modeled in the proposed design. 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.

2.8 Garage/Storage

An attached, unconditioned space is modeled as a separate unconditioned zone. While the features of this space have no effect on compliance directly, it is modeled to accurately represent the building. The modeling of the garage/storage area will shade the walls adjacent to conditioned space and will have a lower air temperature (than the outside) adjacent to those walls. The walls and door that separate the conditioned zone from the garage/storage area 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.

2.9 Domestic Hot Water (DHW)

Water heating energy use is based on the number of bedrooms, fuel type, distribution system, water heater type, and conditioned floor area. Detailed calculation information is included in Appendix B.

Proposed Design

The water heating system is defined by the heater type (gas, electric resistance, or heat pump), tank type, dwelling-unit distribution type, efficiency (either uniform energy factor (UEF) or recovery efficiency with the standby loss), tank volume, exterior insulation R-value (only for indirect), rated input, and tank location (for electric resistance and heat pump water heater only).

Heat pump water heaters are defined by UEF and optionally E_{50} and E_{95}, and volume or, for Northwest Energy Efficiency Alliance (NEEA) Advanced Water Heating Specification (AWHS) qualified heat pumps, by selecting the tier qualification level, and entering the UEF and optionally E_{50} and E_{95} or the specific heater brand and model.

Water heater and tank types include:

- Consumer storage: ≤ 75,000 Btu/h gas/propane, ≤ 12 kW electric, or ≤ 24 amps heat pump, rated with UEF.
- Consumer instantaneous: ≤ 200,000 Btu/h gas or propane or ≤ 12 kW electric. An instantaneous water heater is a water heater with an input rating of ≥ 4,000 Btu/h/gallon of stored water, rated with a UEF.
- Residential-duty commercial storage: > 75,000 Btu/h, ≤ 105,000 Btu/h gas/propane, ≤ 12 kW electric, ≤ 24 amps heat pump, and rated storage volume < 120 gallons, rated with a UEF.
- Residential-duty commercial instantaneous: ≤ 200,000 Btu/h gas/propane, ≤ 58.6 kW electric, rated storage volume ≤ 2 gallons, rated with a UEF.
- Commercial storage: > 75,000 Btu/h gas/propane, >105,000 Btu/h oil, or > 12 kW electric, rated with thermal efficiency and standby loss.
- Commercial instantaneous: >200,000 Btu/h gas/propane, > 12 kW electric. Instantaneous water heater is a water heater with an input rating of ≥ 4,000 Btu/h per gallon of stored water, rated with thermal efficiency.
- Heat pump water heater: ≤ 24 amps AWHS rating or rated with UEF.
- Mini-tank (modeled only in conjunction with an instantaneous gas water heater): a small electric storage buffering tank that may be installed downstream of an instantaneous gas water heater to mitigate delivered water temperatures (for example, cold water sandwich effect). If the standby loss of this aftermarket tank is not listed in the CEC appliance database, a standby loss of 35 W must be assumed.
- 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.
- Gas.
- Heat pump.

Dwelling unit distribution system types include:

- Standard (all distribution pipes insulated).
- Point of use.
- Central parallel piping.
- Recirculation with non-demand control (continuous pumping).

- Recirculation with demand control, push button.
- Recirculation with demand control, occupancy/motion sensor.
- ECC-required pipe insulation, all lines.
- ECC-required central parallel piping.
- ECC-required recirculation, demand control, push button.
- ECC-required recirculation with demand control, occupancy/motion sensor.

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

2.9.1Compact Hot Water Distribution

The compact hot water distribution system compliance credit is available for water heating distribution systems that are designed with short distances between the water heater and the fixture. Distribution compactness is determined by comparing the "Weighted Distance" from the water heater to key fixtures, with a threshold criteria identified as the "Qualification Distance." There are three compact distribution choices:

None.

Compact Distribution Basic Credit (non-HERS Verified), see Reference Appendices, Reference Appendix RA 4.4.6.

HERS-Verified Compact Hot Water Distribution Expanded Credit, see Reference Appendices, Reference Appendix RA 4.4.16..

Once basic credit or expanded credit is specified, either the plan view fixture distances (to master bathroom, kitchen, and furthest fixture) will need to be input for the DHW system or, if the distances are unknown, allow a user input compactness factor to be used.

If the fixture distances are specified, the software will determine if the distances qualify for the credit.

If the fixture distances are not specified, compliance with the user input compactness factor will be verified on the CF2R where the actual fixture distances for the design will need to be specified.

2.9.2Drain Water Heat Recovery

Drain water heat recovery (DWHR) is a system where the waste heat from shower drains is used to preheat the cold inlet water. The preheat water can be routed to the served shower, water heater, or both.

The user specifies the DWHR device for the water heating system. The rated efficiency of the DWHR device, the number of shower(s) served, and the configuration must be specified. The configuration choices include:

> Equal flow to shower and water heater: The potable-side heat exchanger output feeds both the fixture and the water heater inlet. Potable and drain flow rates are equal, assuming no other simultaneous hot water draws.
>
> Unequal flow to shower: The potable-side heat exchanger output feeds the inlet(s) of the water heater(s) that are part of the parent DHW system. (The inlet temperature is adjusted to reflect recovered heat.)
>
> Unequal flow to water heater: The potable-side heat exchanger output feeds only the associated fixture.

Multiple DWHR devices can be used for a water heater system.

Drain water heat recovery is a ECC-verified measure.

2.9.3Domestic Water Heating Systems

When calculating the standard design efficiency LSC, the standard design for all climate zones uses a single heat pump water heater (HPWH) with 2.0 UEF. If the proposed building has an attached garage, then the HPWH location in the standard design is the garage. If the proposed building does not have an attached garage, then the HPWH location in the standard design is in the conditioned space with the air inlet and outlet ducted to the outside. In climate zones 1 or 16, the standard design will include a compact distribution system. In climate zone 16, the standard design will include both a compact distribution system and a drain water heat recovery system.

For buildings that are 500 square feet or less, if the proposed design is an instantaneous electric water heater, or an electric consumer storage water heater that is less than or equal to 20 gallons with point of use distribution, the standard design is the same. When calculating the PV LSC standard design, the domestic water heating system is dependent on the fuel type of the proposed system. If the proposed system is gas fueled, the standard design is an instantaneous gas tankless water heater with an input of 200,000 Btu/h, a high draw pattern, and 0.81 UEF. If the proposed system is electric, the standard design is a HPWH with 2.0 UEF as described for the standard design Efficiency LSC.

When calculating the source energy, the domestic water heating system is an instantaneous gas tankless water heater with an input of 200,000 BTU/h, a high draw pattern, and 0.81 UEF.

2.9.4Solar Thermal Water Heating Credit

When water heating is provided by a solar thermal system, the user enters information about the Solar Rating and Certification Corporation (SRCC) OG-100 approved collector (manufacturer, brand, model number), including details of the installation (azimuth, tilt).

Alternatively, the user can enter the OG-300 rated solar fraction for their specific climate zone.

2.9.5JA13 HPWH Basic Control Credit

JA13 HPWH Basic Control Credit provides compliance credit for systems that provide daily load shifting, as applicable, for the purpose of bill reductions, maximization of solar self-utilization, and grid harmonization. The Basic Control Credits are based on CBECC modeling of typical HPWHs, where the control turns the water heater on and off at optimal times for maximum LSC benefits without exceeding the user set point temperature. Variation by climate zone is dependent on LSC values and climate condition such as ambient air and ground water temperatures in each climate zone. Any Reference Appendices, Joint Appendix JA13 compliant HPWH will receive the LSC percentage credit which is climate zone specific as specified in Table 26: JA13 HPWH Basic Control Credit. The LSC percentage reduction is applied to the Proposed Design water heating annual LSC budget which is part of the Efficiency LSC, upon completion of the compliance software simulation run.

Table 26: JA13 HPWH Basic Control Credit

Climate Zone	JA13 Credit
1	6.7%
2	3.7%
3	7.6%
4	4.0%
5	8.5%
6	6.8%
7	8.8%
8	4.4%
9	4.4%
10	4.4%
11	4.2%
12	4.7%

13	8.0%
14	3.1%
15	8.2%
16	2.7%

Source: California Energy Commission

2.10 Additions/Alterations

Addition and alteration compliance is based on Energy Code, Section150.2. The energy budget for additions and alterations is based on LSC energy. Alterations must model the entire dwelling unit. Additions may be modeled as addition alone, as "existing+addition+alteration," or the entire building may be modeled to meet all of the requirements for a newly constructed building (whole building, Section150.2(c)). Additions that are 1,000 ft^2 or less are not required to meet the dwelling unit ventilation requirements of Section150.0(o)1C, Section150.0(o)1E, or Section150.0(o)1F. When an addition to any building creates a new dwelling unit, this exception does not apply.

The standard design does not include:

- Cool roof when an addition is 300 ft^2 or less.
- Ventilation cooling for additions that are 1,000 ft^2 or less.
- Solar generation/PV requirements.

2.10.1 Accessory Dwelling Units

When an accessory dwelling unit (ADU) is detached and newly constructed, it must comply using the whole building approach as described in 2.10.2 Whole Building. When an ADU is created by conditioning an existing unconditioned space and is either attached or detached, it may comply using any of the compliance approaches allowed for additions as described in 2.10.3 Alteration-Alone Approach or 2.10.4 Addition-Alone Approach.

2.10.2 Whole Building

The entire proposed building, including all additions or alterations or both, is modeled the same as a newly constructed building. The building complies if the proposed design uses equal to or less energy than the standard design.

2.10.3 Alteration-Alone Approach

The proposed alteration alone floor area is modeled. The alteration requirements of Section150.2(b) are applied to any features that do not exist.

2.10.4 Addition-Alone Approach

The proposed addition alone is modeled the same as a newly constructed building except that the internal gains are prorated based on the size of the dwelling. None of the exceptions included for prescriptive additions, which are implemented in the existing plus addition plus alteration compliance approach (2.10.5 Existing + Addition + Alteration Approach), are given to the addition-alone approach. (See Energy Code, Section150.2[a]2.B.) The addition complies if the proposed design uses equal to or less space heating, space cooling, and water heating LSC 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 are treated as adiabatic surfaces. All other features of the addition shall be modeled the same as a newly constructed building.

When an existing HVAC system is extended to serve the addition, the standard design shall assume the same efficiency for the HVAC equipment as the proposed design. (See 2.4.1 Heating Subsystems and 2.4.4 Cooling Subsystems.)

When a dual-glazed greenhouse or garden window is installed in an addition, the proposed design U-factor can be assumed to be 0.30.

STANDARD DESIGN

The addition alone is modeled the same as a newly constructed building, with the following exceptions:

> When roofing requirements are included in Table 150.1-A, they are included in the standard design if the added conditioned floor area is greater than 300 ft^2.
>
> When ventilation cooling (whole-house fan) is required by Table 150.1-A, it is included in the standard design when the added conditioned floor area is greater than 1,000 ft^2. The capacity shall be based on 1.5 CFM/ft^2 of conditioned floor area for the entire dwelling unit conditioned floor area.
>
> When compliance with IAQ requirements of Section150.0(o) apply to an addition with greater than 1,000 ft^2 added, the conditioned floor area of the entire dwelling unit shall be used to determine the required ventilation airflow. For additions with 1,000 ft^2 or less of added conditioned floor area, no IAQ requirements apply.
>
> PV requirements are not included.
>
> The standard design HVAC system is a split heat pump. See 2.4.1 Heating Subsystems for equipment efficiencies and operating details for each type of system. The cooling system for the standard design building is a nonzonal control system, split-system ducted cooling system, meeting the minimum requirements of

the *Appliance Efficiency Regulations*. See 2.4.4 Cooling Subsystems for equipment efficiencies and operating details for each type of system.
The domestic water heating system is a heat pump water heater. For additions 500 square feet or less, the standard design is an instantaneous electric water heater if the proposed design is an instantaneous electric water heater, or the standard design is an electric consumer storage water heater less than or equal to 20 gallons if the proposed design is an electric consumer storage water heater less than or equal to 20 gallons.

2.10.5Existing + Addition + Alteration Approach

Energy Code Section150.2(a)2 contains the provisions for additions and Section150.2(b)2 for alterations when the existing building is included in the calculations. These provisions are the "Existing + Addition + Alteration" (or "E+A+A") performance approach.

PROPOSED DESIGN

The proposed design is modeled by identifying each energy feature as part of the existing building (as existing, altered, or new), or as part of the addition. The compliance software uses this information to create an E+A+A standard design using the rules in the standards that take into account whether altered components meet or exceed the threshold at which they receive a compliance credit and whether any related measures are triggered by altering a given component.

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: The surface or system remains unchanged within the proposed design. (Both standard design and proposed design have the same features and characteristics.)

Altered: the surface or system is altered in the proposed design. No verification of existing conditions is assumed with this designation.

Verified Altered: the surface or system is altered in the proposed design, and the original condition is verified by a ECC Rater (an optional selection).

New: a new surface or system is added in the proposed design (may be in the existing building or the addition).

Deleted features are not included in the proposed design.

Section 150.2, Table 150.2-G specifies the details of the standard design for altered components based on whether verification of existing conditions is selected:

Altered with no 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 attributes of the existing condition are undefined, with the standard design for altered components based on Section150.2, Table 150.2-G, and the climate zone. Energy compliance credit or penalty is a function of the difference between the value for that specific feature allowed in Table 150.2-G and the modeled/installed efficiency of the feature.

Verified Altered existing conditions. This compliance path requires that a ECC Rater perform an on-site inspection of pre-alteration conditions prior to construction. If an altered component or system meets or exceeds the prescriptive alteration requirements, the compliance software uses the user-defined and verified 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.

QII

STANDARD DESIGN

The standard design includes QII for additions greater than 700 ft^2 in any single-family residential building in climate zones 1–16 (Section150.2[a]1Bv).

The provisions of Section150.2(a)1Aiv, as applied to converting an existing unconditioned space to conditioned space, are accommodations made by the ECC Rater in the field. No adjustments to the energy budget are made.

PV

STANDARD DESIGN

The standard design does not include PV for additions and alterations.

Roof/Ceilings

STANDARD DESIGN

The standard design roof/ceiling construction assembly is based on the proposed design assembly type as shown in Table 27: Standard Design for New and Verified Altered Roofs/Ceilings. For additions equal to or less than 700 ft^2, radiant barrier requirements follow Option C (Section150.1(c)9B). The standard design for unaltered ceilings and roofs is the existing condition.

Table 27: Standard Design for New and Verified Altered Roofs/Ceilings

Proposed Design Roof/Ceiling Types	Addition < 300 ft^2	Addition > 300 ft^2 and < 700 ft	Addition > 700 ft^2	Altered	Verified Altered
Roof Deck Insulation (below-deck,	NR	NR	CZ 4, 8-16 = R-19	CZ 3, 5-7 = NR CZ 1, 2, 4, 8-16 = R-14/U-0.39	Existing

Proposed Design Roof/Ceiling Types	Addition < 300 ft²	Addition > 300 ft² and < 700 ft	Addition > 700 ft²	Altered	Verified Altered
where required) at vented attic					
Ceilings Below Attic	CZ 1, 2, 4, 8-16 = R-38 CZ 3, 5-7 = R-30	CZ 1, 2, 4, 8-16 = R-38 CZ 3, 5-7 = R-30	CZ 1, 2, 4, 8-16 = R-38 CZ 3, 5-7 = R-30	CZ 5, 7 = R-19 CZ 1-4, 6, 8-16 = R-49	Existing
Non-Attic (Cathedral) Ceilings and Roofs	R-22/U-0.043	R-22/U-0.043	R-38	R-19/U-0.054	Existing
Radiant Barrier	CZ 2-15 REQ CZ 1, 16 NR	CZ 2-15 REQ CZ 1, 16 NR	CZ 2, 3, 5-7 REQ CZ 1, 4, 8-16 NR	NR	Existing
Roofing Surface (Cool Roof) Steep-Sloped	NR	CZ 10-15 =0.20 Reflectance, =0.75 Emittance	CZ 10-15 =0.20 Reflectance, =0.75 Emittance	CZ 4, 8-15 =0.20 Reflectance =0.75 Emittance	Existing
Roofing Surface (Cool Roof) Low-Sloped	NR	CZ 13, 15 = 0.63 Reflectance, =0.75 Emittance	CZ 13, 15 = 0.63 Reflectance, =0.75 Emittance	CZ 4, 6-15 =0.64 Reflectance =0.75 Emittance	Existing
Above Deck Insulation, Low-Sloped	NR	NR	NR	CZ 1, 2, 4, 8-16 = R-14 Continuous	Existing

Source: California Energy Commission

Table 28: Standard Design for Altered Roofs/Ceilings

Proposed Design Roof/Ceiling Types	Altered (and Existing if new ductwork and air handler in ventilated attic)
Knob and Tube (exception)	R-19 or standard design = proposed design if proposed design is existing
Limited space	R-19 or standard design = proposed design if proposed design is existing
Ceilings Below Attic	If CZ is 5 or 7, standard design = R-19. If CZ is 1-4, 6, and 8-16, standard design = R-49
Ceilings Below Attic in CZ 1, 3, 6 where existing insulation is > R-19	Standard design = R-19
Ceilings Below Attic where existing insulation is > R-38	Standard design = R-38
Roof surface <50% altered	No requirements
Roof surface >50% altered	Section 150.2(b)1I

Source: California Energy Commission

Exterior Walls and Doors

PROPOSED DESIGN

Existing structures with insulated wood-framed walls that are being converted to conditioned space using an E+A+A approach are allowed to show compliance using the existing wall framing, without having to upgrade to current prescriptive continuous insulation requirements. The walls are modeled as an assembly with the existing framing and either R-15 (in 2x4 framing) or R-21 (in 2x6 framing) insulation (Exception to Section 150.0(c)1 and Section150.2(a)1).

STANDARD DESIGN

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

For new framed and unframed walls of an addition or an existing zone, the gross exterior wall area (excluding knee walls) is equally divided among the four building orientations: front, left, back and right.

The standard design exterior wall construction assembly is based on the proposed design assembly type as shown in Table 29: Standard Design for Walls and Doors. Framed walls are modeled as 16-in. on center wood framing. The standard design for unaltered walls is the existing condition.

The standard design for exterior opaque or swinging doors is 0.20 U-factor. Fire-rated doors (from the house to garage) use the proposed design door U-factor as the standard design U-factor.

Table 29: Standard Design for Walls and Doors

Proposed Design Exterior Wall Assembly Type or Door	Addition	Altered	Verified Altered
Framed & Non-Mass Exterior Walls	CZ 1-5, 8-16 = R-21+R-5 in 2x6 (U0.048) CZ 6-7 = R-15+R-4 in 2x4 (U-0.065)	R-15 in 2x4 R-21 in 2x6	Existing
Wood framed existing walls where siding is not removed, or an extension of an existing wall	R-15 in 2x4 R-21 in 2x6	R-15 in 2x4 R-21 in 2x6	Existing
Framed Wall Adjacent to Unconditioned (e.g., Demising or Garage Wall)	R-15 in 2x4 R-21 in 2x6	R-15 in 2x4 R-21 in 2x6	Existing
Above Grade Mass Interior Insulated	CZ 1-15 = R-13 (0.077) CZ 16 = R-17 (0.059)	N/R Mandatory requirements have no insulation for mass walls	Existing

Proposed Design Exterior Wall Assembly Type or Door	Addition	Altered	Verified Altered
Below Grade Mass Interior Insulation	CZ 1-15 = R-13 (0.077) CZ 16 = R-15 (0.067)	N/R Mandatory requirements have no insulation for mass walls	Existing
Swinging Doors	0.20	0.20	Existing

Source: California Energy Commission

Fenestration

PROPOSED DESIGN

Fenestration areas are modeled in the addition as new. In an existing building, they may be existing, altered, or new. Altered (replacement) fenestration is defined in Section 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 ..." Altered also includes fenestration installed in the same existing wall, even if in a different location on that wall. Added fenestration area in an existing wall or roof is fenestration that did not previously exist and is modeled as new.

STANDARD DESIGN

Standard design fenestration U-factor and SHGC are based on the scope of the project (addition vs. alteration), and for additions, the square footage is taken into consideration as well, as shown in Table 30: Standard Design for Fenestration (in Walls and Roofs). Vertical glazing includes all fenestration in exterior walls such as windows, clerestories, and glazed doors. Skylights include all glazed openings in roofs and ceilings.

New fenestration in an alteration is modeled with the same U-factor and SHGC as required for an addition.

West-facing limitations are combined with the maximum fenestration allowed and are not an additional allowance.

The standard design is set for fenestration areas and orientations as shown in Table 30: Standard Design for Fenestration (in Walls and Roofs):

Proposed design < allowed percentage of total fenestration area:

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

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

Proposed design > allowed percentage of total fenestration area:

The standard design first calculates the allowed total fenestration area as the total existing and altered fenestration area in existing or altered walls and roofs. Added to this is the percentage of fenestration allowed in the addition based on the conditioned floor area of the addition.

Table 30: Standard Design for Fenestration (in Walls and Roofs)

Proposed Design Fenestration Type	Addition < 400 ft^2	Addition > 400 and < 700 ft^2	Addition > 700 ft^2	Altered	Verified Altered
Vertical Glazing: Area and Orientation	75 ft^2 or 30%	120 ft^2 or 25%	175 ft^2 or 20%	See full description below.	Existing
West-Facing Maximum Allowed	CZ 2, 4, 6 - 15=60 ft^2	CZ 2, 4, 6 - 15=60 ft^2	CZ 2, 4, 6 - 15=70 ft^2 or 5%	NR	NR
Vertical Glazing: U-Factor	CZ 1-5, 11-14, 16=0.27 CZ 6-10, 15=0.30	CZ 1-5, 11-14, 16=0.27 CZ 6-10, 15=0.30	CZ 1-5, 11-14, 16=0.27 CZ 6-10, 15=0.30	0.27	Existing
Vertical Glazing: SHGC	CZ 2, 4, 6-14=0.23 CZ 15=0.20 CZ 1,3, 5 & 16=0.35	CZ 2, 4, 6-14=0.23 CZ 15=0.20 CZ 1,3, 5 & 16=0.35	CZ 2, 4, 6-15=0.23 CZ 1,3, 5 & 16=0.35	CZ 2, 4, 6-15=0.23 CZ 1,3, 5 & 16=0.35	Existing
Skylight: Area and Orientation	No skylight area in the standard design	No skylight area in the standard design	No skylight area in the standard design	NR	Existing
Skylight: U-Factor	0.30	0.30	0.30	0.40	Existing
Skylight: SHGC	CZ 2, 4, 6 - 14=0.23 CZ 15=0.20	CZ 2, 4, 6 - 14=0.23	CZ 2, 4, 6 - 14=0.23	CZ 2, 4, 6 - 15=0.30 CZ 1,3 5 & 16=0.35	Existing

Proposed Design Fenestration Type	Addition < 400 ft²	Addition > 400 and < 700 ft²	Addition > 700 ft²	Altered	Verified Altered
	CZ 1,3 5 & 16=0.35	CZ 15=0.20 CZ 1,3 5 & 16=0.35	CZ 15=0.20 CZ 1,3 5 & 16=0.35		

Source: California Energy Commission

Overhangs, Sidefins, and Other Exterior Shading

Standard Design

The standard design for a proposed building with overhangs, sidefins, and exterior shades is shown in Table 31: Standard Design for Overhangs, Sidefins, and Other Exterior Shading. Exterior shading (limited to bug screens) is treated differently than fixed overhangs and sidefins, as explained in Section 2.5.6.9 Exterior Shading.

Table 31: Standard Design for Overhangs, Sidefins, and Other Exterior Shading

Proposed Design Shading Type	Addition	Altered	Verified Altered
Overhangs and Sidefins	No overhangs or sidefins	Proposed altered condition	Same as altered
Exterior Shading	Standard (bug screens on fenestration, none on skylights)	Proposed altered condition	Existing exterior shading
Window Film	No window film	Proposed altered condition	Existing exterior shading

Source: California Energy Commission

Window Film

Proposed Design

A window film must have at least a 15-year warranty and is treated as a window replacement. The values modeled are either the default values from Tables 110.6-A and 110.6-B or the NFRC Window Film Energy Performance Label.

Floors

Standard Design

Table 150.2-C requires that the standard design be based on the mandatory requirements from Section 150.0(d). The standard design for floors is shown in Table 32: Standard Designs for Floors.

Table 32: Standard Designs for Floors

Proposed Design Floor Type	Addition	Altered (mandatory)	Verified Altered
Raised Floor Over Crawl Space or Over Exterior	R-19 in 2x6 16" o.c. wood framing	R-19 in 2x6 16" o.c. wood framing	If proposed U < 0.037, standard design = existing raised; if proposed U > 0.037, standard design = 0.037
Slab-on-Grade: Unheated	CZ1-15: R-0 CZ16: R-7 16" vertical	R-0	Existing unheated slab-on-grade
Slab-on-Grade: Heated	CZ1-15: R-5 16" vertical CZ 16: R-10 16" vertical	CZ1-15: R-5 16" vertical CZ 16: R-10 16" vertical	Existing heated slab-on-grade
Raised Concrete Slab	CZ1,2,11,13,14,16: R-8 CZ3-10: R-0 CZ12,15: R-4	R-0	Existing raised concrete slab

Source: California Energy Commission

Thermal Mass

STANDARD DESIGN

The standard design for thermal mass in existing plus addition plus alteration calculations is the same as for all newly constructed buildings as explained in 2.5.4 Internal Thermal Mass.

Air Leakage and Infiltration

STANDARD DESIGN

Standard design air leakage and infiltration are shown in Table 33: Standard Design for Air Leakage and Infiltration.

Table 33: Standard Design for Air Leakage and Infiltration

Proposed Air Leakage and Infiltration	Addition	Altered	Verified Altered
Single-Family Residential Buildings	5 ACH50	5 ACH50	Diagnostic testing of existing ACH50 value by ECC Rater

Source: California Energy Commission

Space Conditioning System

Standard Design

The standard design for space-conditioning systems is shown in Table 34: Standard Design for Space-Conditioning Systems.

When cooling ventilation (whole-house fan) is required by Section 150.1 and Section 150.2, the capacity is 1.5 CFM/ft^2 of conditioned floor area for the entire dwelling unit.

When compliance with IAQ requirements of Section 150.0(o) apply to an addition with greater than 1,000 ft^2 added, the conditioned floor area of the entire dwelling unit is used to determine the required ventilation airflow. For additions with 1,000 ft^2 or less of added conditioned floor area, no IAQ requirements shall apply.

Table 34: Standard Design for Space-Conditioning Systems

Proposed Design Space-Conditioning System Type	Addition	Altered	Verified Altered
Heating System Efficiency	See 2.10.4 Addition-Alone Approach and 2015 Federal Appliance Standards based on fuel source and equipment type	Proposed heating fuel type and equipment type/efficiency. If the existing equipment is electric resistance and none of the exceptions to Section150.2(b)1G are met, the Standard Design system shall be a heat pump meeting the requirements of	Same as altered.

Proposed Design Space-Conditioning System Type	Addition	Altered	Verified Altered
		2.10.4 Addition-Alone Approach.	
Cooling System Efficiency	See 2.10.4 Addition-Alone Approach and 2015 Federal Appliance Standards based on fuel source and equipment type	Same as Addition	Existing cooling equipment type/efficiency
Refrigerant Charge	All heat pumps Air conditioners in CZ 2 and 8 – 15	Yes	Existing
Whole-House Fan (WHF) applies only if addition > 1,000 ft2	CZ 8-14; 1.5 CFM/ft^2	N/A	Existing condition. To count as Existing, the WHF must be > 1.5 CFM/ft^2 and be CEC-rated
Indoor Air Quality applies only if addition > 1,000 ft2 or if addition is a dwelling unit	Meet mandatory ventilation for entire dwelling	Same as Addition	Existing

Source: California Energy Commission

Duct System

Proposed Design

Duct insulation shall be based on the new or replacement R-value input by the user. Duct leakage shall be based on the tested duct leakage rate entered by the user or a default rate of 30 percent.

Standard Design

Table 35: Standard Design for Duct Systems

Proposed Design Duct System Type	No Verification of Existing Conditions	Verified Existing Conditions
Altered or Extended Ducts Serving Existing Space	CZ 1-2, 4, 8-16: Duct insulation R-8 and total leakage of 10% CZ 3, 5-7: Duct insulation R-6 and total leakage of 10% No HERS-verification for 25 ft or less of altered or extended ducts in existing space	Existing duct R-value and total leakage the lesser of 30% or the existing leakage rate
Extended Ducts Serving Addition	CZ 1-2, 4, 8-16: Duct insulation R-8 and total leakage of 10% CZ 3, 5-7: Duct insulation R-6 and total leakage of 10% No HERS-verification for 25 ft or less of altered or extended ducts serving addition	Existing duct R-value and total leakage the lesser of 30% or the existing leakage rate
Altered Ducts in Garage	All CZs: Duct insulation R-6 and total leakage of 6%	N/A
New Ducts not in Ventilated Attic	CZ 1-2, 4, 8-16: Duct insulation R-8 and total leakage of 7% CZ 3, 5-7: Duct insulation R-6 and total leakage of 7%	N/A
New Ducts when Air Handler in Ventilated Attic	CZ 1-2, 4, 8-16: Duct insulation R-8 and total leakage of 5% CZ 3, 5-7: Duct insulation R-6 and total leakage of 5% Triggered Table for Altered Ceiling	N/A

Based on Table 150.2-A

Note 1: Refer to Section150.2(b)1Diia for definition of an "Entirely New or Complete Replacement Duct System."

Source: California Energy Commission

Water Heating System

STANDARD DESIGN

Table 36: Standard Design for Water Heater Systems

Proposed Design Water Heating System Type	Addition (adding water heater)	Altered	Verified Altered
Single-Family Residential Buildings	Prescriptive water heating system as specified by 2.10.4 Addition-Alone Approach	Proposed fuel type (heat pump water heater if electric), proposed tank type, mandatory requirements with no solar	Existing water heater type(s), efficiency, distribution system.

Source: California Energy Commission

2.11 Documentation

The software shall be capable of displaying and printing an output of the energy use summary and a text file of the building features. These are the same features as shown on the CF1R when generated using the report manager.

See public domain software user guide or vendor software guide for detailed modeling guidelines.

2.12 CALGreen

The software can calculate a LSC and Source Energy results as required in the California Green Building Standards (CALGreen, Title 24, Part 11). The LSC and Source implementation applies only to newly constructed single-family residential buildings.

APPENDIX A – SPECIAL FEATURES

Measure, CF1R Documentation Requirement

General

Battery System kWh, Special feature

Community Solar: kWdc of [utility and project name], Special feature

Controlled-Ventilation Crawlspace (CVC), Not yet implemented

PV System kWdc, Special feature

PV module type: Premium, Special feature

PV module type: Thin Film, Special feature

PV array type: Tracking (one axis), Special feature

PV array type: Tracking (two axis), Special feature

PV power electronics: Microinverters, Special feature

PV power electronics: DC power optimizers, Special feature

PV exception 1: Effective solar access < 80 ft2, Special feature

PV exception 2: Smaller of solar access and home area-based size (CZ 15 only), Special feature

PV exception 3: 2 habitable stories, Special feature

PV exception 4: 3 habitable stories, Special feature

PV exception 5: 80-200 ft2 solar ready zone approved before 1/1/20, Special feature

PV exception 6: AB 178 Declared emergency area, Special feature

Self-utilization credit, Special feature

Zonal heating controls, Special feature

Envelope

Insulation above roof deck, Special feature

Advanced wall framing (see opaque surface constructions), Special feature

Insulation below roof deck, Special feature

Building air leakage/reduced infiltration, Energy Code Compliance (ECC) verification of reported ACH50 value

Ceiling has high level of insulation, Special feature

Cool roof, Special feature

Dynamic glazing, Not yet implemented

Exterior shading device, Not yet implemented

Exposed slab floor in conditioned zone, Special feature

Metal-framed assembly, Special feature

Window overhangs and sidefins, Special feature

Quality insulation installation (QII), ECC verification

High R-value Spray Foam Insulation, ECC verification

Raised heel truss (height above top plate), Special feature

Structurally insulated panel (SIP) assembly, Special feature

Mechanical

Fan Efficacy Watts/CFM, ECC verification

Minimum Airflow, ECC verification

Central fan ventilation cooling, fixed speed, ECC verification

Central fan ventilation cooling, variable speed, ECC verification

Verified EER, ECC verification

Evaporatively-cooled condenser, ECC verification

Evaporative cooling, indirect, indirect/direct, Not yet implemented

Verified heat pump rated heating capacity, ECC verification

Verified HSPF, ECC verification

Verified SEER, ECC verification

Indoor air quality mechanical ventilation, ECC verification

Indoor air quality, balanced fan, Special feature

Kitchen range hood, ECC verificationNo cooling system installed, Special feature

Pre-cooling credit, Special feature

Verified Refrigerant Charge), ECC verification

Refrigerant charge verification required if a refrigerant containing component is altered, ECC verification

Whole house fan airflow and fan efficacy, ECC verification

Whole house fan, Special feature

Ducts

Duct design specifies buried duct, ECC verification

Bypass duct conditions in zonal system(s), ECC verification

Duct design specifies deeply buried duct, ECC verification

Duct leakage testing, ECC verification

Ducts located entirely in conditioned space confirmed by duct leakage testing, ECC verification

Ducts in crawl space, Special feature

Duct sealing required if a duct system component, plenum, or air handling unit is altered, ECC verification

Ducts with high level of insulation, Special feature

Low leakage air handling unit, ECC verification

Verified low leakage ducts in conditioned space must meet maximum 25 cfm leakage to outside (RA3.1.4.3.8), ECC verification

New ductwork added is less than 40 ft. in length, Special feature

Non-standard duct leakage target, ECC verification

Non-standard duct location (any location other than attic), Special feature

Verified duct design (RA3.1.4.1.1), ECC verification

Water Heating

Compact distribution system basic credit, Special feature

Compact distribution system expanded credit, ECC verification

Drain water heat recovery system, ECC verification

Multifamily: Drain water heat recovery system, ECC verification

Multifamily: Recirculating demand control, Special feature

Multifamily: No loops or recirc pump, Special feature

Multifamily: Recirculating with no control (continuous pumping), Special feature

Multifamily: Recirculating with temperature modulation, Special feature

Multifamily: Recirculating with temperature modulation and monitoring, Special feature

Solar water heating credit, Multi-family, Special feature

Central parallel piping, Special feature

Central parallel piping, ECC verification

Pipe Insulation, All Lines, ECC verification

Point of use, Special feature

Recirculating with demand control, occupancy/ motion sensor, Special feature

Recirculation, demand control occupancy/motion, ECC verification

Recirculating with demand control, push button, Special feature

Recirculation, demand control push button, ECC verification

Recirculating with non-demand control (continuous pumping), Special feature

Solar water heating credit, single family, Special feature

Northwest Energy Efficiency Alliance (NEEA) rated heat pump water heater; specific brand/model, or equivalent, must be installed, Special feature

Additions/Alterations

Verified existing conditions, ECC verification

APPENDIX B:
Water Heating Calculation Method

B1. Purpose and Scope

This appendix documents the methods and assumptions used for calculating the hourly energy use for residential water heating systems for 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 long-term system cost (LSC) factor. The calculation procedure applies to low-rise single-family, low-rise multifamily, and high-rise residential.

Calculations are described below for gas and electric water heaters. The internal water heater modeling is performed within the California Simulation Engine (CSE). The compliance modeling rules documented here are implemented in the (California Building Energy Code Compliance) CBECC-Res ruleset and determine the input values passed to CSE.

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 distribution types that shall be recognized by the compliance software.

Table B-1: Distribution Systems Within a Dwelling Unit with One or More Water Heaters

Option #	Description
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.

Option #	Description
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 dwelling units.

Source: California Energy Commission

B2. Water Heating Systems

Water heating distribution systems may serve more than one dwelling unit and may have more than one water heater and more than one water heating system. The energy used by a water heating system is calculated as the sum of the energy used by each 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 calculate the energy used by each water heater and water heating system, the following variables are used.

CFA — Conditioned floor area, ft^2, of the building.

NFloor — Number of floors in the building

Nunit — Number of dwelling units in the building

NK — Number of water heating systems in the building

NWH_k — Number of water heaters in the k^{th} system

$NLoop_k$ — Number of recirculation loops in the k^{th} system (multiunit dwellings only)

CFA_i — Conditioned floor area of the i^{th} dwelling unit, ft^2

$CFAU_k$ — Average dwelling unit conditioned floor area served by kth system, ft^2

NL_k — number of unfired- or indirectly fired storage tanks in the k^{th} system

B3. Hot Water Consumption

The schedule of hot water use that drives energy calculations is derived from measured data as described in Appendix F (Kruis, 2019). That analysis produced 365 day sets of fixture water draw events for dwelling units having a range of number of bedrooms. The draws are defined in the file DHWDU.TXT (for single-family) that installs with CBECC-Res. Each draw is characterized by a start time, duration, flow rate, and end use. The flow rates given are the total flow at the point of use (fixture or appliance). This detailed representation allows derivation of draw patterns at 1-minute intervals as is required for realistic simulation of heat pump water heaters.

The fixture flow events are converted to water heater (hot water) draws by (1) accounting for mixing at the point of use and (2) accounting for waste and distribution heat losses:

$$VSk - VDk\ x \int dur\ x\ VQk\ x \int hot\text{V} \qquad \text{Equation 1}$$

Where

VS_k = Hot water draw at the k^{th} water heating system's delivery point (gal)

VD_k = Mixed water draw duration at an appliance or fixture (min) served by the k^{th} water heating system, as specified by input schedule

VQ_k = Mixed water flow at an appliance or fixture (gpm) served by the k^{th} water heating system, as specified by input schedule

f_{hot}, f_{dur}, f_q = End-use-specific factors from the following:

Shower/bath

f_{hot} $\frac{105-T_{inlet}}{T_s-T_{inlet}}$

f_{dur} $WF_k \times DLM_k$

Faucet

f_{hot} 0.50

f_{dur} 1

Clothes washer

f_{hot} 0.22

f_{dur} 1

Dish washer

f_{hot} 1

f_{dur} 1

T_s = Hot water supply temperature (ºF); assumed to be 115°F

T_{inlet} = Cold water inlet temperature (°F) as defined in Section B1.2. Note that T_{inlet} may be tempered by drain water heat recovery (DWHR).

WF_k = Hot water waste factor

- WF_k = 0.9 for within-dwelling-unit pumped circulation systems (see Table B-2)
- WF_k = 1.0 otherwise

DLM_k = Distribution loss multiplier (unitless), see *Equation 5*

The individual water heater draws are combined to derive the overall demand for hot water.

For each hour of the simulation, all water heater draws are allocated to 1-minute bins using the starting time and duration of each draw. This yields a set of 60 $VS_{k,t}$ values for each hour that is used as input to the detailed heat pump water heater (HPWH) and instantaneous water heater models in later sections. For hourly efficiency-based models used for some water heater types, the minute-by-minute values are summed to give an hourly hot water requirement:

$$GPH_k = \sum_{t=1}^{60} VS_{k,t} \quad \text{Equation 2}$$

In cases where multiple dwelling units are served by a common water heating system, the dwelling unit draws are summed.

In cases where there are multiple water heating systems within a dwelling unit, the draws are divided equally among the systems. For minute-by-minute draws, this allocation is accomplished by assigning draws to systems in rotation within each end use weighted by the number of fixtures of each type are served by each system. This assignment ensures that some peak draw events within each end use get assigned to each system. Since heat pump water heater performance is nonlinear with load (due to activation of resistance backup), allocation of entire events to systems is essential. The assignment scheme allocates draws by end use as opposed to specific draws to specific systems. Explicit draw assignment would require plumbing layout information — capturing that is deemed to impose an unacceptable user input burden.

B4. Hourly Adjusted Recovery Load

The hourly adjusted recovery load for the kth water heating system is calculated as:

$$HARL_k = HSEU_k + HRDL_k + \sum_{1}^{NL_k} HJL_l + HPPL_k \quad \text{Equation 3}$$

Where

$HSEU_k$ = Hourly standard end use at all use points (Btu), see Equation 4

HRDLk = Hourly recirculation distribution loss (Btu), see Equation 14

15; $HRDL_k$ is nonzero only for multifamily central water heating systems

NL_k = Number of unfired or indirectly fired storage tanks in the k^{th} system

HJL_l = Tank surface losses of the l^{th} unfired tank of the k^{th} system (Btu), see Equation 41

$HPPL_k$= Hourly water heating plant pipe heat loss (Btu), see Equation 45

Equation 4 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 DT (difference between the cold water inlet temperature and the hot water supply temperature) times the heat required to elevate a gallon of water 1°F (the 8.345 constant).

$$\boldsymbol{HSEU_k = 8.345 \times GPH_k \times (T_s - T_{inlet})} \qquad \textit{Equation 4}$$

Where

$HSEU_k$ = Hourly standard end use (Btu)

GPH_k = Hourly hot water consumption (gallons) from *Equation 2*

Equation 5 calculates the distribution loss multiplier (DLM), which combines the standard distribution loss multiplier (SDLM), which depends on the floor area of the dwelling unit and the distribution system multiplier (DSM).

$$\boldsymbol{DLM_k = 1 + (SDLM_k - 1) \times DSM_k} \qquad \textit{Equation 5}$$

Where

DLM_k = Distribution loss multiplier (unitless)

$SDLM_k$ = Standard distribution loss multiplier (unitless). See *Equation 6*

DSM_k = Distribution system multiplier (unitless). See Section Distribution Losses Withing the Dwelling Unit. Several relationships depend on CFA_k, the floor area served (see below).

Equation 6 calculates the standard distribution loss multiplier (SDLM) based on dwelling unit floor area. In *Equation 6*, that floor area $CFAU_k$ is capped at 2500 ft^2. Without that limit, *Equation 6* produces unrealistic $SDLM_k$ values for large floor areas.

$$SDLM_k = 1.0032 = 0.0001864 \text{ x } CFAU_k - 0.00000002165 \text{ x } CFAU_k^2 \qquad \textit{Equation 6}$$

Where

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

$CFAU_k$= Dwelling unit conditioned floor area (ft^2) served by the kth system, calculated using methods specified in *Equation 7*.

Single dwelling unit,

$$CFAU_k = CFA/NK$$

For multiple dwelling units served by a central system:

$$CFAU_k = \frac{\sum_{\text{all units served by system k}} CFA_i}{Nunit_k}$$

Alternatively, if the system-to-unit relationships not known:

$$CFAU_k = \frac{\sum_{\text{all units served by any central system}} CFA_i}{\text{Number of units served by any central system}} \qquad \textit{Equation 7}$$

Method WH-

CFAU

Note: "Method" designations are invariant tags that facilitate cross-references from comments in implementation code.

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, as shown in *Equation 8.*

$$HARL_j = \frac{HARL_k}{NWH_k} \qquad \text{Equation 8}$$

Where

$HARL_j$ = Hourly adjusted recovery load for the j^{th} water heater of the k^{th} system (Btu)

$HARL_k$ = Hourly adjusted total recovery load for the k^{th} system (Btu)

NWH_k = The number of water heaters in the k^{th} system

Distribution Losses Within the Dwelling Unit

The distribution system multiplier (DSM, unitless) is an adjustment for alternative water heating distribution systems within the dwelling unit. A DSM value of 1.00 will be reached in "standard" distribution systems, defined as a nonrecirculating system, with the full length of distribution piping insulated in accordance with Section 150.0(j)2.

$$DSM_k = ADSM_k \times CF_k \qquad \text{Equation 9}$$

Where

$ADSM_k$ = Assigned Distribution System Multiplier, see below.

CF_k = Compactness factor (unitless), default value is 1.0, calculated according to Section 5.6.2.4 of the *Residential Compliance Manual*.

ADSM values for alternative distribution systems are given in Table B-2. Improved ADSM values are available for cases where voluntary Energy Code Compliance (ECC) inspections are completed, as per the eligibility criteria shown in Reference Residential Appendix RA4.4. Detailed descriptions of all of the distribution system measures are found in Residential Appendix RA 4.4.

Table B-2: Distribution System Multipliers Within a Dwelling Unit With One or More Water Heaters

Distribution System Types	Assigned Distribution System Multiplier (ADSM)	System Types 1 and 2	System Type 3 and 4
No ECC Inspection Required			
Trunk and Branch -Standard (STD)	1.0	Yes	Yes
Central Parallel Piping (PP)	1.10	Yes	
Point of Use (POU)	0.30	Yes	
Recirculation: Nondemand Control Options (R-ND)	9.80*	Yes	
Recirculation with Manual Demand Control (R-DRmc)	1.75*	Yes	
Recirculation with Motion Sensor Demand Control (R-DRsc)	2.60*	Yes	
Optional Cases: ECC Inspection Required			
Pipe Insulation (PIC-H)	0.85	Yes	Yes
Central Parallel Piping with 5' maximum length (PP-H)	1.00	Yes	
Compact Design (CHWDS-H)	0.70	Yes	
Recirculation with Manual Demand Control (R-DRmc-H)	1.60*	Yes	
Recirculation with Motion Sensor Demand Control (RDRsc-H)	2.40*	Yes	

***Recirculation ADSMs reflect the effect of reduced hot water consumption associated with recirculation systems.**

Source: California Energy Commission

Cold Water Inlet Temperature

The water heater inlet temperature is assumed to vary daily and depends on mains water temperature, drain water heat recovery, and solar preheating.

For each day of the year, T_{mains} is calculated as follows:

$$Tmain = Tground\ x\ 0.65 + Tavg31\ x\ 0.035 \qquad \textit{Equation 10}$$

T_{avg31} = Outdoor dry-bulb temperature averaged over all hours of the previous 31 days (for January days, weather data from December will be used.)

T_{ground} = Ground temperature (°F) for current day of year, calculated using: *Equation 11*.

each day (q = 1 TO 365)

$$T_{ground}(\theta) = TyrAve - 0.5 \times (TyrMax - TyrMin) \times COS(2 \times \pi \times ((\theta - 1)/PB) - PO - PHI) \times GM$$

Equation 11

Where

TyrAve	=	average annual temperature, °F
TyrMin	=	the lowest average monthly temperature, °F
TyrMax	=	the highest average monthly temperature, °F
PB	=	365
PO	=	0.6
DIF	=	0.025 ft^2/hr
BETA	=	SQR(p/(DIF*PB*24))*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)))

The water heater inlet temperature, T_{inlet}, is calculated as follows:

$$T_{inlet} = (1 - SSF_k)(T_{mains} + \Delta T_{dwhr}) + SSF_k \times T_s \qquad \textit{Equation 11}$$

Where

SSF_k = Solar savings fraction for k^{th} system (see below), unitless

ΔT_{dwhr} = Water temperature increase due to drain water heat recovery, °F (0 if no DWHR). See Section 0

T_s = Hot water supply temperature

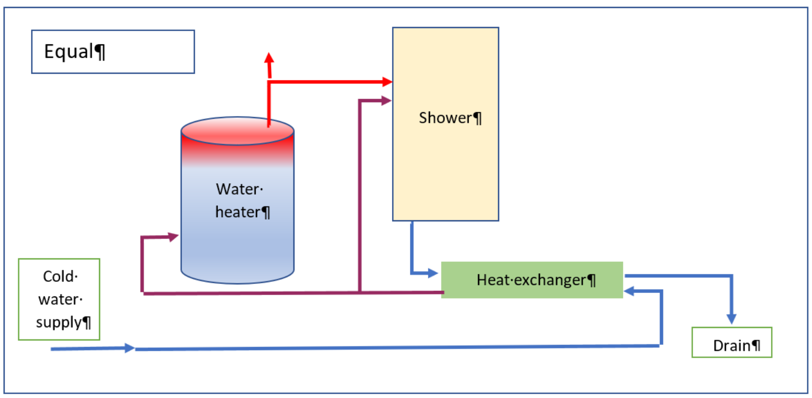
All water heaters in a water heating system are assumed to have the same T_{inlet}.

The hourly solar savings fraction for the k^{th} water heating system, SSF_k, is the fraction of the total water heating load that is provided by solar hot water heating. The annual average value for SSF is provided from the results generated by the California Energy Commission-approved calculations approaches for the OG-100 and OG-300 test procedure. A Commission-approved method shall be used to convert the annual average value for SSF to hourly SSFk values for use in compliance calculations.

Drain Water Heat Recovery

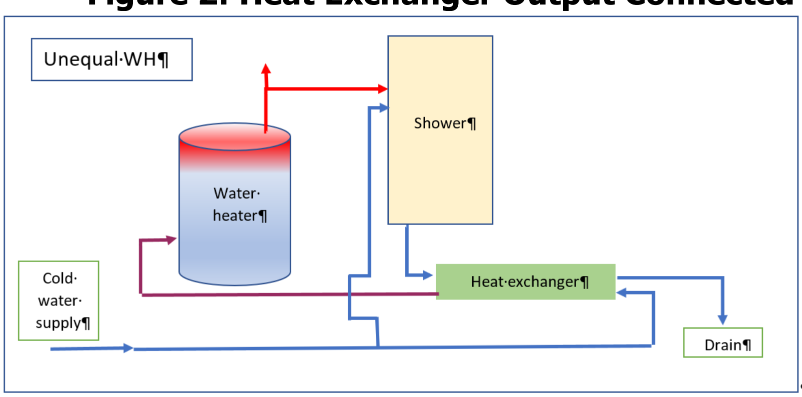
Drain water heat recovery (DWHR) devices are heat exchangers that transfer heat from warm drain water to incoming cold (mains) water. These operate on draws where supply and drain flow are simultaneous — for example, showers (as opposed to dishwashers). In CBECC-Res, only shower draws support DWHR. Several plumbing configurations are possible.

Figure 1: Heat Exchanger Output Connected to Both Shower Water Heater Cold Sides



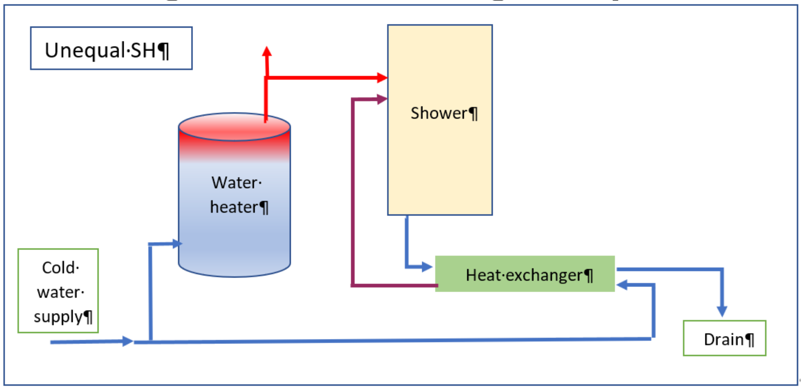
Source: California Energy Commission

Figure 2: Heat Exchanger Output Connected to Water Heater Cold Side



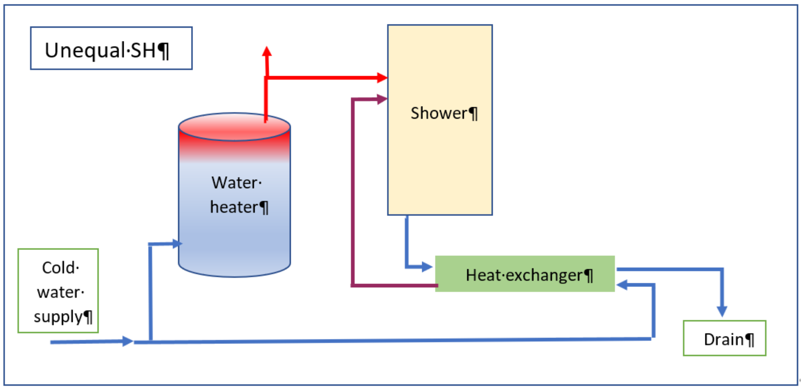
Source: California Energy Commission

Figure 3: Heat Exchanger Output Connected to Shower Cold Side



Source: California Energy Commission

Figure 4: Heat Exchanger Output Connected to Both Shower Water Heater Cold Side



Source: California Energy Commission

In practice, there are many combination plumbing configurations that are possible. For example, only some showers may drain via DWHR devices, or more than one shower may drain via a shared DHWR device. CBECC-Res input structure allows flexible specification of such arrangements.

The drain water heat recovery temperature increase, ΔT_{dwhr}, is modeled within CSE using effectiveness derived using correlations presented in:

- *Drain Water Heat Recovery – Final Report.* Measure Number: 2019-RES-DHW2-F. Available at http://title24stakeholders.com/wp-content/uploads/2017/09/2019-T24-CASE-Report_DWHR_Final_September-2017.pdf
- *Explanation of Drain Water Heat Recovery Calculations*. NegaWatt Consulting. Dec. 13, 2017.

DWHR is supported only for shower draws. Based on experimental data, the effectiveness correlation is function of potable water flow rate, potable water entering temperature, and drain water flow rate, as shown here:

$$t_{pi} = \min(t_{mains}, 81)$$
$$f_t = \left(-3.06\times10^{-5} t_{pi}^{\ 2} + 4.96\times10^{-3} t_{pi} + 0.281\right)\Big/0.466$$
$$f_v = -6.98484455\times10^{-4} v_p^{\ 4} + 1.28561447\times10^{-2} v_p^{\ 3} - 7.02399803\times10^{-2} v_p^{\ 2}$$
$$+ 1.33657748\times10^{-2} v_p + 1.23339312$$
$$\varepsilon = \left[0, \left(1 + 0.3452 \ln(v_d / v_p\right) f_t f_v \varepsilon_{rated}, 0.95\right]$$

Equation 12

Where

t_{pi} = DWHR potable water inlet temperature, °F

v_p = Potable volume flow rate, gpm. v_p depends on the plumbing configuration and is various combinations of the fixture hot water draw, the fixture cold water draw, and the total hot water draw.

v_d = Drain volume flow rate, gpm. The drain volume is equal to the total (mixed) draws of fixture(s) evaluated *not including f_{dur}* (see Equation 1) since no heat can be recovered during warmup.

e = DWHR effectiveness under current conditions, unitless

e_{rated} = DWHR-rated effectiveness = efficiency/100, rated at CSA B55.1 conditions (9.5 lpm, equal flow)

The effectiveness, *e*, is used to calculate the potable water temperature increase.

$$\Delta T_{dwhr} = \frac{\varepsilon \, min(v_p, v_d)(t_d - t_{pi})}{v_p}$$

Equation 13

Where

t_d = DWHR drain-side entering temperature, °F = shower use temperature (105°F) – 4.6°F. The latter adjustment approximates heat loss between the shower and the DWHR device.

In this model with some plumbing configurations, effectiveness depends on *v_p,* and *v_p* depends on effectiveness. An iterative solution technique is required to find consistent conditions.

When only some shower fixtures within a dwelling unit drain via a DWHR system, savings are assumed proportional to the number of included shower fixtures. This is implemented by assigning shower draws in rotation to DWHR or non-DWHR arrangements.

B5. Hourly Distribution Loss for Central Water Heating Systems

This section is applicable to the DHW system Types 3 and 4, as defined in B1. The distribution losses accounted for in the distribution loss multiplier (DLM), Equation *5*, reflect distribution heat loss within each dwelling unit. Additional distribution losses occur outside dwelling units and include losses from recirculation loop pipes and branch piping feeding dwelling units. The hourly values of these losses, HRDL, shall be calculated according to Equation 17

. Compliance software shall provide input for specifying recirculation system designs and controls according to the following algorithms.

$$HRDL_k = NLoop_k \times HRLL_k + HRBL_k \qquad \textit{Equation 14}$$

Where

$HRDL_k$= Hourly central system distribution loss for k^{th} system (Btu).

$HRLL_k$= Hourly recirculation loop pipe heat loss (Btu). This component is only applicable to system Type 4, see Equation 15

$HRBL_k$= Hourly recirculation branch pipe heat loss (Btu), see Equation 23

$NLoop_k$= Number of recirculation loops in water heating system k; this component is only applicable to system Type 4, see Section 0

A recirculation loop usually includes multiple pipe sections, not necessarily having the same diameter, that 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 0

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

Hourly Recirculation Loop Pipe Heat Loss Calculation

Hourly recirculation loop pipe heat loss ($HRLL_k$) is the hourly heat loss from all six pipe sections. There are two pipe heat loss modes — pipe heat loss with nonzero 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 are no hot water draw flows, such as in recirculation return pipes.

Compliance software shall provide four options of recirculation system controls listed in

Table B-3 or Table B-4. A proposed design shall select a control type from one of the four options. The standard design shall use demand control.

Table B-3: Recirculation Loop Supply Temperature and Pump Operation Schedule (With No Control or Demand Control)

Hour	No Control Temperature	No Control Input for $SCH_{k,m}$	Demand Control Temperature	Demand Control Input for $SCH_{k,m}$
1 through 24	130	1	130	0.2

Source: California Energy Commission

Table B-4. Recirculation Loop Supply Temperature and Pump Operation Schedule (With Temperature Modulation Control)

Hour	Without Continuous Monitoring Temperature	Without Continuous Monitoring Input for $SCH_{k,m}$	With Continuous Monitoring Temperature	With Continuous Monitoring Input for $SCH_{k,m}$
1 through 5	120	1	115	1
6	125	1	120	1
7 through 23	130	1	125	1
24	125	1	120	1

Source: California Energy Commission

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 ($HRLL_k$) is the heat loss from all six pipe sections, according to the following equation:

$$HRLL_k = \sum_n [PLWF_n + PLCD_n]$$ Equation 15

Where

$PLWF_n$= Hourly pipe heat loss with non-zero water flow (Btu/hr), see Equation 16

$PLCD_n$= Hourly pipe heat loss without water flow (Btu/hr), see Equation 21

n= Recirculation pipe section index, 1 through 6

$$PLWF_n = Flow_n \times (1 - f_{noflow,n}) \times \rho \times C_p \times (T_{n,in} - T_{n,out})$$ Equation 16

Where

$Flow_n$ = $Flow_{recirc}$ + $Flow_{n,draw}$ (gph), assuming

$Flow_{n,draw}$ = Average hourly hot water draw flow (gph); for supply sections, n=1, 2, or 3, $Flow_{n,draw}$ = $GPH_k/NLoop_k$; for return pipes, n=4, 5, and 6, $Flow_{n,draw}$ = 0

$Flow_{recirc}$ = Hourly recirculation flow (gph), shall be calculated as $Nunit_k/Nfloor_k$ x 0.5 x 60 x F_{bv}. F_{bv} is the balancing valve and variable speed recirculation pump flow reduction factor. For the standard design, f_{BV} is 1.0. For the proposed design, if the recirculation system meets all criteria of Reference Residential Appendix RA 4.4.3, f_{BV} is 0.6. Otherwise, f_{BV} is 1.0.

$f_{noflow,n}$ = Fraction of the hour for pipe section n to have zero water flow, see Equation 17

ρ = Density of water, 8.345 (lb/gal)

C_p = Specific heat of water, 1 (Btu/lb-˚F)

$T_{n,in}$ = Input temperature of section n (˚F); for the first section (n=1), $T_{1,in}$ shall be determined based on

Table B-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, $T_{n,in}$ = $T_{n-1,out}$

$T_{n,out}$ = Output temperature of section n (˚F), see Equation 18

$$f_{noflow,n} = (1 - SCH_{k,m}) \times NoDraw_n$$

Equation 17

Where

$NoDraw_n$ = Fraction of the hour that is assumed to have no hot water draw flow for pipe section n; $NoDraw_1$ = 0.2, $NoDraw_2$ = 0.4, $NoDraw_3$ = 0.6, $NoDraw_4$ = $NoDraw_5$ = $NoDraw_6$ = 1

$SCH_{k,m}$ = Recirculation pump operation schedule, representing the fraction of the hour that the recirculation pump is turned off, see

Table B-3 or Table B-3. $SCH_{k,m}$ for the proposed design shall be based on proposed recirculation system controls. Recirculation system control for the standard design is demand control.

$$T_{out,n} = T_{amb,n} + (T_{in,n} - T_{amb,n}) \times e^{-\frac{UA_n}{\rho C_p Flow_n}}$$

Equation 18

Where

$T_{Amb,n}$ = Ambient temperature of section n (˚F), which can be outside air, underground, conditioned, or semiconditioned air. Outside air temperatures shall be the dry-bulb temperature from the weather file. Underground temperatures shall be obtained from **Error! Reference source not found.**Equation 11. Hourly conditioned air temperatures shall be the same as conditioned space temperature. For the proposed design, $T_{amb,n}$ options shall be based on user input. The standard design assumes all pipes are in conditioned air.

UA_n = Heat loss rate of section n (Btu/hr-°F), see Equation 19

$$UA_n = Len_n \times min(U_{bare,n}, f_{UA} \times U_{insul,n})$$

Equation 19

Where

Len_n = Section n pipe length (ft); for the proposed design, use user input; for the standard design, see

$U_{bare,n}$, $U_{insul,n}$ = Loss rates for bare (uninsulated) and insulated pipe (Btu/hr-ft-˚F), evaluated using Equation 20 with section-specific values, as follows:

Dia_n = Section n pipe nominal diameter (inch); for the proposed design, use user input; for the standard design, see.

$Thick_n$ = Pipe insulation minimum thickness (inch) as defined in the Title 24 Section 120.3, TABLE 120.3-A for service hot water system

$Cond_n$ = Insulation conductivity shall be assumed = 0.26 (Btu inch/h·sf·F)

h_n = Section n combined convective/radiant surface coefficient (Btu/hr-ft2-˚F) assumed = 1.5

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. For the standard design, f_{UA} is 2.0. For proposed designs, f_{UA} is 2.0 if the pipe insulation installation is verified per Residential Reference Appendix RA 3.6.3. Otherwise, f_{UA} is 2.4.

Equation 20 defines general relationships used to calculate heat loss rates for both loop and branches using appropriate parameters.

$$Dia_o = Dia + 0.125$$

$$U_{bare} = h \times \pi \times \frac{Dia_o}{12}$$

$$Dia_x = Dia_o + 2 \times Thick$$

$$U_{insul} = \frac{\pi}{\frac{ln\left(\frac{Dia_x}{Dia_o}\right)}{\frac{2 \times Cond}{12}} + \frac{12}{h \times Dia_x}}$$

Equation 20

Where

Dia = Pipe nominal size (in)

Dia_o = Pipe outside diameter (in)

Dia_x = Pipe + insulation outside diameter (in)

Thick = Pipe insulation thickness (in)

Cond = Insulation conductivity (Btu in/hr-ft^2- ˚F)

h = Combined convective/radiant surface coefficient (Btu/hr-ft^2- ˚F)

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

$$PLCD_n = Vol_n \times \rho \times C_p \times \left(T_{n,start} - T_{n,end}\right)$$

Equation 21

Where

Vol_n = Volume of section n (gal) is calculated as 7.48 x π x $\left(\frac{Dia_o}{24}\right)^2$ x *Len_n* where 7.48 is the volumetric unit conversion factor from cubic feet to gallons. Note that the volume of the pipe wall is included to approximate the heat capacity of the pipe material.

$T_{n,start}$ = Average pipe temperature (°F) of pipe section n at the beginning of the hour. It is the average of $T_{n,in}$ and $T_{n,out}$ calculated according to Equation 18 and associated procedures.

$T_{n,end}$ = Average pipe temperature (°F) of pipe section n at the end of pipe cool down, see Equation 22

$$T_{n,end} = T_{amb,n} + \left(T_{n,start} - T_{amb,n}\right) \times e^{-\frac{UA_n \times f_{noflow,n}}{Vol_n \times \rho \times C_p}}$$ Equation 22

Equation 22 calculates average pipe temperature after cooling down, so the pipe heat loss calculated by Equation 21 is for pipe with zero flow for fraction $f_{noflow,n}$ of an hour. Recirculation pumps are usually turned off for less than an hour and there could be hot water draw flows in the pipe. As a result, recirculation pipes usually cool down for less than an hour. The factor $f_{noflow,n}$ calculated according to Equation 17 is used to reflect this effect in Equation 22.

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:

$$HRBL_k = Nbranch_k \times (HBUL + HBWL)$$ Equation 23

Where

HBUL = Hourly pipe loss for one branch when water is in use (Btu/hr), see Equation 24

HBWL = Hourly pipe loss for one branch due to hot water waste (Btu/hr), see Equation 27

$Nbranch_k$ = Number of branches in water heating system k, see Equation 32

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

$$HBUL = \left(\frac{GPH_k}{NBranch_k}\right) \times \rho \times C_p \times \left(T_{b,in} - T_{b,out}\right)$$ Equation 24

Where

$T_{b,in}$ = Average branch input temperature (°F). It is assumed to be equal to the output temperature of the first recirculation loop section, $T_{1,out}$

$T_{b,out}$ = Average branch output temperature (˚F), see Equation 25

$$T_{b,out} = T_{amb,b} + \left(T_{b,in} - T_{amb,b}\right) \times e^{-\frac{UA_b}{\rho \times C_p \times Flow_b}}$$ Equation 25

Where

$T_{amb,b}$ = Branch pipe ambient temperature (°F). Branch pipes are assumed to be located in the conditioned or semiconditioned air.

UA_b = Branch pipe heat loss rate (Btu/hr-°F), see Equation 26

$Flow_b$ = Branch hot water flow rate during use (gal/hr). It is assumed to be 2 gpm or 120 gal/hr.

The branch pipe heat loss rate is

$$UA_b = Len_b \times U_{insul,b}$$ Equation 26

Where

Len_b = Branch pipe length (ft), see

$U_{insul,b}$ = Loss rate for insulated pipe (Btu/hr-ft-˚F), evaluated using Equation 20 with branch-specific values, as follows:

Dia_b = Branch pipe diameter (inch), see

$Thick_b$ = Branch pipe insulation minimum thickness (inch) as defined in the Title 24 Section 120.3, TABLE 120.3-A for service hot water system.

$Cond_b$ = Branch insulation conductivity, assumed = 0.26 Btu in/hr-ft^2- ˚F

h_b = Branch combined convective/radiant surface coefficient (Btu/hr-ft^2- ˚F) assumed = 1.5

The hourly pipe loss for one branch due to hot water waste is calculated as follows:

$$HBWL = N_{waste} \times SCH_{waste,m} \times f_{vol} \times 7.48 \times \pi \times \left(\frac{Dia_b + 0.125}{24}\right)^2 \times Len_b \times \rho \times C_p \times (T_{b,in} - T_{inlet})$$

Equation 27

Where

N_{waste} = Number of times in a day for which water is dumped before use. This number depends on the number of dwelling units served by a branch. Statistically, the number of times of hot water waste is wasted is inversely proportional to the number of units a branch serves, see Equation 28.

$SCH_{waste,m}$ = Hourly schedule of water waste, see Table B-5

f_{vol} = 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.

$T_{in,b}$ = Average branch input temperature (°F) is assumed to equal the output temperature of the first recirculation loop section, $T_{OUT,1}$

T_{inlet} = The cold water inlet temperature (°F) according to Section 3.3 Cold Water Inlet Temperature

$$N_{waste} = 19.84 \times e^{-0.544 \times Nunit_b}$$

Equation 28

Method WH-BRWF

Where

$Nunit_b$= Number of dwelling units served by the branch, calculated using Equation 29 ($Nunit_b$ is not necessarily integral).

$$Nunit_b = \frac{Nfloor}{2}$$ Equation 29

Method WH-BRNU

Table B-5: Branch Water Waste Schedule

Hour	$SCH_{waste,m}$
1	0.01
2	0.02
3	0.05
4	0.22
5	0.25
6	0.22
7	0.06
8	0.01
9	0.01
10	0.01
11	0.01
12	0.01
13	0.01
14	0.01
15	0.01
16	0.01
17	0.01
18	0.01
19	0.01
20	0.01
21	0.01
22	0.01
23	0.01
24	0.01

Source: California Energy Commission

Recirculation System Plumbing Designs

A recirculation system consists of multiple pipes, which are connected in sequence to form a loop. Within a recirculation loop, there can be multiple parallel flow paths formed by riser pipes between supply and return pipes. The compliance software shall use six pipe sections, with three supply pipe sections and three return pipe sections, to represent a recirculation loop. The compliance software shall model recirculation systems according to the piping design described in the following sections. This piping design is based on typical recirculation system piping layout practices and pipe sizing methods defined in California Plumbing Code Appendix A and Appendix M.

Supply pipes start from the water heating plant master mixing valve outlet located on the first floor and are routed to the corridor ceiling. Supply pipes run horizontally to each end of the building. Horizontal riser pipes connected to supply pipes bring hot water to each first-floor dwelling unit. Each horizontal riser is connected to vertical riser pipes to bring hot water to dwelling units on upper floors. In the ceiling of the top floor, vertical riser pipes are connected to horizontal riser pipes, which bring hot water to recirculation return pipes in the corridor ceiling. A vertical recirculation return pipe brings hot water to the heating plant on the first floor to complete the loop. This recirculation loop design uses risers to bring hot water to each dwelling unit and, therefore, branch pipes for connecting riser pipes and pipes leading to individual hot water fixtures are relatively short.

All supply pipes and the bottom half of riser pipes are converted into three sections of supply pipes in the default recirculation loop design. All return pipes and the top half of riser pipes are converted into three sections of return pipes in the default recirculation loop design. The first pipe section includes pipes from the water heating plant master mixing valve outlet to the first riser. The second pipe section includes supply pipes for the first half risers and the bottom half of these first half risers. The third pipe section includes the remaining supply pipes and the bottom half of the second half risers. The first pipe section represents pipes for supplying the whole building and, therefore, has the largest pipe diameter. The second section has a smaller pipe diameter because it represents the supply pipes and riser pipes with smaller pipe diameters. Pipe diameter for the third section is smallest because it represents pipes serving the fewest dwelling units. Return pipe sections (4, 5, and 6) represent return pipes and the top half of riser pipes in a similar way as supply pipe sections. Each return pipe section has the same pipe length as the corresponding supply pipe section. Pipe diameters for all return pipe sections are 0.75 inch.

For both the standard and proposed design, pipe section lengths are calculated as follows:

Length of recirculation pipe sections (ft):

$$Len_1 = Len_6 = 0.3 \times Nunit_k + 4 \qquad \text{Equation 30}$$

$$Len_2 = Len_3 = Len_4 = Len_5 = 5.5 \times Nunit_k \qquad \text{Equation 31}$$

Method WH-LOOPLEN

Pipe diameters for recirculation loop supply sections depend on the number of dwelling units being served and return section diameters depend only on building type, as follows:

> Dia_1, Dia_2, and Dia_3: derived from Table B-6. The standard design shall use values listed under California Plumbing Code Appendix M Pipe Sizing Method in Table B-6. Proposed designs shall use the same values as the standard design if pipes are sized using California Plumbing Code Appendix M Pipe Sizing Method. Otherwise, values listed under California Plumbing Code Appendix A Pipe Sizing Method shall be used.
>
> $Dia_4 = Dia_5 = Dia_6 = 0.75$ in

Method WH-LOOPSZ

Branch pipe parameters include number of branches, branch length, and branch diameter. The number of branches in water heating system k is calculated as (note: not necessarily an integer):

$$Nbranch_k = Nunit_k \qquad \text{Equation 32}$$

Method WH-BRN

The branch pipe diameter, Dia_b, shall be 0.75 in.

Method WH-BRSZ

Branch pipes connect riser pipes to pipes connected to individual hot water fixtures in dwelling units. The branch length, Len_b, shall be 2 feet.

Method WH-BRLEN

Proposed designs shall use the same branch configurations as those in the standard design.

Table B-6: Pipe Size Schedule for Supply Pipe Sections

Number of dwelling units served $NUnit_n$	CPC Appendix A Dia1 (in)	CPC Appendix A Dia2 (in)	CPC Appendix A Dia3 (in)	CPC Appendix M Dia1	CPC Appendix M Dia2	CPC Appendix M Dia3
< 5	1	0.75	0.75	1	0.75	0.75
5 ≤ N < 8	1.5	1	0.75	1.5	1	0.75
8 ≤ N < 21	2	1.5	1.5	1.5	1.5	1
21 ≤ N < 36	2.5	1.5	1.5	1.5	1.5	1
36 ≤ N < 68	3	1.5	1.5	2	1.5	1
68 ≤ N < 101	3.5	2	1.5	3	1.5	1
101 ≤ N < 145	4	2	1.5	3	1.5	1
145 ≤ N < 198	5	2	1.5	3	1.5	1
N >= 198	6	2	1.5	3	1.5	1

Source: California Energy Commission

B6. 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 that 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 that use electric trace heating instead of gas, the program shall assume equivalency.

B7. Energy Use of 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 and summed.

Consumer or Residential-Duty Commercial Storage Water Heaters

Storage water heaters are rated either by EF (energy factor) or the newer UEF (Uniform Energy Factor). The calculation algorithm for these devices derives a Load Dependent Energy Factor (LDEF) from EF. For water heaters rated with UEF, CBECC-Res calculates an equivalent EF.

The hourly energy use of storage gas water heaters is given by the following equation.

$$WHEU_j = \frac{HARL_j \times HPAF_j}{LDEF_j}$$ Equation 33

Where

$WHEU_j$ = Hourly energy use of the water heater (Btu for fuel or kWh for electric); Equation 33 provides a value in units 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)

$HPAF_j$ = 1 for all non-heat-pump water heaters

$LDEF_j$ = The hourly Load Dependent Energy Factor (LDEF) is given by

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

Equation 34. This equation adjusts the nominal EF rating for storage water heaters for different load conditions.

$$LDEF_j = min\left[LDEF\ max\left(LDEF\ ln\left(\frac{AAHARL_j \times 24}{1000}\right)(a \times EF_j + b)(c \times EF_j + d)_{min}\ ()\right)_{max}\right]$$ Equation 34

Where

a,b,c,d = Coefficients from the table below based on the water heater type

Table B-7: LDEF Coefficients

Coefficient	Storage Gas
A	-0.098311
B	0.240182
C	1.356491
D	-0.872446
$LDEF_{min}$	.1
$LDEF_{max}$	.90

Source: California Energy Commission

$AAHARL_j$ = Annual average hourly adjusted load (Btu) = $\frac{1}{8760}\sum_{1}^{8760} HARL_j$; 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 with volume less than 20 gallons must be assumed to be 0.58 unless the manufacturer has voluntarily reported an actual EF to the California Energy Commission.

CBECC-Res derives EF_j from UEF for water heaters that are rated using updated DOE procedures.

Consumer and Residential-Duty Commercial Water Heaters

UEF-rated consumer and residential-duty commercial instantaneous water heaters (gas and electric) are modeled on a minute-by-minute basis using procedures documented by Lutz (2019).

Small Instantaneous Gas Water Heaters

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

$$WHEU_j = \frac{HARL_j}{EF_j \times 0.92} \qquad \text{Equation 35}$$

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) taken from manufacturers' literature or from the CEC Appliance Database

0.92 = Efficiency adjustment factor

Small Instantaneous Electric Water Heaters

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

$$WHEU_{j,elec} = \frac{HARL_j}{EF_j \cdot 0.92 \cdot 3413} \qquad \text{Equation 36}$$

Where

$WHEU_{j,elec}$ = 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)

Mini-Tank Electric Water Heater

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 35 W should be assumed.)

$$WHEU_{j,elec} = MTSBL_j/1000 \qquad \text{Equation 37}$$

Where

$WHEU_{j,elec}$ = Hourly standby electrical energy use of mini-tank electric water heaters (kWh)

$MTSBL_j$ = Mini-tank standby power (W) for tank j (if not listed in CEC Appliance directory, assume 35 W)

Large/Commercial Gas Storage Water Heaters

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

$$WHEU_j = \frac{HARL_j}{EFF_j} + SBL_j \qquad \text{Equation 38}$$

Where

$WHEU_j$ = Hourly fuel energy use of the water heater (Btu)

$HARL_j$ = Hourly adjusted recovery load (Btu)

SBL_j = 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 $(V)^{1/2}$, where Q is the input rating in Btu/hour, and V 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.

Large/Commercial Instantaneous, Indirect Gas, and Hot Water Supply Boilers

Energy use for these types of water heaters is given as follows:

$$WHEU_j = \frac{HARL_j}{EFF_j \times 0.92} + PILOT_j \qquad \text{Equation 39}$$

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 B3.

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.

Consumer Storage Electric or Heat Pump Water Heaters

Energy use for small electric water heaters is calculated as described in the HPWHsim Project Report (Ecotope, 2016) and in documents specified in Section B6. (See also study by NEEA referenced in Appendix F.) The HPWH model uses a detailed, physically based, multinode model that operates on a one-minute time step implemented using a suitable loop at the time-step level within CSE. Tank heat losses and heat pump source temperatures are linked to the CSE zone heat balance as appropriate. Thus, for example, the modeled air temperature of a garage containing a heat pump water heater will reflect the heat extracted.

HPWHsim can model three classes of equipment:

- Specific air-source heat pump water heaters identified by manufacturer and model. These units have been tested by Ecotope, and measured parameters are built into the HPWH code.
- Generic air-source heat pump water heaters, characterized by EF and tank volume. This approach provides compliance flexibility. The performance characteristics of the generic model are tuned to use somewhat more energy than any specific unit across a realistic range of UEF values.
- Electric resistance water heaters, characterized by EF, tank volume, and resistance element power.

Several issues arise from integration of a detailed, short time-step model into an hourly framework. HPWH is driven by water draw quantities, not energy requirements. Thus, to approximate central system distribution and unfired tank losses, fictitious draws are added to the scheduled water uses, as follows:

$$V_{j,t} = \frac{VS_{k,t} + \dfrac{HRDL_k + \sum_1^{NL_k} HJL_l}{60 \times 8.345 \times (t_s - t_{inlet})}}{NWH_k}$$

Equation 40

Where

$HRDL_k$ = Hourly recirculation distribution loss (Btu), see Equation 14; $HRDL_k$ is nonzero only for multifamily central water heating systems

HJL_l = Tank surface losses of the l^{th} unfired tank of the k^{th} system (Btu), see Equation 41

VS_k = Hot water draw at the k^{th} water heating system's delivery point (gal)

$V_{j,t}$ = Hot water draw (gal) on j^{th} water heater for minute t

Another issue is that the HPWH hot water output temperature varies based on factors such as control hysteresis and tank mixing. For compliance applications, it is required that all system alternatives deliver the same energy. To address this, the HPWH tank setup point is modeled at 125°F, and delivered water is tempered to t_s. If the HPWH output temperature is above t_s, it is assumed that inlet water is mixed with it (thus reducing $V_{i,t}$). If the output temperature is below t_s, sufficient electrical resistance heating is supplied to bring the temperature up to t_s (preventing undersizing from being exploited as a compliance advantage).

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:

$$HJL_l = \frac{TSA_l \times \Delta TS}{RTI_l + REI_l} + FTL_l$$ Equation 41

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), see Equation 42

ΔTS = Temperature difference between ambient surrounding tank and hot water supply temperature (°F). Hot water supply temperature shall be 124°F. For tanks located inside conditioned space use 75°F for the ambient temperature. For tanks in outside conditions, use hourly dry bulb temperature ambient.

FTL_l = Fitting losses; 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

Tank surface area (TSA) is used to calculate the hourly jacket loss (HJL) for unfired or indirectly fired tanks. TSA is given in the following equation as a function of the tank volume.

$$TSA_l = (1.254 \times VOL_l^{0.33} + .531)^2$$ Equation 42

Where

VOL_l = Tank capacity (gal)

Water Heating Plant Pipe Heat Loss

Pipes in the heating plan connect water heating equipment, hot water storage equipment, and the master mixing valve. The hourly pipe heat loss of water heating plant in the k^{th} system is calculated as:

$$HPPL_k = (PSA_{plant,k} \times f_{A,plant}) \times (U_{plant,k} \times f_{U,plant}) \times (T_{plant,k} - T_{Amb_{plant},k})$$ Equation 43

Where

$PSA_{plant,k}$ = Pipe surface area (ft^2) of pipes in the heat plant. Note that pipes downstream of the master mixing valve are considered part of the hot water distribution system. It is calculated based on the number of dwelling units, $Nunit_k$, served by the heating system k as follows:

2.4 x $Nunit_k$ for heat pump water heater-based heating plant

3.5 x $Nunit_k$ for natural gas water heater or boiler-based heating plant

$f_{A,plant}$ = Correction factor to reflect improvement in pipe surface area reduction by using smaller pipes according to California Plumbing Code Appendix M. For the standard design, $f_{A,plant}$ is 0.8. For the proposed design, the default value is 1.0. If plant pipes in the proposed design are sized according to the California Plumbing Code Appendix M and the number of dwelling units served by the heating plan, $Nunit_k$ is more than 8, $f_{A,plant}$ is 0.8.

$U_{plant,k}$ = Average heat transfer coefficient between pipes and the ambient air, 25.2 Btu/hr-ft^2-°F.

$F_{U,plant}$ = Correction factor to reflect field installation quality of pipe insulation. For the standard design, $F_{u,plant}$ is 1. For proposed design, the default value is 1.4. If pipe insulation is field inspected and verified by a ECC rater per Residential Reference Appendix RA2.2, $f_{U,plant}$ is 1.

$T_{plant,k}$ = Average pipe surface temperature for pipes in the heat plant, 125 °F.

$T_{Amb\_plant,k}$ = Ambient temperature of the water heating plant, which can be the temperature of outside air or unconditioned air. Outside air temperatures shall be the dry-bulb temperature from the weather file. Hourly unconditioned air temperatures shall be the average of outside air dry-bulb temperature and conditioned air dry-bulb temperature. The standard design shall have the same water heating plant ambient temperature as the proposed design. For proposed designs, the water heating plant ambient temperature shall be based on user input of the water heating plant location.

Electricity Use for Circulation Pumping

For single-family recirculation systems, hourly pumping energy is fixed as shown in Table B-8.

Multifamily 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.

$$HEUP_k = \frac{0.746 \times PUMP_k \times SCH_{k,m,}}{\eta_k}$$ Equation 44

Where

$HEUP_k$ = Hourly electricity use for the circulation pump (kWh)

$PUMP_k$ = Pump brake horsepower (bhp)

η_k = Pump motor efficiency

$SCH_{k,m}$ = Operating schedule of the circulation pump. (See

Table B-3.) The operating schedule for the proposed design shall be based on user input control method. The standard design operation schedule is demand control.

Table B-8: Single-Family Recirculation Energy Use (kWh) by Hour of Day

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

Source: California Energy Commission

B8. Energy Use of Central Heat Pump Water Heater Systems

Energy use for central heat pump water heater (CHPWH) systems is calculated by HPWHsim in a way similar to consumer electric heat pump water heaters. The HPWH model uses a detailed, physically based, multinode model that operates on a 1-minute time step. This model is implemented using a suitable loop at the time-step level within CSE. Unlike with consumer electric HPWH, the central HPWH systems are built from several components selected by the building designer. The energy performance of central water heating systems is determined by these components: the primary heating equipment, primary heating storage volume, location, secondary heating equipment, secondary heating storage volume, set point controls, and the way in which the components are plumbed.

To calculate the energy use, CBECC uses information regarding the characteristics of the central HPWH system defined in the following tables and lists.

Table B-9: DHW Central/Recirculation Type

Name	DHW System Description
Non-Central	A system with a water heater for each dwelling unit.
Central, no Recirculation	A DHW system with equipment providing hot water for all dwelling units in the building. No hot water temperature maintenance recirculation loop is used.
Central with Recirculation	A DHW system with equipment providing hot water for all dwelling units in the building. Hot water temperature maintenance recirculation loop is used. Plumbing of recirculation loop in relation to central heating equipment is specified.

Source: California Energy Commission

Table B-10: Central HPWH Primary System Type

Name	HPWH Description
Single-Pass Primary	A split-system HPWH that regulates flow such that it heats cold water to setpoint in a single trip through the heating equipment.
Multi-Pass Primary	A split-system HPWH with constant flow that incrementally heats water through multiple trips through the heating equipment.
Integrated/Packaged System	A HPWH that contains the heat pump components and storage tank in one device. These may also contain one or two electric resistance heating elements.

Source: California Energy Commission

For single-pass primary/multi-pass primary either primary or secondary types:

- **HPWH/Compressor Model** — The manufacturer and model number of the HPWH, with heating capacity provided 40˚F ambient air.

- **Compressor/Heater Count** — Number of single-pass primary or multi-pass compressors, either primary or secondary.
- **Total Tank Volume** — Total storage volume of all tanks, either primary or secondary.
- **Tank Count** — The number of storage tanks that the total tank volume is distributed over, either primary or secondary.
- **Tank R-Value** — The R-Value of the insulation around the storage tanks, either primary or secondary.

Table B-11 applies to integrated/packaged system, either primary or secondary types.

Table B-11: Integrated/Packaged Type

Name	Integrated/Packaged Type Description
Residential (NEEA rated) Product	An integrated/packaged HPWH listed in NEEA's Residential Unitary Qualified Products List.
Commercial Product	An integrated/packaged HPWH of storage volume greater than or equal to 120 gallons or heating capacity greater than 6 kW.

Source: California Energy Commission

For residential (NEEA-rated) product:

- **NEEA HPWH Brand/Model** — The manufacturer and model number of the HPWH, provided with the nominal storage capacity, for either the primary or secondary type.
- **NEEA HPWH Count** — An integer number of residential (NEEA-rated) integrated/packaged HPWHs, this includes the storage tank and the heating elements.

For commercial product:

- **Commercial HPWH Product** — The manufacturer and model number of the HPWH, provided with the nominal storage capacity, for either the primary or secondary type.
- **HPWH Count** — An integer number of commercial integrated/packaged HPWHs, this includes the storage tank and the heating elements.

For all HPWH types as either primary or secondary:

- **Tank Location** — The location of the storage tanks, either outside or a specific zone, for the primary or secondary tank.
- **Source Air From** — The location that the HPWH draws air from, either outside or a specific zone. For a split-system single-pass or multi-pass HPWH the HPWH may be

located in a separate location than the tank location, or for an integrated/packaged type, the source air can be ducted from a separate location.

Table B-12: Secondary Tank Configuration

Name	Secondary Tank Configuration Description
None (Return to Primary)	No secondary or loop tank for the recirculation loop to return to. The recirculation loop is returned to the bottom of the primary tank.
Series (Swing)	A tank where the outlet of the primary tank is piped to the bottom of the secondary tank, to mix the secondary tank through thermal buoyancy effects. The recirculation loop is piped to the bottom of the secondary tank.
Parallel	A tank where the outlet of the primary tank is piped to the top of the secondary tank, to maintain thermal stratification in the secondary tank. The recirculation loop is piped to the bottom of the secondary tank.

Source: California Energy Commission

The secondary tank type is largely the same as the primary system type but includes the option for an electric resistance heater.

Table B-13: Secondary Tank Type

Name	Secondary Tank Type Description
Electric Resistance	An electric resistance water heater with two resistance elements. The total heating capacity is 350 W per apartment unit in the building, and it has a set point of 136°F to supply a minimum of 125°F water with a 10° F deadband.
Integrated/Packaged System	A HPWH that contains the heat pump components and storage tank in one device. These also contain one or two electric resistance heating elements.
Single Pass Primary	A split-system HPWH that regulates flow such that it heats cold water to set point in a single trip through the heating equipment.

Multi Pass Primary	A split-system HPWH with constant flow that incrementally heats water through multiple trips through the heating equipment.

Source: California Energy Commission

In CHPWH systems, there is always a primary system type and, optionally, a secondary system type. The primary system heats incoming cold water to the primary tank setpoint. If a recirculation loop is present, the primary system may be configured to heat return water from the recirculation loop. In that case, the recirculation loop is returned to the bottom of the primary tank storage volume. Alternatively, a secondary heating system may be used. In which case, the recirculation loop is returned to the secondary tank.

CBECC is designed to simulate all the following CHPWH system alternatives. The temperature set points are fixed within the simulation based on the HPWH type and application:

- Single-pass primary (not CO_2 refrigerant): 140˚F
- Single-pass primary (CO_2 refrigerant): 149˚F
- Multi-pass primary: 140˚F
- Integrated/packaged primary: 135˚F
- Secondary (not CO_2 refrigerant): 136˚F
- Secondary (CO_2 refrigerant): 149˚F

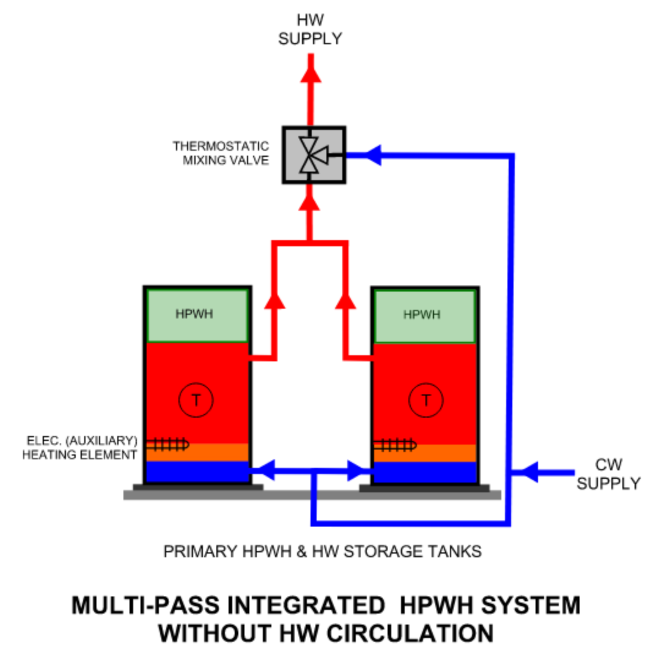
Like consumer HPWH, hot water output temperature varies based on factors such as control hysteresis and tank mixing. For compliance applications, it is required that all system alternatives deliver the same energy. To address this, the HPWH tank setup point is modeled above the delivered water temperature, which is tempered to 125˚F (t_s) with a thermostatic mixing valve. If the HPWH output temperature is above t_s, it is assumed that inlet water is mixed with it (thus reducing $V_{i,t}$). If the output temperature is below t_s, sufficient electrical resistance heating is supplied to bring the temperature up to t_s (preventing under sizing from being exploited as a compliance advantage).

The particular components, piping configuration, control, and system sizing possibilities are described in the subsequent sections for each hot water configuration.

Multi-Pass Integrated HPWH System Without Hot Water Circulation

Narrative: This schematic is applicable for use with integrated HPWH equipment. One or more integrated HPWHs may be specified. When multiple HPWHs are specified, they are piped in parallel. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system. There is no hot water circulation system present in this system configuration.

Figure 5: Multi-Pass Integrated HPWH System Without Hot Water Circulation



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the integrated HPWH equipment. Outgoing hot water is connected to the upper portion of the integrated HPWH equipment. When multiple integrated HPWHs are specified, the incoming cold water supply to the HPWH equipment and outgoing hot water supply from the HWPH equipment are split and configured to supply equal flow to all integrated HPWH units. The outgoing hot water from the integrated HPWH(s) is connected to the hot supply side of the mixing valve. A cold water connection is provided to the cold supply side of the mixing valve. The tempered side of the mixing valve is connected to the building hot water distribution piping system.

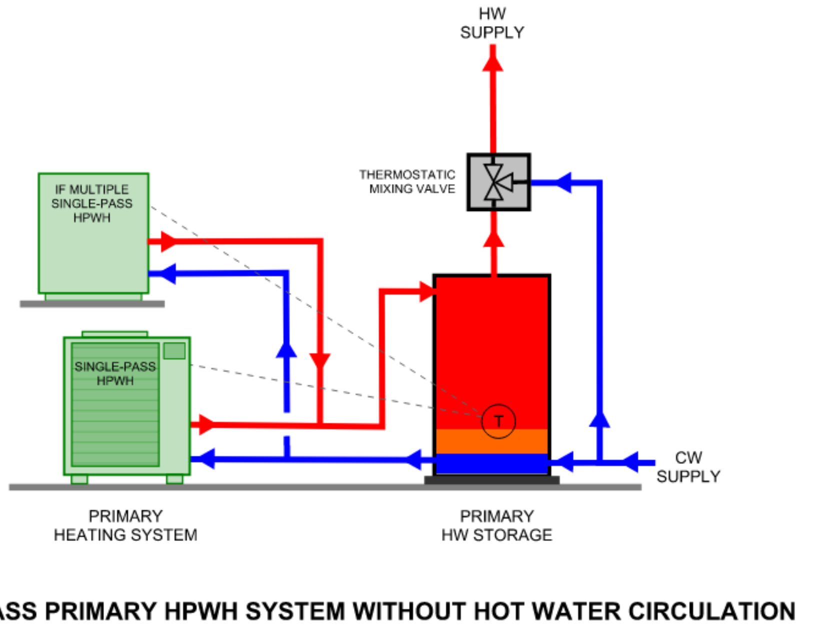
Control: The integrated HPWH equipment is controlled by the internal equipment control system to prioritize compressor heating energy use and minimize auxiliary electric resistance heating energy use.

System Sizing: The integrated HPWH equipment is sized to meet the domestic hot water load. Several integrated HPWHs are specified when a single integrated HPWH equipment cannot meet the load.

Single-Pass Primary HPWH System Without Hot Water Circulation

Narrative: This schematic is applicable for use with single-pass HPWH equipment. One or more heat pumps (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system. There is no hot water circulation system present in this system configuration.

Figure 6: Single-Pass Primary HPWH System Without Hot Water Circulation



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the storage tank. Outgoing hot water is connected to the upper portion of the storage tank. The single-pass split system HPWH(s) is connected to draw water from the lower portion of the tank, heat this water to temperature, and supply to the upper portion of the storage tank. When multiple storage tanks are specified, the storage tanks are configured in series with the top of the first tank connected to the bottom of the second tank. This top-to-bottom connection is repeated for all storage tanks in series. The cold water is supplied to the lower portion of the first tank, and the outgoing hot water is supplied from the upper portion of the last storage tank in series. The outgoing hot water from the storage tank (or last storage tank in series) is connected to the hot supply side of the mixing valve. A cold water connection is provided to the cold supply side of the mixing valve. The outgoing tempered side of the mixing valve is connected to the building hot water distribution piping system.

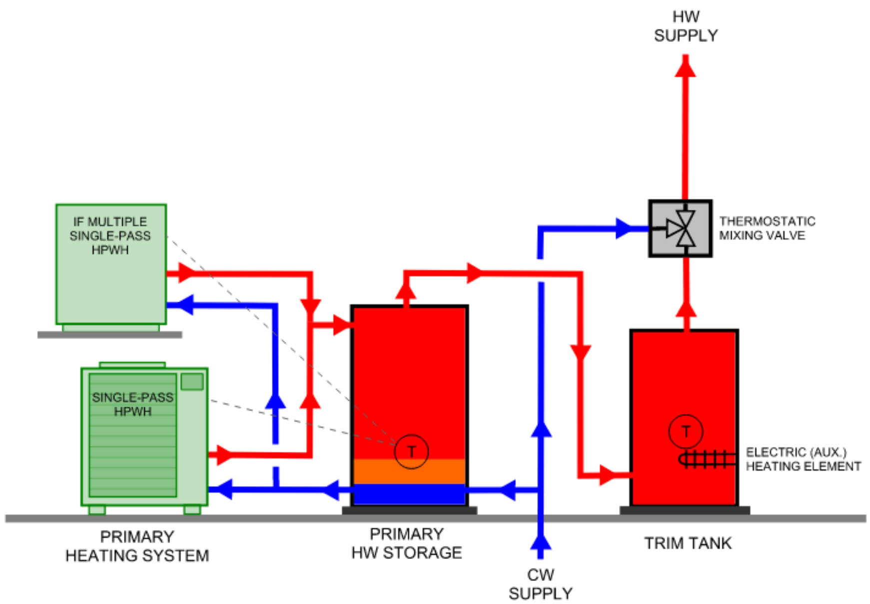
Control: The single-pass split system HPWH(s) are controlled by a temperature sensor or multiple temperature sensors in the primary storage tank(s). Multiple parallel HPWHs are controlled in a single stage.

System Sizing: The HPWH equipment is sized to meet the domestic hot water load. Multiple HPWHs are specified when a single HPWH cannot meet the load.

Single-Pass Primary HPWH System with Secondary Electric Resistance Trim Heater Tank and Without Hot Water Circulation

Narrative: This schematic is applicable for use with single-pass HPWH equipment in combination with a secondary electric resistance trim tank. One or more heat pumps (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system. There is no hot water circulation system present in this system configuration.

Figure 7: Single-Pass Primary HPWH with Trim Tank



SINGLE-PASS PRIMARY HPWH WITH TRIM TANK

Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the storage tank. Outgoing hot water is connected to the upper portion of the storage tank and passes through a secondary electric resistance trim tank. The single-pass split system HPWH(s) is connected to draw water from the lower portion of the tank, heat this water to temperature, and supply it to the upper portion of the storage tank. When multiple storage tanks are specified, the storage tanks are configured in series with the top of the first tank connected to the bottom of the second tank. This top-to-bottom connection is repeated for all storage tanks in series. The cold water is supplied to the lower portion of the first tank, and the outgoing hot water is supplied from the upper portion of the last storage tank in series. The outgoing hot water from the storage tank (or last storage tank in series) is connected to a secondary electric resistance water heater pipped in series. The outgoing hot water connection from the secondary electric resistance heater is connected to the hot supply side of the mixing valve. A cold water connection is provided to the cold supply side of the mixing valve. The outgoing tempered side of the mixing valve is connected to the building hot water distribution piping system.

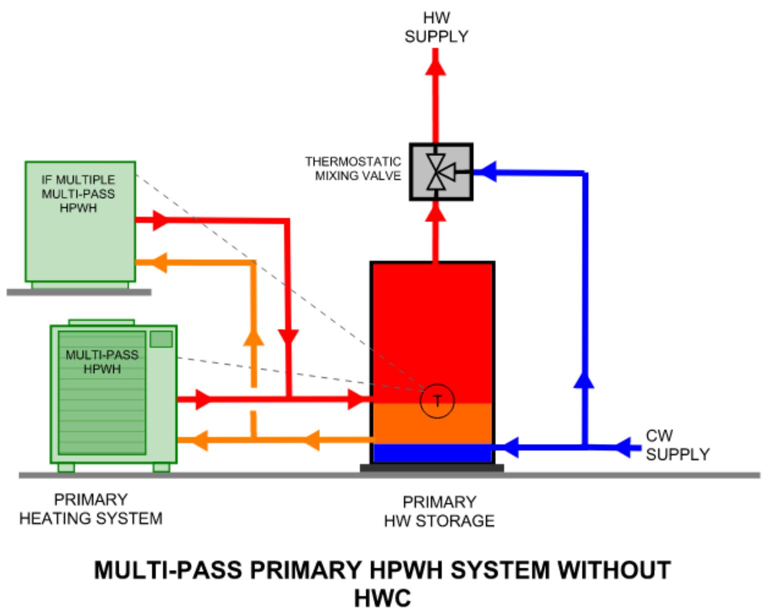
Control: The single-pass split system HPWH(s) is controlled by a temperature sensor or multiple temperature sensors in the primary storage tank(s). Multiple parallel HPWHs are controlled in a single stage.

System Sizing: The HPWH equipment is sized to meet the domestic hot water load. Multiple HPWHs are specified when a single HPWH cannot meet the load. A secondary electric resistance tank is provided for backup or redundancy and sized to meet the domestic hot water load.

Multi-Pass Primary HPWH System Without Hot Water Circulation

Narrative: This schematic is applicable for use with multi-pass HPWH equipment. One or more heat pumps (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system. There is no hot water circulation system present in this system configuration.

Figure 8: Multi-Pass Primary HPWH System Without Hot Water Circulation



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the storage tank. Outgoing hot water is connected to the upper portion of the storage tank. The multi-pass split system HPWH(s) is connected to draw water from the lower portion of the tank, heat this water approximately 10°F, and supply it to the middle portion of the storage tank. When multiple storage tanks are specified, the storage tanks are configured in parallel with equal flow through all parallel storage tanks. The outgoing hot water from the storage tank(s) is connected to the hot supply side of the mixing valve. A cold water connection is provided to the cold supply side of the mixing valve. The outgoing tempered side of the mixing valve is connected to the building hot water distribution piping system.

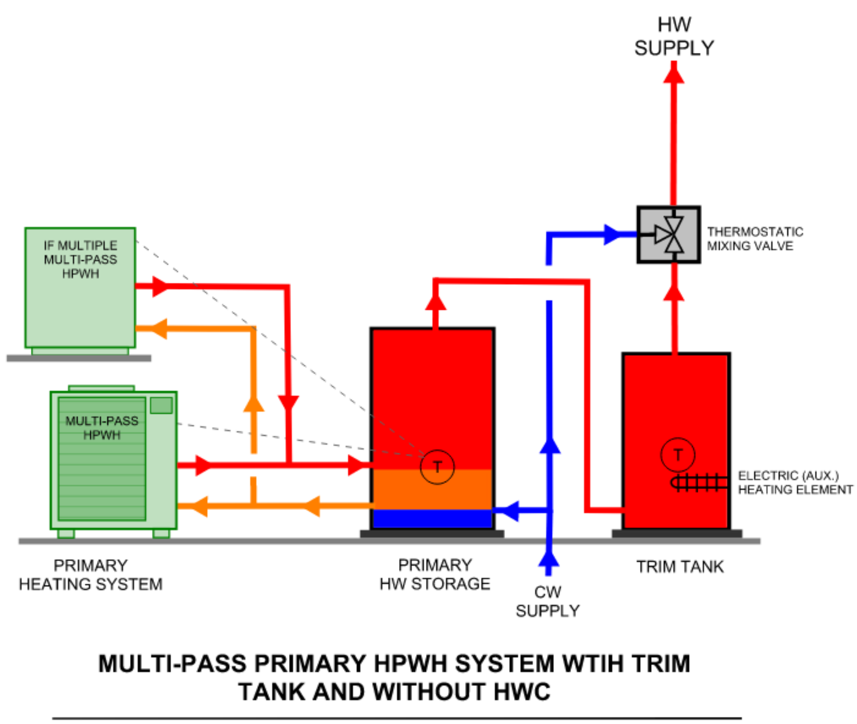
Control: The multi-pass split system HPWH(s) is controlled by a temperature sensor or multiple temperature sensors in the primary storage tank(s). Multiple parallel HPWHs are controlled in a single stage.

System Sizing: The HPWH equipment is sized to meet the domestic hot water load. Multiple HPWHs are specified when a single HPWH equipment cannot meet the load.

Multi-Pass Primary HPWH System with Secondary Electric Resistance Trim Heater Tank and Without Hot Water Circulation

Narrative: This schematic is applicable for use with multi-pass HPWH equipment in combination with a secondary electric resistance trim tank. One or more heat pumps (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system. There is no hot water circulation system present in this system configuration.

Figure 9: Multi-Pass Primary HPWH System with Trim Tank and Without Hot Water Circulation



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the storage tank. Outgoing hot water is connected to the upper portion of the storage tank and passes through a secondary electric resistance trim tank. The multi-pass split system HPWH(s) is connected to draw water from the lower portion of the tank, heat this water about 10°F, and supply it to the middle portion of the storage tank. When multiple storage tanks are specified, the storage tanks are configured in parallel with equal flow through all parallel storage tanks. The outgoing hot water from the storage tank(s) is connected to a secondary electric water heater piped in series. The outgoing hot water connection from the secondary electric resistance heater is connected to the hot supply side of the mixing valve. A cold water connection is provided to the cold supply side of the mixing valve. The outgoing tempered side of the mixing valve is connected to the building hot water distribution piping system.

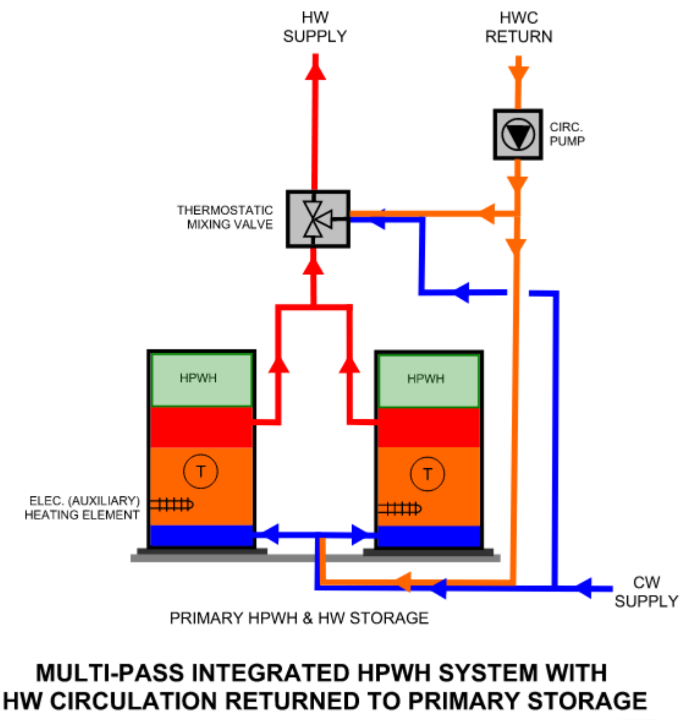
Control: The multi-pass split system HPWH(s) is controlled by a temperature sensor or multiple temperature sensors in the primary storage tank(s). Multiple parallel HPWHs are controlled in a single stage.

System Sizing: The HPWH equipment is sized to meet the domestic hot water load. Multiple HPWHs are specified when a single HPWH equipment cannot meet the load. A secondary electric resistance tank is provided for backup or redundancy and sized to meet the domestic hot water load.

Multi-Pass Integrated HPWH System with Hot Water Circulation

Narrative: This schematic is applicable for use with integrated HPWH equipment. One or more integrated HPWHs (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system. The return water from the hot water circulation system is piped back to the primary heating system.

Figure 10: Multi-Pass Integrated HPWH System with Hot Water Circulation Returned to Primary Storage



Source: California Energy Commission

Piping Configuration: Cold water and return water from the hot water circulation system is supplied to the lower portion of the integrated HPWH equipment. Outgoing hot water is connected to the upper portion of the integrated HPWH equipment. When multiple integrated HPWHs are specified, the incoming cold water and return water from the hot water circulation system is supplied to the HPWH equipment, and outgoing hot water supply from the HWPH equipment is split and configured to supply equal flow to all integrated HPWH units. The outgoing hot water from the integrated HPWH(s) is connected to the hot supply side of the mixing valve. A cold water connection is provided to the cold supply side of the mixing valve. The tempered side of the mixing valve is connected to the building hot water distribution piping system.

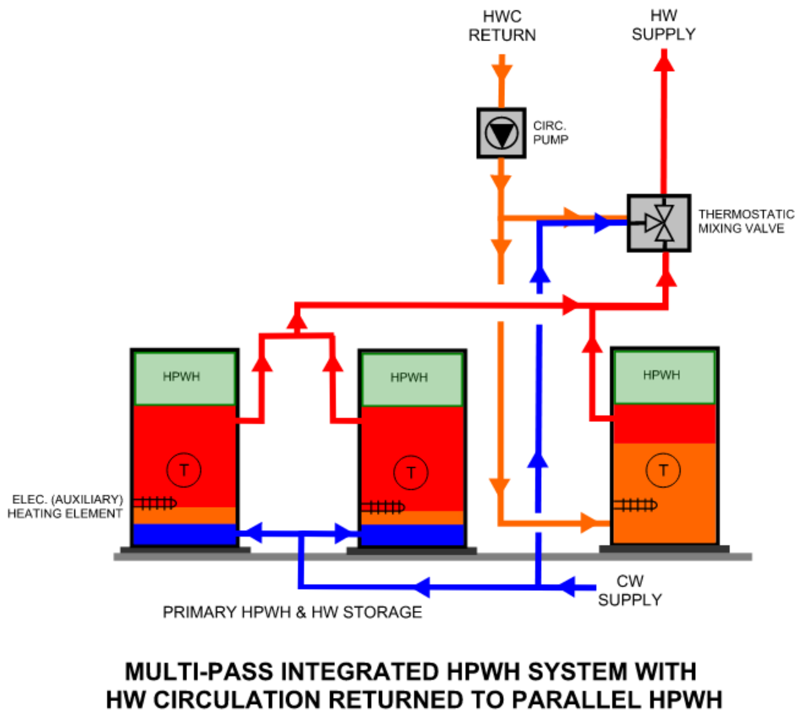
Control: The integrated HPWH equipment is controlled by the internal equipment control system to prioritize compressor heating energy use and minimize auxiliary electric resistance heating energy use.

System Sizing: The integrated HPWH equipment is sized to meet the primary and temperature maintenance domestic hot water loads. Multiple integrated HPWHs are specified when a single integrated HPWH equipment cannot meet the load.

Multi-Pass Integrated HPWH System with Hot Water Circulation Returned to Parallel HPWH

Narrative: This schematic is applicable for use with integrated HPWH equipment serving the primary heating load in combination with a dedicated integrated HPWH in parallel to serve the temperature maintenance hot water circulation load. One or more integrated HPWHs (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A dedicated integrated HPWH is configured in parallel with the primary HPWHs to treat the temperature maintenance load. The return water from the hot water circulation system is fed directly to the dedicated temperature maintenance HPWH. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system.

Figure 11: Multi-Pass Integrated HPWH System with Hot Water Circulation Returned to Parallel HPWH



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the integrated HPWH. Outgoing hot water is connected to the upper portion of the integrated HPWH. When multiple integrated HPWHs are specified to serve the primary heating load, the HPWHs are configured in parallel to supply equal flow rates through all integrated HPWH units. The outgoing hot water from the integrated HPWH(s) is connected to the hot supply side of the mixing valve. A dedicated integrated HPWH is configured in parallel with the primary HPWHs and serves the temperature maintenance load from the hot water circulation system. The two systems are piped together before connecting to the hot supply side of the thermostatic mixing valve. A cold water connection is provided to the cold supply side of the mixing valve. The tempered side of the mixing valve is connected to the building hot water distribution piping system.

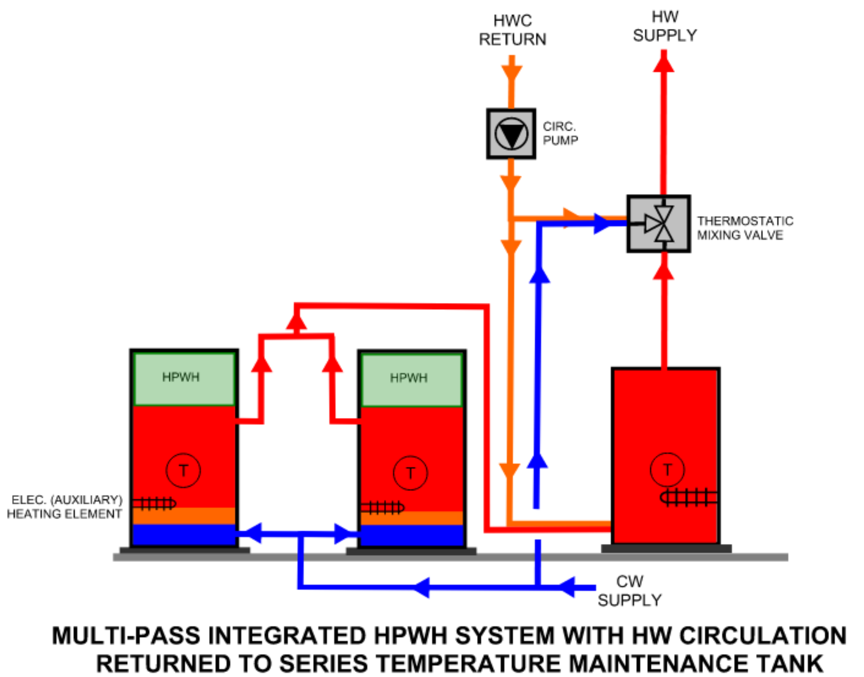
Control: The integrated HPWH equipment is controlled by the internal equipment control system to prioritize compressor heating energy use and minimize auxiliary electric resistance heating energy use.

System Sizing: The integrated HPWH equipment is sized to meet the primary domestic hot water load. A dedicated integrated HPWH is also provided and sized to meet the temperature maintenance hot water circulation load. Multiple integrated HPWHs are specified when a single integrated HPWH equipment cannot meet the load.

Multi-Pass Integrated HPWH System with Hot Water Circulation Returned to Series Temperature Maintenance Tank

Narrative: This schematic is applicable for use with integrated HPWH equipment serving the primary heating load in combination with a dedicated in-series temperature maintenance tank (swing tank) to serve hot water circulation load. One or more integrated HPWHs (compressors) may be specified and are be piped in parallel. When multiple HPWHs are specified, they are piped in parallel. A dedicated electric water heater (swing tank) is configured in series with the primary HPWHs to treat the temperature maintenance load. The return water from the hot water circulation system is fed directly to the dedicated temperature maintenance tank. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system.

Figure 12: Multi-Pass Integrated HPWH System with Hot Water Circulation Returned to Series Temperature Maintenance Tank



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the integrated HPWH equipment. Outgoing hot water is connected to the upper portion of the integrated HPWH equipment. When multiple integrated HPWHs are specified to serve the primary heating load, the HPWHs are configured in parallel to supply equal flow rates through all integrated HPWH units. The outgoing hot water from the integrated HPWH(s) is connected to the bottom of the temperature maintenance tank (swing tank) so that it is in series with the primary system. The hot water outlet of the temperature maintenance tank (swing tank) is connected to the hot supply side of the mixing valve. A cold water connection is provided to the cold supply side of the mixing valve. The tempered side of the mixing valve is connected to the building hot water distribution piping system.

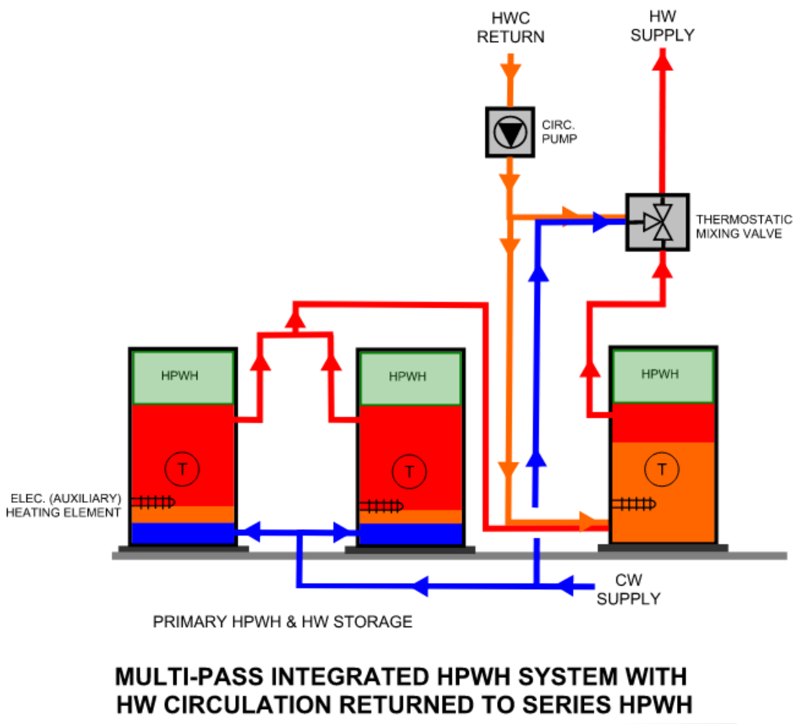
Control: The integrated HPWH equipment is controlled by the internal equipment control system to prioritize compressor heating energy use and minimize auxiliary electric resistance heating energy use. The temperature maintenance tank includes an electric resistance heat element and is controlled by the internal electric water heater control system.

System Sizing: The integrated HPWH equipment is sized to meet the primary and temperature maintenance hot water domestic hot water load. The dedicated in series temperature maintenance tank is sized to meet the hot water circulation load. Multiple integrated HPWHs are specified when a single integrated HPWH equipment cannot meet the load.

Multi-Pass Integrated HPWH System with Hot Water Circulation Returned to Series Integrated HPWH

Narrative: This schematic is applicable for use with integrated HPWH equipment serving the primary heating load in combination with a dedicated in-series integrated HPWH to serve hot water circulation load. One or more integrated HPWHs (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A dedicated integrated HPWH is configured in series with the primary HPWHs to treat the temperature maintenance load. The return water from the hot water circulation system is fed directly to the dedicated temperature maintenance tank. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system.

Figure 13: Multi-Pass Integrated HPWH System with Hot Water Circulation Returned to Series HPWH



Source: California Energy Commission

Piping Configuration: Cold water and return water from the hot water circulation system is supplied to the lower portion of the integrated HPWH equipment. Outgoing hot water is connected to the upper portion of the integrated HPWH equipment. When multiple integrated HPWHs are specified to serve the primary heating load, the HPWHs are configured in parallel to supply equal flow rates through all integrated HPWH units. The outgoing hot water from the integrated HPWH(s) is connected to the bottom of the temperature maintenance HPWH so that it is in series with the primary system. The hot water outlet of the temperature maintenance tank (swing tank) is connected to the hot supply side of the mixing valve. A cold water connection is provided to the cold supply side of the mixing valve. The tempered side of the mixing valve is connected to the building hot water distribution piping system.

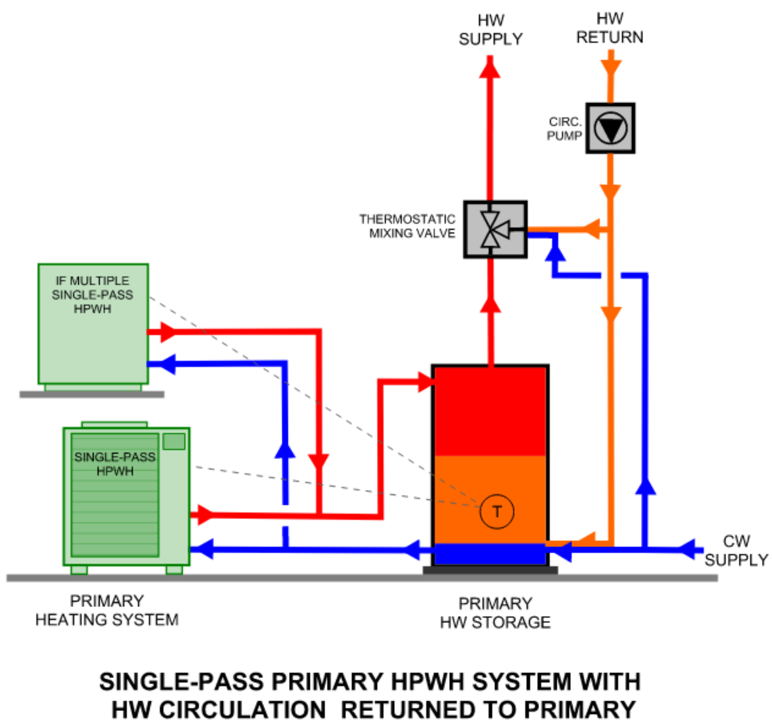
Control: The integrated HPWH equipment is controlled by the internal equipment control system to prioritize compressor heating energy use and minimize auxiliary electric resistance heating energy use. The temperature maintenance integrated HPWH is controlled by the internal HPWH control system.

System Sizing: The integrated HPWH equipment is sized to meet the primary and temperature maintenance hot water domestic hot water load. The dedicated in-series integrated HPWH is sized to meet the hot water circulation load. Multiple integrated HPWHs are specified when a single integrated HPWH equipment cannot meet the load.

Single-Pass HPWH System with Hot Water Circulation Returned to Primary System

Narrative: This schematic is applicable for use with split system single-pass HPWHs. One or more split system single-pass HPWHs (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. The return water from the hot water circulation system is fed back to the primary storage tank(s). A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system.

Figure 14: Single-Pass Primary HPWH System with Hot Water Circulation Returned to Primary



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the primary storage tank(s). The primary single-pass HPWHs pull water from the lower portion of the primary storage tank(s) and supply hot water to the top of the primary storage tank(s). When multiple split system single-pass HPWHs are specified to serve the primary heating load, the HPWHs are configured in parallel. The return water from the hot water circulation system is connected to the bottom of the primary storage tank(s). The hot water outlet of the primary storage tank(s) is connected to the hot supply side of the mixing valve. A cold water connection and hot water circulation connection are provided to the cold supply side of the mixing valve. The tempered side of the mixing valve is connected to the building hot water distribution piping system.

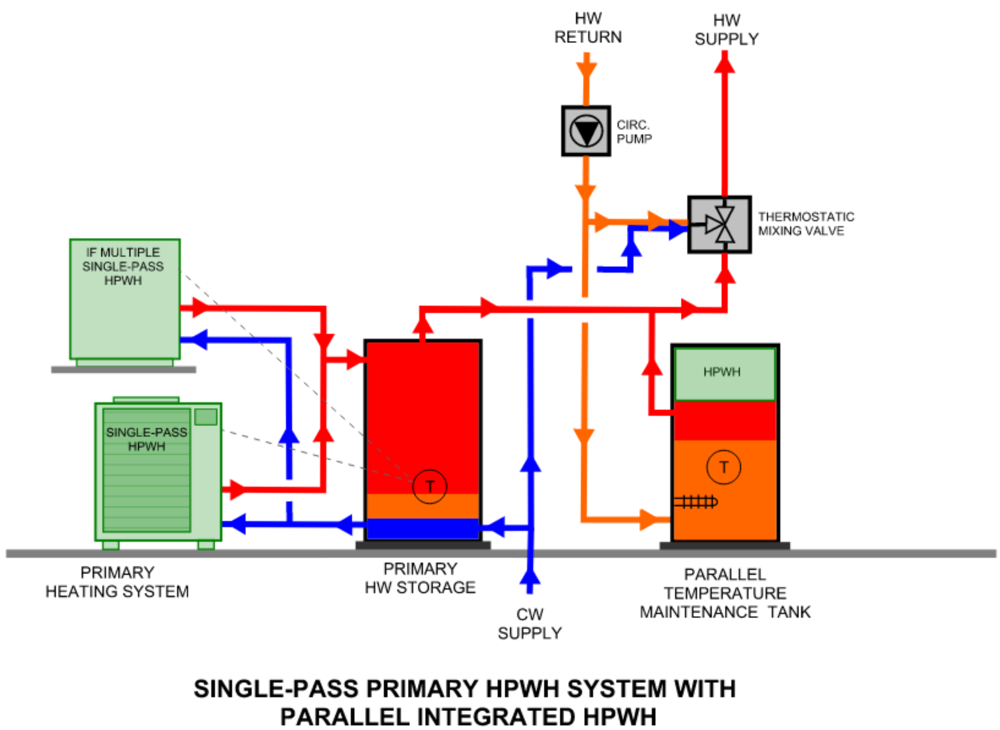
Control: The split-system single-pass HPWH equipment is controlled by the internal equipment control system to prioritize compressor heating energy use.

System Sizing: The split-system single-pass HPWH equipment is sized to meet the primary and temperature maintenance hot water domestic hot water load. Multiple split-system single-pass HPWHs are specified when a single integrated HPWH equipment cannot meet the load.

Single-Pass Primary HPWH System with Parallel Integrated HPWH

Narrative: This schematic is applicable for use with single-pass HPWH in combination with a parallel integrated HPWH for temperature maintenance in the hot water circulation system. One or more heat pumps (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system.

Figure 15: Single-Pass Primary HPWH With Parallel Integrated HPWH



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the storage tank. Outgoing hot water is connected to the upper portion of the storage tank and connects to the hot supply side of the thermostatic mixing valve. The single-pass split-system HPWH(s) is connected to draw water from the lower portion of the tank, heat this water to temperature, and supply it to the upper portion of the storage tank. When multiple storage tanks are specified, the storage tanks are configured in series with the top of the first tank connected to the bottom of the second tank. This top-to-bottom connection is repeated for all storage tanks in the series. The cold water is supplied to the lower portion of the first tank, and the outgoing hot water is supplied from the upper portion of the last storage tank in series. The outgoing hot water from the storage tank (or last storage tank in series) is connected to the hot supply side of the thermostatic mixing valve. An integrated HPWH is provided for temperature maintenance to keep the hot water circulation system at the set temperature. The return water from the hot water circulation system is connected to the lower portion of the integrated HPWH. The outlet of the integrated HPWH is connected in parallel with the hot outlet from the hot water storage tank. These two water paths combine before connecting to the hot-supply side of the thermostatic mixing valve. A cold water connection and the return water from the hot water circulation system are provided to the cold-supply side of the mixing valve. The outgoing tempered side of the mixing valve is connected to the building hot water distribution piping system.

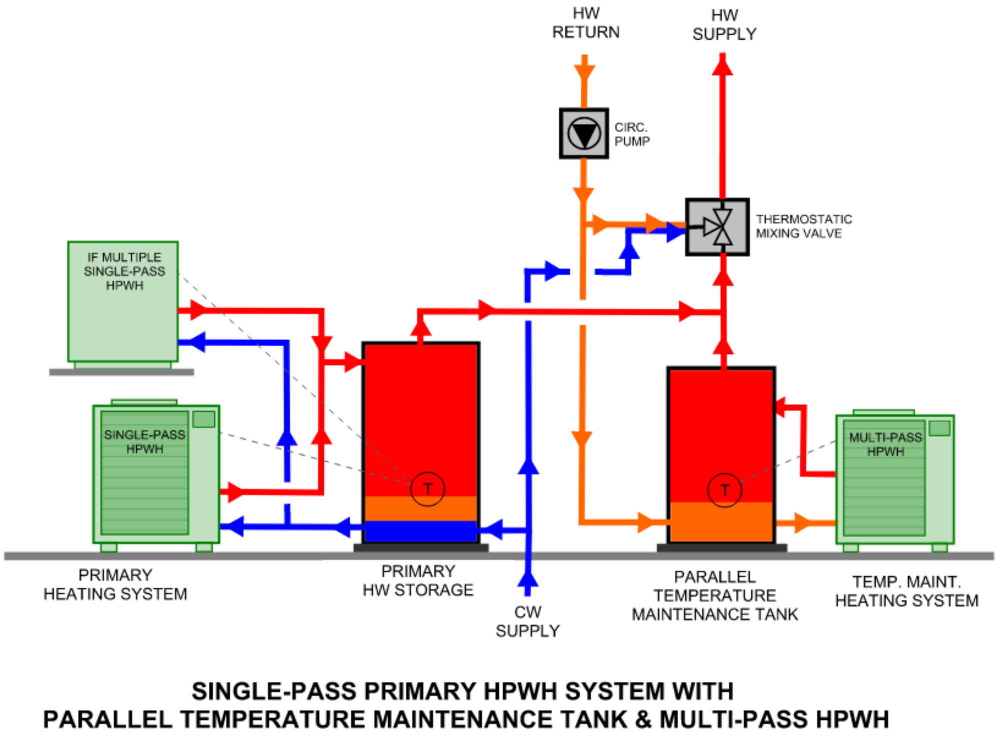
Control: The single-pass split-system HPWH(s) is controlled by a temperature sensor or multiple temperature sensors in the primary storage tank(s). Multiple parallel HPWHs are controlled in a single stage. The integrated HPWH that is part of the temperature maintenance system is controlled independently of the primary single-pass HPWH(s).

System Sizing: The HPWH equipment is sized to meet the primary domestic hot water load. Multiple HPWHs are specified when a single HPWH cannot meet the load. An integrated HPWH is sized to meet the temperature maintenance load associated with the hot water circulation system.

Single-Pass Primary HPWH System with Parallel Multi-Pass HPWH

Narrative: This schematic is applicable for use with single-pass HPWHs in combination with a parallel temperature maintenance system with multi-pass HPWH. One or more primary HPWHs (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A dedicated temperature maintenance system is provided to serve the hot water circulation load and is configured in parallel with the primary heating system. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system.

Figure 16: Single-Pass Primary HPWH with Parallel Temperature Maintenance Tanke and Multi-Pass HPWH



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the primary storage tank(s). Outgoing hot water is connected to the upper portion of the storage tank and to the hot-supply side of the thermostatic mixing valve. The single-pass split-system HPWH(s) is connected to draw water from the lower portion of the tank, heat this water to temperature, and supply it to the upper portion of the storage tank. A dedicated storage tank and multi-pass HPWH are provided and serve the hot water circulation temperature maintenance load. This system is configured in parallel with the primary heating system. The return water from the hot water circulation system is connected to the lower portion of the temperature maintenance storage tank. A multi-pass HPWH is connected to the dedicated temperature maintenance storage tank to provide heat to the system. The outlet of the temperature maintenance storage tank is connected in parallel with the hot outlet from the hot water storage tank so that these two water paths combine before connecting to the hot-supply side of the thermostatic mixing valve. A cold water connection and the return water from the hot water circulation system are provided to the cold supply side of the mixing valve. The outgoing tempered side of the mixing valve is connected to the building hot water distribution piping system.

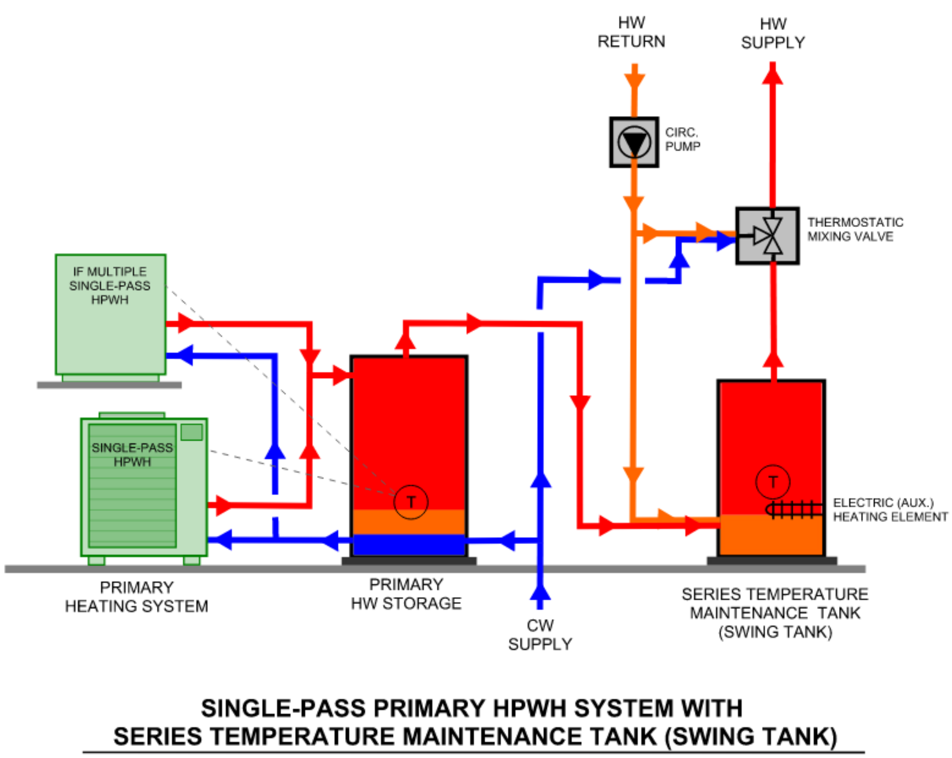
Control: The single-pass split-system HPWH(s) is controlled by a temperature sensor or multiple temperature sensors in the primary storage tank(s). Multiple parallel HPWHs are controlled in a single stage. The multi-pass HPWH that is part of the temperature maintenance system is controlled independently of the primary single-pass HPWH(s).

System Sizing: The HPWH is sized to meet the primary domestic hot water load. Multiple HPWHs are specified when a single HPWH cannot meet the load. The multi-pass HPWH is sized to meet the temperature maintenance load associated with the hot water circulation system.

Single-Pass Primary HPWH System with Series Temperature Maintenance Tank

Narrative: This configuration is used for the standard design system. This schematic is applicable for use with single-pass HPWH serving the primary heating load in combination with a dedicated in-series temperature maintenance tank (swing tank) to serve hot water circulation load. One or more single-pass HPWHs (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. A dedicated temperature maintenance tank (swing tank) is configured in series with the primary HPWHs to treat the temperature maintenance load. The return water from the hot water circulation system is fed directly to the dedicated temperature maintenance tank. A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system.

Figure 17: Single-Pass Primary HPWH with Series Temperature Maintenance Tank (Swing Tank)



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the primary storage tank(s). Outgoing hot water is connected to the upper portion of the primary storage tank(s). When multiple single-pass HPWHs is specified to serve the primary heating load, the HPWHs are configured in parallel. The single-pass split-system HPWH(s) are connected to draw water from the lower portion of the tank, heat this water to temperature, and supply it to the upper portion of the storage tank. A dedicated temperature maintenance tank is provided. The outgoing hot water from the primary storage is connected to the bottom of the temperature maintenance tank (swing tank) so that it is in series with the primary system. The hot water outlet of the temperature maintenance tank (swing tank) is connected to the hot supply side of the mixing valve. A cold water connection is provided to the cold-supply side of the mixing valve. The tempered side of the mixing valve is connected to the building hot water distribution piping system.

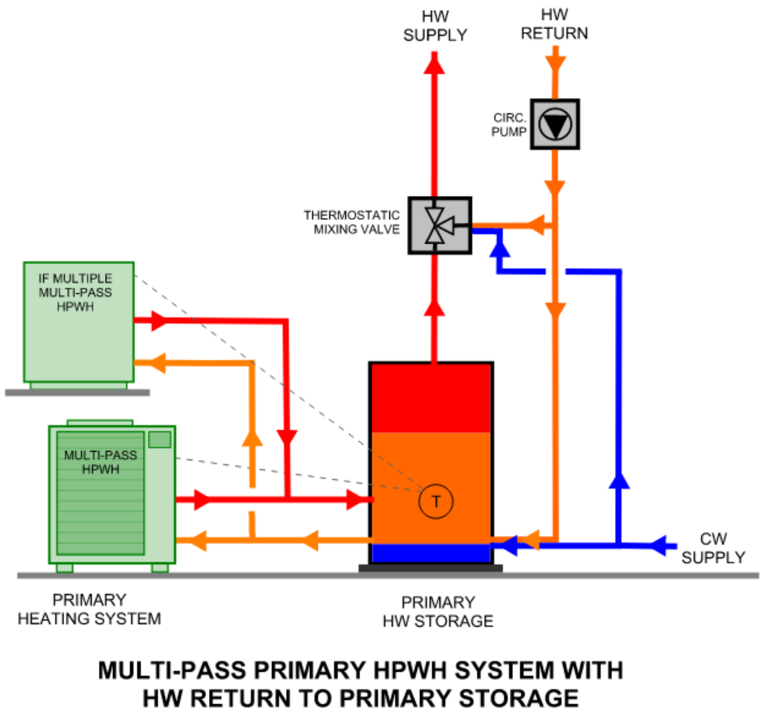
Control: The single-pass HPWH equipment is controlled by the internal equipment control system to prioritize compressor heating energy use and minimize auxiliary electric resistance heating energy use. The temperature maintenance tank includes an electric resistance heat element and is controlled by the internal electric water heater control system.

System Sizing: The single-pass HPWH equipment is sized to meet the primary and temperature maintenance hot water domestic hot water load. The dedicated in-series temperature maintenance tank is sized to meet the hot water circulation load. Multiple single-pass primary HPWHs are specified when a single HPWH cannot meet the load.

Multi-Pass HPWH System with Hot Water Circulation Returned to Primary System

Narrative: This schematic is applicable for use with split-system multi-pass HPWH equipment. One or more multi-pass HPWHs (compressors) may be specified. When multiple HPWHs are specified, they are piped in parallel. The return water from the hot water circulation system is fed back to the primary storage tank(s). A thermostatic mixing valve is provided to temper the hot water supplied to the building hot water distribution system.

Figure 18: Multi-Pass Primary HPWH System with Hot Water Return to Primary Storage



Source: California Energy Commission

Piping Configuration: Cold water is supplied to the lower portion of the primary storage tank(s). The primary multi-pass HPWHs pull water from the lower portion of the primary storage tank(s) and supply hot water to the middle portion of the primary storage tank(s). When multiple multi-pass HPWHs are specified to serve the primary and temperature maintenance heating loads, the HPWHs are configured in parallel. The return water from the hot water circulation system is connected to the bottom of the primary storage tank(s). The hot water outlet of the primary storage tank(s) is connected to the hot supply side of the mixing valve. A cold water connection and hot water circulation connection are provided to the cold supply side of the mixing valve. The tempered side of the mixing valve is connected to the building hot water distribution piping system.

Control: The split-system single-pass HPWH is controlled by the internal equipment control system to prioritize compressor heating energy use.

System Sizing: The split-system multi-pass HPWH is sized to meet the primary and temperature maintenance hot water domestic hot water load. Multiple split-system multi-pass HPWHs are specified when a single integrated HPWH equipment cannot meet the load.

APPENDIX C: PHOTOVOLTAICS

Photovoltaics

Compliance software shall calculate energy generated by photovoltaic (PV) systems on an hourly basis using the National Renewable Energy Laboratory (NREL) System Advisor Model (SAM) algorithms upon which the PVWatts program is based (see Appendix F), or using a similar calculation method approved by the Energy Commission. PV systems with and without sub-array power electronics (i.e., microinverters and DC power optimizers) are further considered based on user inputs. Appendix C describes calculations and assumptions used in the California Building Energy Code Compliance (CBECC) and CBECC-Res compliance managers.

Power electronics are used to help minimize efficiency losses when the output of sub-array components (e.g., modules or cells) operate under different conditions. The largest driver of variation in conditions across a PV array is partial shading from nearby obstacles. A small fraction of shaded cells could lead to disproportionate reductions in PV power output. PVWatts, does not explicitly handle this effect. Literature describes a shading impact factor (SIF) which is the ratio of relative power output to fraction shaded:

$$P_{sh} = P_{sys} \cdot (1\text{-}SIF \cdot f_{sh})$$

Where P_{sh} is the power output of the shaded system, P_{sys} is the power output of the unshaded system, and f_{sh} is the fraction shaded.

A value of 1.0 implies that the power output declines proportionally to the fraction shaded. This is a theoretical minimum value of SIF in that it implies there are power electronics that are maintaining output consistent with the level of shading across the module. A value greater than 1.0 implies that shading has a disproportionate effect on system output.

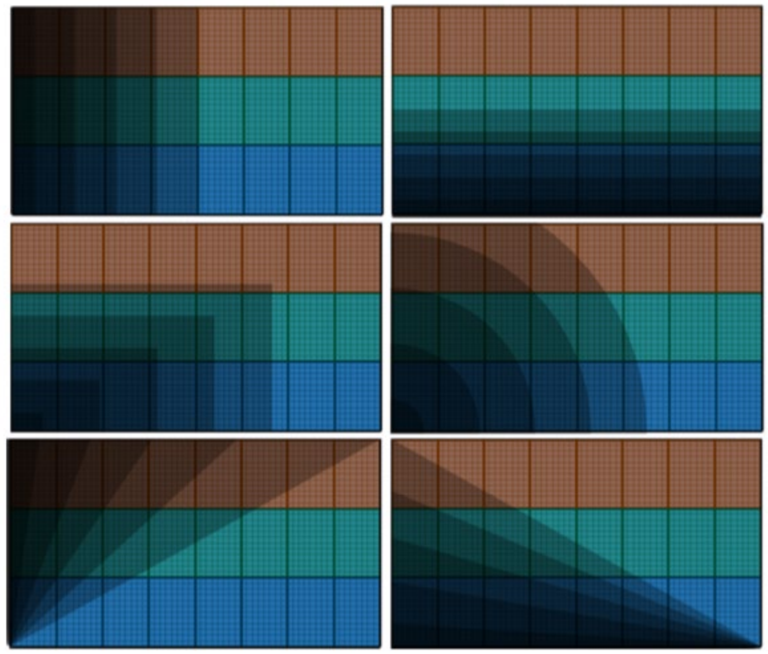
How the individual cells within an array are shaded can have a significant impact on SIF. This is illustrated in a study on a PV module without power electronics (see

Figure C-1).

In this study the same module was shaded in different fashions (see Figure C-2). For a given shade ratio, the actual output from the PV system can differ by 30 percent depending on which portions of the system are shaded (Note: the dotted lines in the first figure represent SIF values of 1.0 [$y = 1 - 1.0*x$] and 2.0 [$y = 1 - 2.0*x$] and serve as approximate bounds on the impact). Without cell-level fidelity in our shading model, it is impossible to know which specific cells are shaded at any given time. The compliance software will use a coarse approximation of SIF appropriate for panel and/or array level analysis.

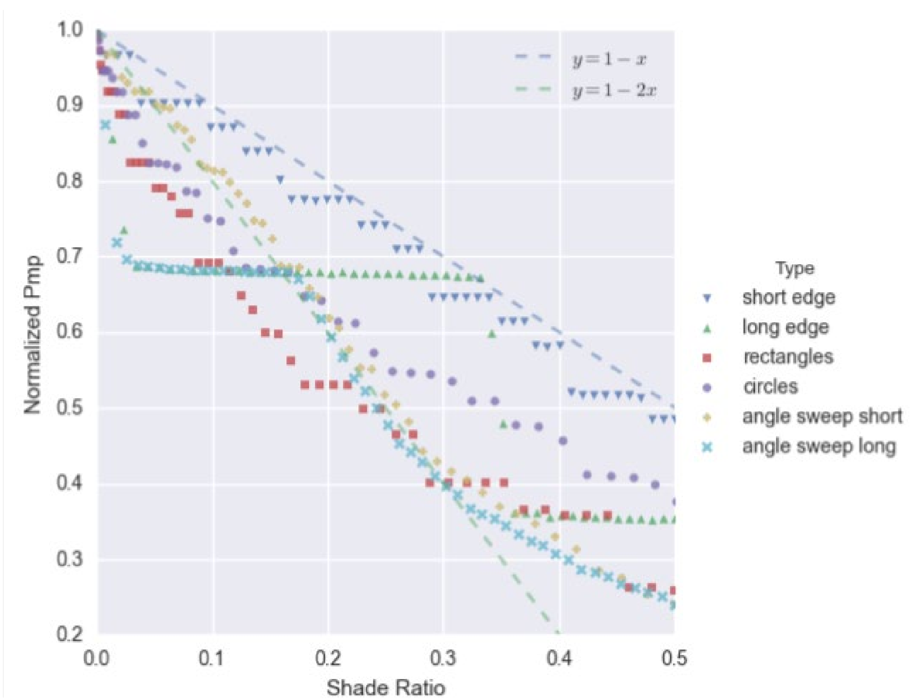
SIF should also change with higher levels of irradiance as shown in this study (see Table C-2). However, considering the coarseness of array-wide shading fraction (vs. cell-by-cell), accounting for this effect is not likely to provide a substantial increase in overall accuracy.

FIGURE C-1



Source: California Energy Commission

FIGURE C-2



Source: California Energy Commission

One problem with applying shading impact factors directly to the power output of the system is that there is a theoretical lower limit to PV production under shaded conditions: diffuse irradiance. Unless a cell is also blocked from diffuse solar (e.g., the shade is very close to the panel and blocking cells from the rest of the sky), all cells will receive a minimum level of incidence. To account for this, we propose introducing an alternative formulation using an “effective” plane-of-array incidence, where only the beam component is affected by shading.

$I_{poa,eff} = I_{poa,diff} + I_{poa,beam,eff}$

$I_{poa,beam,eff} = \max(I_{poa,beam} * (1 - SIF * f_{sh}), 0.0)$

The compliance software shall use an SIF value of 2.0 for central inverters (CEC default) and a value of 1.2 for systems with power electronics (based on a 40 percent shade loss recovery as defined in this paper--see Table C-2. SIF for Total Inverter Efficiency).

System Loss Assumptions

In PVWatts, a single derating factor is used to cover a variety of system inefficiencies. The compliance software uses slightly different assumptions for this derating factor as described in the table below:

TABLE C-1. DERATING FACTOR

Loss Type	Value	Differences from PVWatts Default Assumptions
Soiling	0.02	N/A
Shading	0.0	Modeled explicitly
Snow	0.0	N/A
Mismatch	0.0	Mismatch from shading is characterized using SIF
Wiring	0.02	N/A
Connections	0.005	N/A
Light-induced degradation	0.015	N/A
Nameplate rating	0.01	N/A
Age	0.05	Estimated 0.5 percent degradation over 20 years based on these references: [1, 2, 3]
Availability	0.03	N/A
Total	0.14	N/A

Source: California Energy Commission

Inverter Efficiency

The software shall characterize the inverter efficiency corresponding to either a central inverter or microinverters depending on the type of power electronics used in the system.

Power Electronics

Options for power electronics are described below:

TABLE C-2. SIF FOR TOTAL INVERTER EFFICIENCY

Option	SIF	Total Inverter Efficiency
None	2.0	User input
Microinverters	1.2	User input
DC Power Optimizers	1.2	Optimizer efficiency * user input

Source: California Energy Commission

Optimizer efficiencies are assumed to be 0.99 (corresponding to suggestions in this document).

Space Function to PV/Battery Building Type Mapping

The software shall determine the size of the building PV and battery system based on the PV Capacity Factors and Battery Storage Capacity Factors from Energy Code Tables 140.10-A/170.2-U and 140.10-B/170.2-V. The PV Capacity Factors identify the capacity of a PV system based on the climate zone, building type, and conditioned floor area. The Battery Storage Capacity Factors identify the Energy Capacity or Power Capacity based on the building type and PV capacity. The default mapping of space function to PV capacity factor building type is in Appendix 5.4A. Default PV/Battery Building Type is editable so that users may adjust factors to match the proposed building type, or multiple building types when one or more are in the proposed building, according to definitions and requirements in the Energy Code.

Battery Storage

See Status of Modeling Batteries for California Residential Code Compliance, Appendix D.

APPENDIX D – STATUS OF MODELING BATTERIES FOR CALIFORNIA SINGLE-FAMILY AND MULTIFAMILY RESIDENTIAL CODE COMPLIANCE

D1 Modeling of Residential Battery/PV Systems for Self-Utilization Compliance Credit

Overview

The California Energy Commission added a self-utilization credit for residential battery systems to its residential building energy efficiency standards for 2019. Under these standards, a residential battery paired with an on-site photovoltaic (PV) system would receive fair credit toward the long-term system cost (LSC) energy. This document defines how the CBECC-Res compliance software will produce the battery credit for single-family residential buildings, and how compliance software will produce the battery calculations within the compliance framework for multifamily residential buildings.

Whereas most energy upgrades reduce energy use in a house or multifamily building, battery systems actually increase electricity consumption in exchange for some shaping of the load. A 14-kWh battery, with a 90% round-trip efficiency, that cycles 13 of those kWh 300 times a year, will consume 4.1 MWh of electricity and discharge 3.7 MWh of electricity per annum. But by charging when there is excess PV production and discharging when PV production is low and electricity is expensive, the battery both saves money for the residence and provides value to the electricity system overall. Thus, the single-family and multifamily self-utilization credit must account not for energy savings, but for savings in value-of-energy.

Distributed electric storage can provide value to the electricity system overall through load shaping and other behaviors. Bolstering demand during low periods helps to leave efficient power plants running full time and reduces ramping requirements. Reducing peak demand helps in a number of ways, including by allowing expensive peaker plants to remain idle more days of the year. In addition, having the batteries on-site can help reduce wear-and-tear on distribution systems.

D2 Long-term System Cost (LSC) and Source Energy

The 2025 Building Energy Efficiency Standards use LSC energy to account for the time value of energy for load and for self-generation credit. LSC is a composite measure of the actual cost of energy (for each of electricity, natural gas, and propane) to the utility, customers, and society at large. It has been crafted for evaluating energy efficiency savings based on when those savings manifest.

The LSC concept allows even-footing comparison of a set of time-series simulations of how different building designs use energy. Accordingly, it is the mechanism by which the CBECC-Res (for single-family residential) and compliance software for multifamily residential converts a residential battery's load shaping patterns into a self-utilization credit. If a building charges a battery from on-site PV during midday, the simulation foregoes a small LSC credit for power it would have fed to the grid. When the battery discharges in the evening, it can earn a much larger credit for reducing load when LSC is high. That net-LSC reduction counts toward reducing the single-family residential or the multifamily residential building's performance with respect to the compliance margin.

The 2025 Building Energy Efficiency Standards also useSource Energy factors to determine compliance for single-family residential and multifamily residential buildings.

D3 Calculating Compliance

For single-family residential buildings, CBECC-Res calculates compliance for a proposed design based on LSC energy, and Source Energy.

Compliance for a proposed design in CBECC-Res and compliance software for multifamily residential has three requirements:

1. The LSC, ignoring contributions from renewable generation and battery storage (except for the self-utilization credit described below), must be equal or lower than the LSC of the code prescriptive standard design (also ignoring contributions from renewable generation and battery storage). These values are called the Efficiency LSC for the respective proposed and standard designs. The intent of this requirement is to encourage designs that reduce loads in addition to generating energy.
2. The LSC of the final design (including contributions from renewable generation and battery storage) must be equal or lower than the LSC of the code prescriptive standard design (also including contributions from renewable generation and battery storage). These values are called the Total LSC for the respective proposed and standard designs.
3. The Source Energy of the proposed design must be equal or lower than the Source Energy of the standard design.

A minimum of six annual calculations are required to evaluate the compliance of a specific proposed design:

1. Proposed design the Efficiency LSC
2. Proposed design the Total LSC
3. Proposed design Source Energy
4. Standard design the Efficiency LSC
5. Standard design the Total LSC
6. Standard design Source Energy

The specific computations that produce these values are described in the Nonresidential and Multifamily Alternative Compliance Method (ACM) Reference Manual. The standard design is also described in the ACM.

Self-Utilization Credit

Initially implemented in the 2019 energy code, the self-utilization credit for a residential battery system allows proposed designs with PV systems and batteries (5 kWh or larger) to subtract additional LSC from the Efficiency LSC of the proposed design. The self-utilization credit is capped at a fraction of the PV-related LSC of the standard design. The cap varies by climate zone and is between 7% and 14% for a single-family residence and between 2% and 9% for a multi-family building.

The actual credit applied to the Efficiency LSC of the proposed design is the lesser of the battery related LSC in the final proposed design and the cap defined above. Effectively, the self-utilization credit allows the proposed the Efficiency LSC design to also get credit for a portion of the LSC savings that would otherwise be seen only in the final design.

D4 Compliance Software Requirements

Appendix JA12 provides the qualification requirements for energy storage systems.

Compliance software for multifamily buildings must consider usable capacity when determining the effect of energy storage on multifamily building performance. Usable capacity is the energy storage capacity in kWh that a manufacturer allows to be used for charging and discharging. For performance compliance, the usable capacity must be a minimum of 5 kWh.

Compliance software for multifamily buildings must model the time of use strategy and controls for separate energy storage systems as described in Appendix JA12. Software may also model the basic control strategies as described in Appendix JA12.

D5 CBECC-Res, CBECC and California Simulation Engine (CSE) Software Packages

Annual building loads used in the annual LSC calculation for single-family buildings in CBECC-Res and for multifamily buildings in CBECC are simulated using the underlying California Simulation Engine (CSE). CSE models the thermal and electrical interactions within a building. CBECC-Res and CBECC generates CSE input files based on the Title 24 rulesets. Separate CSE inputs files are created to simulate the standard design, and proposed design. For single-family buildings, CBECC-Res then processes the CSE simulation results to determine the Efficiency LSC, the Total LSC, and the Source Energy values as described in the previous section. Similarly for multifamily buildings, CBECC processes the CSE simulation results to determine the Efficiency LSC, the Total LSC, and the Source Energy values described in the previous section.

While the capability of CBECC-Res and CBECC are intentionally constrained by ruleset definitions, CSE has much greater flexibility to simulate a wide range of building components. CSE has the unique capability to define dynamic battery system control strategy using its built-in expression language. CSE predicts the building load and PV generation and operates the battery according to expressions pre-defined by CBECC-Res and CBECC rules.

D6 Battery Representation in CSE

In each simulated timestep, the control strategy sends a charge/discharge request to the battery module. The control strategies themselves are described in the next section. For now, it will suffice to say that the input to the battery module is a charge request (in kW) that can be either positive or negative.

```
charge_request > 0   // charge
charge_request < 0   // discharge
charge_request = 0   // do nothing
```

The battery has maximum charge and discharge rates (kW) with default values set based on the battery's size. CBECC-Res and CBECC define both defaults as the same fixed fraction (kW/kWh) of the battery's user-defined maximum capacity (kWh). The maximum capacity is based on the compliance cycling capacity in the case of single-family buildings, or the usable capacity in the case of multifamily buildings. These default values may be overridden with custom values by the user.

```
max_charge_power = 0.42 * max_capacity
max_discharge_power = 0.42 * max_capacity
```

And both a charge and discharge efficiency (fraction), which are user-defined:

```
η_charge
η_discharge
```

The user has the option to input a round-trip efficiency (fraction) as an alternative to inputting both the charge and discharge efficiencies. In this case, the charge and discharge efficiency would be equal to:

```
η_charge = sqrt(η_rte)
η_discharge = sqrt(η_rte)
```

At each timestep, there are also maximum charge and discharge limits (kW) defined by the state of charge on the battery. Charge and discharge power levels are measured at the battery's edge: before efficiency losses in the case of charging and after efficiency losses in the case of discharging. The battery's state-of-charge is metered between the two efficiency multipliers.

```
max_charge_available = (max_capacity - charge_level) /
                        η_charge * (timestep_minutes / 60)
max_discharge_available = charge_level * η_discharge *
                        (timestep_minutes / 60)
```

Altogether, that enables the module to determine the amount the battery should charge or discharge in the hour:

```
if charge_request > 0:
        charge_power = min(charge_request, max_charge_rate,
        max_charge_available)
else if charge_request < 0:
        charge_power = max(charge_request, max_discharge_rate,
        max_discharge_available)
else:
        charge_power = 0
```

At the conclusion of that timestep, the battery's charge level will have been updated:

```
if charge_power > 0:  // charging
        charge_level = charge_level + charge_power*η_charge
else if charge_power < 0  // discharging
        charge_level = charge_level + charge_power/η_discharge
else:
        charge_level = charge_level
```

D7 Battery Control Strategies in CSE

There are two battery control strategies enabled in CBECC-Res and CBECC: "Basic" and "Time of Use" (TOU). These strategies are responsible for the timestep-by-timestep charge requests that are sent to the CSE battery module.

Basic Strategy

The Basic strategy charges when a) production exceeds demand and b) the battery is not fully charged and discharges when a) demand exceeds production and b) the battery is not fully drained. That is, the battery both charges and discharges as soon as it can.

```
charge_request = -load_seen
```

By charging from any excess production and discharging as soon as it can to serve load, the basic strategy maximizes self-consumption of the on-site PV production. The other strategies account for the time-varying value of electricity (e.g., as measured by LSC) to varying degrees to increase the LSC-savings the battery provides.

If the battery system is standalone (no PV system), then basic control is not an available control option.

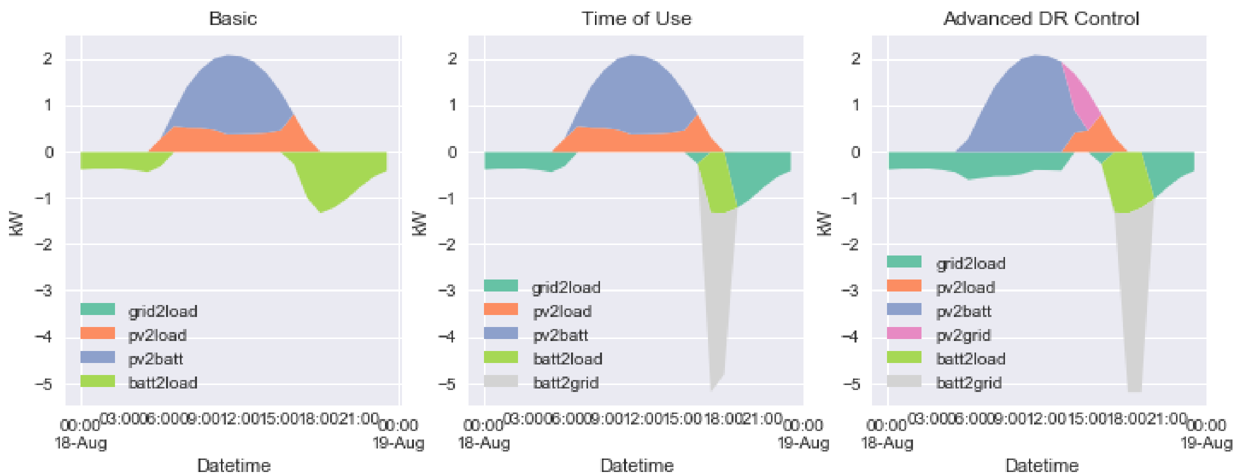


Figure 2: Illustrations of the battery control strategies' different responses to a single day. Note that the TOU and Advanced strategies can discharge directly to the grid. Also notice that Advanced charges the battery from PV while serving loads from the grid.

Time of Use Strategy

The TOU strategy attempts to preferentially discharge during high-value hours during a selected period of months. For a PV-tied system, the default duration for TOU months is July through September. For a standalone battery storage system, the default duration for TOU months is all year. Users can optionally input custom values for the first and last months to apply TOU control.

Charging rules are the same as the basic strategy for battery storage systems paired with a solar PV system. For standalone battery storage systems, the software provides a prescribed input to specify the hour of each day to start charging called "Charge Start Hour". The charging starts at midnight (hour 1) of each day.

Battery discharge follows the same approach for PV-tied and standalone batteries. The discharge period is statically defined (per climate zone) by the first hour of the expected TOU peak, which is a user-input within CBECC-Res and CBECC called "Discharge Start Hour." The default value for "Discharge Start Hour" is 19:00 for Climate Zones 2, 4, 8-15, and 20:00 for all other Climate Zones. The user has the option to change this value within CBECC-Res and CBECC if desired.

Consider a summer day in which the evening peak is defined to start at 20:00 but during which simulation load exceeds PV production during the 19:00 hour. While a simulation utilizing the Basic strategy would discharge to neutralize the net load during the 19:00 hour, a simulation on the TOU strategy would reserve the battery until 20:00 before commencing discharge. Because the LSC at 20:00 is likely to be higher than the LSC at 19:00, this strategy of reserving the battery for higher-value hours results in a lower (better) annual LSC.

A second difference: During the peak window, the battery is permitted to discharge at full power, even exceeding the site's net load. This is in contrast to the Basic strategy, which is limited to the net load.

```
if charge_start_hour <= this_hour < discharge_start_hour:
        charge_request = -min(load_seen, 0)   // only charge
else:
        charge_request = -1000   //  maximum discharge
```

Outside of selected months for the TOU strategy, control reverts to the Basic strategy.

Battery Parameters Included in CBECC-Res/CBECC/CSE

CBECC-Res and CBECC allow the modeler to adjust several battery parameters (Figure 4):

- Compliance cycling capacity/usable capacity(kWh): the CBECC-Res and CBECC software enforce a 5kW minimum size for the battery to qualify for the Self Utilization Credit.
- A checkbox to indicate if a standalone battery (no PV system) is modeled.
- Control strategy, chosen from the three options described in the Battery Control Strategies section of this appendix.
    - Note that "Basic" control is not an available control option for standalone battery systems

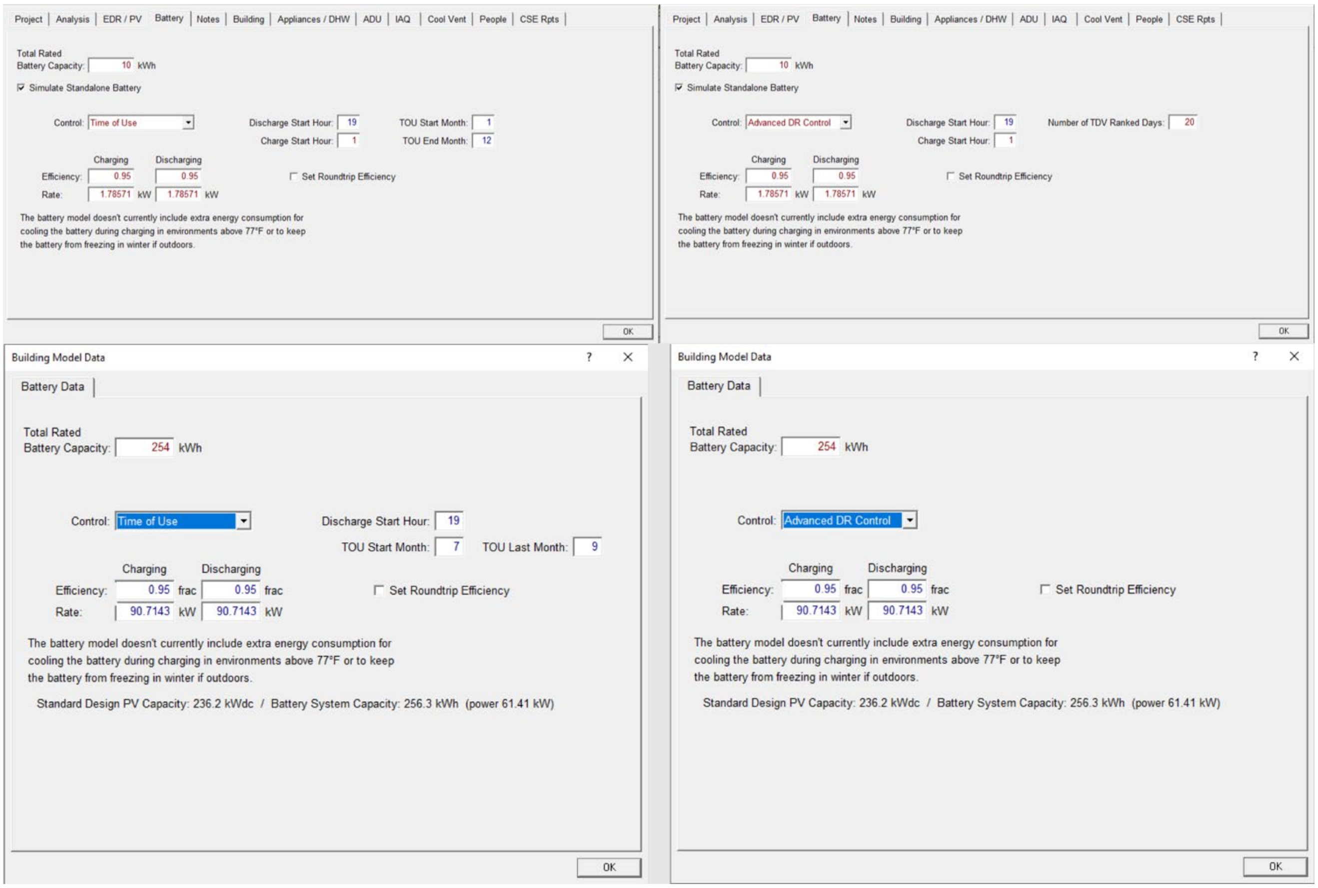


Figure 4: The CBECC-Res (top) and CBECC (bottom) battery dialog box allows the modeler to set battery capacity, control strategy, charge/discharge efficiencies, and other control parameters related to charging and discharging hours and TOU months. Example images are shown for the TOU and Advanced DR Control options.
(Source: screenshot of CBECC-Res and CBECC software user interface.)

- Charging and discharging efficiency (fraction): CSE allows charging and discharging efficiencies to be defined independently. The CBECC-Res and CBECC default is 0.95 for each, resulting in a default round-trip efficiency of 0.9025.
    - A single input for round-trip efficiency may be input by selecting the checkbox "Set Roundtrip Efficiency" (as shown in Figure 4). When checked, the inputs for charge and discharge efficiency are hidden and only the round-trip efficiency input is shown. Round-trip efficiency inputs less than 80% will result in no battery included in the simulation.
- Charge start hour may be input for standalone battery systems. Discharge start hour may be input for standalone and PV-tied battery systems. Allowable inputs are integers between 1 and 24 (inclusive).

- TOU period start and end months may be input. Allowable inputs are integers between 1 and 12 (inclusive).

CBECC-Res and CBECC also makes a set of assumptions to set CSE battery parameters. These are parameters that can be set in the lower-level CSE but that CBECC-Res and CBECC define itself.

- CBECC-Res and CBECC assume that the input battery capacity is the capacity of a brand new system. To account for aging across the battery's life cycle, the software derates the effective battery compliance cycling capacity for single family buildings, or the usable capacity for multifamily buildings to 85% of the input battery capacity. A nominal 10 kWh battery gets 8.5 kWh of usable capacity in the simulation.
- The 85%-of-input-capacity figure interrelates with the fact that battery systems often have different published values for total and usable capacity. The battery management system prevents complete discharges, so the usable capacity is typically single-digit percentages lower than the total capacity (e.g., the Powerwall 2 has 14 kWh total and 13.5 kWh available energy). CBECC-Res and CBECC should clarify whether the input capacity should be total or useful, and the degradation derate figure should be consistent with the input CBECC-Res and CBECC expect.
- CBECC-Res and CBECC derive the CSE parameters Maximum charge rate and Maximum discharge rate (kW/hr) from the battery capacity. They are each defined to be battery capacity * 0.42. That is, the battery is sized to have 2.38 hours of storage at full discharge. (1/0.42 = 2.38). That ratio is likely derived from the 14 kWh capacity and 5 kW discharge power of the Powerwall 2: 14 * 0.85 / 5 = 2.38.
- The battery is assumed to start the simulation fully discharged. It is not required to be fully charged at the conclusion of the simulation.
- Battery-PV installations come in a range of electrical configurations, sometimes with independent inverters for each component (AC-coupled), sometimes sharing an inverter (DC-coupled). CSE assumes an AC-battery-module electrical configuration as shown in Figure 5. The modeling implication of that configuration is that the user-input battery charge and discharge efficiencies should include the losses associated with the battery module's onboard inverter. In CSE, the PV system always has a dedicated PV inverter.

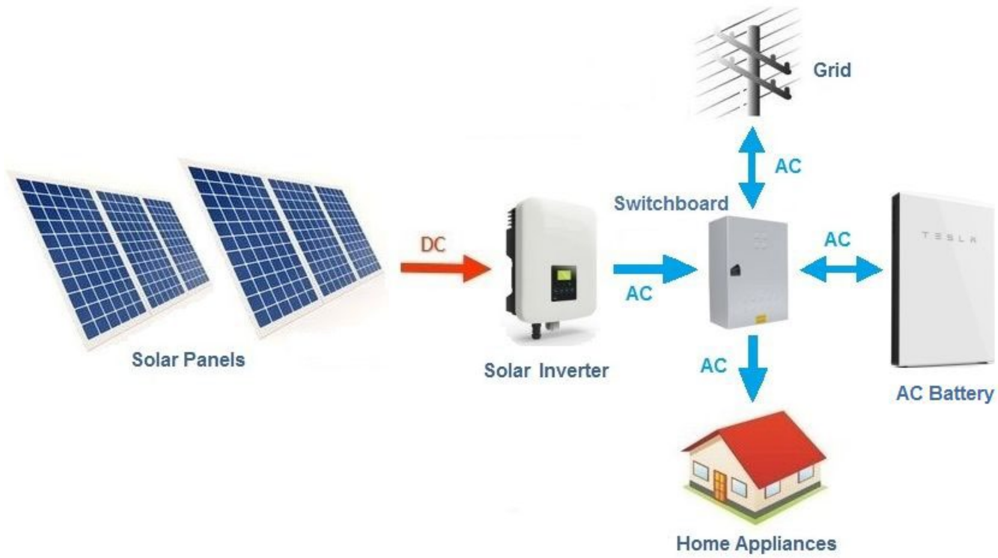


Figure 5: *General diagram of an AC battery module layout of a residential PV-battery system. (Source https://www.cleanenergyreviews.info/blog/ac-coupling-vs-dc-coupling-solar-battery-storage.)*

Simulated battery performance is static in the current CSE implementation. In particular, charge and discharge efficiencies do not vary with either charge rate or temperature. In real-world battery systems, efficiency falls from the benchmark a) with age, b) under rapid charging/discharging, and c) when temperatures are outside an ideal range (e.g., 25 °C/77 °F).

A real-world battery's usable capacity is also subject to age and external conditions. Low temperatures, especially, reduce a battery's in-the-moment usable capacity. CSE neglects those effects as well. The long-term dynamics of how batteries age warrants its own section, below.

The existence of a battery in the CBECC-Res and CBECC models also relaxes size limits on PV systems. Without onsite storage, the PV system is limited by the interconnection rule: solar generation must not exceed the building's electricity consumption over the course of a year. Title 24, Part 6 allows a building with a battery larger than 5 kWh to have a PV system that produces up to 1.6 times the building's annual electricity consumption. The CBECC-Res and CBECC software implement this change.

APPENDIX E – PLUG LOADS AND LIGHTING MODELING

1.1 Appliances, Miscellaneous Energy Use and Internal Gains

Full details of the assumptions for lighting and appliance loads are found in the Codes and Standards Enhancement Initiative (CASE) Plug Loads and Lighting Modeling (Rubin 2016, see Appendix D).

1.1.1 Background

Rulesets for all plug loads (including appliances and miscellaneous electric loads (MELs)) and lighting loads were updated in 2016. The CASE report describes the methodology, data sources, and assumptions used to develop the rulesets. The updated methodology replaces the rulesets from the 2019 *Residential Alternative Calculation Method (ACM) Reference Manual* (ACM Reference Manual), which in turn referenced the 2008 California Home Energy Rating System (HERS) Technical Manual.

The rulesets were modified to reflect efficiency levels assuming 2017 federal code baseline or 2017 projected market average performance, depending on whether or not a product is regulated by federal energy efficiency standards. Miscellaneous loads were disaggregated so that the three largest loads in this group—televisions, set-top boxes, and computers and monitors—are modeled individually. The remaining miscellaneous loads are modeled in aggregate. Garage lighting is also disaggregated from interior lighting. Assumptions about how energy use scales with building size were updated for all plug load and lighting end uses.

Updated load profiles were proposed for the majority of the modeled plug load and lighting end uses. The proposed updates include revisions to both the hourly schedules and seasonal multipliers. The updated load profiles are based on the water heating models described in section 2.9 of the ACM Reference Manual for the applicable end uses and otherwise on recent submetering studies.

1.1.2 Approach

Rulesets for all modeled end uses reflect the estimated energy consumption of those devices in new homes built during the 2025 Title 24 Code Cycle. The plug load rulesets estimate annual energy consumption (AEC) as a function of number of bedrooms (BR/Unit) and the lighting rulesets estimate AEC as a function of conditioned floor area (CFA/Unit). The relationship between AEC and BR/Unit for dishwashers, clothes washers, and clothes dryers was based on the usage assumptions in the water heating model. The relationship between all other plug load AEC and BR/Unit was generally derived from the 2009 Residential Appliance Saturation Survey (RASS), through a statistical and engineering analysis that applied modern efficiency assumptions to estimate what the AEC of plug loads within homes included in the 2009 RASS would be if they were built during the 2016 Title 24 code cycle. The relationship between lighting AEC and CFA/Unit was derived using a similar analysis completed on the RASS data but using data from the 2012 California Lighting and Appliance Saturation Survey.

With additional user inputs, the default AEC equations for primary refrigerators, clothes washers, and clothes dryers can be modified to reflect the efficiency of the devices that are actually installed in the building. That is, the modeled energy use can be adjusted downward if more efficient devices are installed (the software tool can also adjust energy use upward if devices are less efficient).

Updated load profiles are derived from the following data sources:

- **Dishwashers, clothes washers, and clothes dryers:** updated to be consistent with the usage patterns assumed by water heating models described in the ACM Reference Manual.
- **Ovens, cooktops, and televisions:** based on data from the Phased Deep Retrofit (PDR) study conducted by the Florida Solar Energy Center (FSEC), which submetered 60 Florida homes in 2012.
- **Set-top boxes, computers, and monitors:** based on the Northwest Energy Efficiency Alliance (NEEA) Residential Building Stock Assessment (RBSA), released in 2014. This study monitored 100 homes in the Pacific Northwest over the course of one year, submetering major end uses at 15 minute intervals.
- **Exterior lighting:** the proposed hourly schedule for exterior lighting is derived from the NEEA RBSA light logging data; the proposed exterior lighting seasonal multipliers are no longer constant, but instead equivalent to the interior and garage seasonal multipliers.

Load profiles for interior lighting, garage lighting, and residual MELs were not updated in 2016. The current hourly schedules for interior lighting are based on the 1999 Heschong Mahone Group (HMG) study “Lighting Efficiency Technology Report: California Baseline.” The current hourly schedule for residual MELs is derived from the 2008 Building America House Simulation Protocol, which in turn relied on data from a 1989 Pacific Northwest submetering study conducted by the End-Use Load and Consumer Assessment Program (ELCAP).

Refrigerators and freezers use PDR data to adjust estimated energy use on an hourly basis depending on the modeled indoor temperature (using the Title 24 compliance software) in the space where the refrigerator is installed.

1.1.3 Problems

The plug load and lighting rulesets have some limitations. The rulesets generally do not account for differences in energy use patterns between single-family and multi-family housing. For example, they do not account for the energy use of laundry equipment in multi-family residences that is installed in common areas—only laundry equipment in the dwelling units.

The plug load and lighting rulesets should not be used for estimating energy use for existing homes.

1.1.4 Inputs

AEC Inputs and Algorithms

Table 1 summarizes the user inputs that determine the plug load and lighting annual energy consumption (AEC) estimates. The variable 'BR/Unit' refers to the number of bedrooms in a single-family home or the number of bedrooms in each dwelling unit of a multi-family building. Similarly, 'CFA/Unit' refers to the conditioned floor area per dwelling unit. AEC equations are to be applied to each dwelling unit within a multi-family building, not the building as a whole. Users also specify the zone where certain major appliances are located; however, this affects the modeled internal gains from equipment and lighting, not their estimated energy use of the plug load or lighting load and is therefore not included in the table below.

Table 1: User Inputs Affecting Estimated Plug Load and Lighting Energy Use

End Use	User Inputs that Determine Estimated Energy Use	Notes
Primary Refrigerator/ Freezer	- BR/Unit - Optional: rated annual kWh usage from the Energy Guide label of the installed device	- Default kWh can be overridden with the rated annual kWh usage input on the Energy Guide label; however, there is a maximum allowable kWh credit dependent on BR/Unit. - Energy use adjusted on an hourly basis depending on the indoor temperature in the kitchen simulated in the software.
Non-Primary Refrigerators and Separate Freezers	- BR/Unit - Single-family or multi-family housing	- Assumed to be installed in the garage in new, single-family homes. - Assumed to be absent in multi-family dwelling units.
Dishwasher	- BR/Unit - Presence of device - Single-family or multi-family	- Ruleset estimates machine energy use only. - Energy use is only included if user indicates the device will be present. - Assumed different usage patterns in single family and multi-family when developing algorithms.
Clothes Washer	- BR/Unit - Presence of device - Single-family or multi-family - Optional: whether installed device will comply with the 2015 federal efficiency standards (credit for installing new or nearly-new device)	- Ruleset estimates machine energy use only. - Energy use is only included if user indicates the device will be present. - Assumed different usage patterns in single family and multi-family when developing algorithms. - Default energy use can be reduced if the user specifies the device will meets the 2015 federal standard, which can be determined by looking up the model on the California Appliance Efficiency Database.

End Use	User Inputs that Determine Estimated Energy Use	Notes
Clothes Dryer	- Bedrooms per unit - Presence of device - Fuel type (natural gas, propane, or electric) - Single-family or multi-family - Optional: percent remaining moisture content (RMC) of the clothes washer	- Energy use is only included if user indicates the device will be present. - User can select fuel type. If user indicates natural gas is available at the site (see Section 2.2.10 of RACM), then the default fuel type is natural gas. If user indicates that natural gas is not available at the site then the default fuel type is electric. User cannot select natural gas as the fuel type if natural gas is not available at the site. - Default energy use can be reduced if the user specifies that the installed clothes washer has a rated RMC of less than 50 percent.
Oven	- Bedrooms per unit - Presence of device - Fuel type (natural gas, propane, or electric)	- Energy use is only included if user indicates the device will be present. - User can select fuel type, but default assumption is natural gas if user indicates that natural gas is available on-site and electric if user indicates natural gas is not available on-site
Cooktop	N/A	N/A
Televisions, Set-Top Boxes, Computers and Monitors, Residual MELs	- Bedrooms per unit	N/A
Interior Lighting, Exterior Lighting	- CFA/Unit	N/A
Garage Lighting	- CFA/Unit - Presence of garage	- Energy use is only included if user indicates there is a garage present. - Garage lighting is assigned to multi-family buildings if there is at least once garage present. - Carport lighting is covered under the exterior lighting ruleset.

Source: California Energy Commission

Table 2 summarizes the proposed AEC algorithms for plug load and lighting. These linear equations take the following general form where the homes size metric is bedrooms per unit (BR/Unit) for plug loads and CFA/Unit for lighting:

$$y = mx + b$$

Where: y = Estimated AEC measured in kWh/yr or therms/yr

m = how AEC changes with home size

x = home size as measured in BR/Unit for plug loads or CFA/Unit for lighting

b = minimum energy use (energy use at y-intercept)

BR-based equations are capped at 7 bedrooms, meaning that units with eight or more bedrooms have the same estimated AEC as a 7-bedroom unit. CFA-based equations are capped at 4,150 square feet. For those end uses that list 'presence of device' as a user input in Table 2, the AEC equation is only applied if the device is present. Similarly, for the AEC equations for end uses that can be gas or electric are only applied according to the user-specified fuel type. Gas algorithms apply to devices that use natural gas or propane.

Table 2: Algorithms for Plug Load and Lighting Annual Energy Use

End Use	Standard Design Fuel Type	kWh or therms	Intercept	Slope	Per-Unit BR or CFA
Primary Refrigerator/Freezer	Electricity	kWh	454	37.0	BR
Non-Primary Refrigerators and Separate Freezers (Single-Family only)	Electricity	kWh	0	71.0	BR
Oven	Electricity	kWh	138	16	BR
Oven	Gas	therms	6.0	0.95	BR
Oven	Gas	kWh	41	4.79	BR
Cooktop	Electricity	kWh	84	5.68	BR
Cooktop	Gas	therms	5.0	0.30	BR
Cooktop	Gas	kWh	0	0	BR
Televisions	Electricity	kWh	265	31.8	BR
Set-Top Boxes	Electricity	kWh	76	59.4	BR
Computers and Monitors	Electricity	kWh	79	55.4	BR
Residual MELs	Electricity	kWh	672	235	BR
Interior Lighting	Electricity	kWh	100	0.1775	CFA
Exterior Lighting	Electricity	kWh	8.0	0.0532	CFA
Garage Lighting	Electricity	kWh	20	0.0063	CFA

Source: California Energy Commission

Table 3 and Table 4 summarize the AEC algorithms for dishwashers, clothes washers and clothes dryers. These rulesets only include machine energy use from dishwashers and clothes washers. Energy use for water heating is accounted for in the water heating model.

Table 3: Single-Family Residence Algorithms for Dishwasher, Clothes Washer, and Clothes Dryer Annual Energy Use

BRper Unit	Dishwashers (kWh/yr)	Clothes Washers (kWh/yr)	Electric Clothes Dryers (kWh/yr)	Gas Dryer Natural Gas Use (therms/yr)	Gas Dryer Electricity Use (kWh/yr)
0	83	84	634	22	32
1	83	84	634	22	32
2	91	85	636	22	32
3	100	99	748	26	37
4	99	101	758	27	38
5+	119	227	877	31	44

Source: California Energy Commission

Table 4: Multi-Family Dwelling Unit Algorithms for Dishwasher, Clothes Washer, and Clothes Dryer Annual Energy Use

BRper Unit	Dishwashers (kWh/yr)	Clothes Washers (kWh/yr)	Electric Clothes Dryers (kWh/yr)	Gas Dryer Natural Gas Use (therms/yr)	Gas Dryer Electricity Use (kWh/yr)
0	56	66	496	17	25
1	68	70	527	19	26
2	96	99	745	26	37
3	94	97	733	26	37
4	121	118	885	31	44
5+	114	107	805	28	40

Source: California Energy Commission

AEC Algorithms for High-Efficiency Appliances

As indicated in Table 5, if allowed in the software, users could override the default AEC rulesets for the primary refrigerator, clothes washer and clothes dryer if the software user has additional information about the device that will be installed.

For the primary refrigerator, the default AEC ruleset could be replaced with the rated AEC listed on the refrigerator's Energy Guide label. If using this option, the user will input AEC measured in kWh per year, and that value will replace the AEC value for the primary refrigerator calculated using the equation below. The default AEC of the primary refrigerator cannot be adjusted below a certain value, which is dependent on BR/Unit as described in the following equation:

$$MinPrimaryRefrigAEC\frac{kWh}{yr} = \left(8.4\frac{kWh}{BRperUnit\text{-}yr} \times BRperUnit\right) + 291\frac{kWh}{yr}$$

Users could reduce the estimated primary refrigerator AEC to this value, but no lower.

Table 5: Minimum primary refrigerator AEC that builders may claim by BR/Unit

BR/Unit	Default Primary Refrigerator AEC (kWh/yr)	Minimum Allowable Primary Refrigerator AEC (kWh/yr)
0	470	291
1	496	299
2	523	308
3	550	316
4	577	325
5	603	333
6	630	341
7+	657	350

Source: California Energy Commission

For clothes washers, if allowed in the software, the user could specify that the installed clothes washer meets the 2015 federal standards (as documented on the CEC Appliance Efficiency Database). This effectively provides credit if the clothes washer is new or nearly new. Table 6 presents the AEC values used if the washer is compliant with the 2015 federal standards.

Table 6: Minimum allowable high-efficiency AEC for clothes washers

BR/Unit	Single Family Default AEC (kWh/yr)	Single Family High-Efficiency Clothes Washer AEC[1] (kWh/yr)	Multifamily Default AEC (kWh/yr)	Multifamily High-Efficiency Clothes Washer AEC[1] (kWh/yr)
0	84	68	66	53
1	84	68	70	57
2	85	68	99	80
3	100	80	98	79
4	101	81	118	95
5+	117	94	107	86

[1]Applicable to clothes washers that meet the 2015 federal efficiency standards

Source: California Energy Commission

For clothes dryers, if allowed in the software, the user could specify the percent remaining moisture content (RMC) of the installed clothes washer (as documented on the CEC Appliance Efficiency Database) to override the default clothes dryer AEC ruleset. The RMC-adjusted clothes dryer AEC should be calculated using the equations provided below. For natural gas dryers the RMC-adjusted AEC modifies natural gas use but does not impact electricity use.

Electric Dryer: RMC-adjusted AEC (kWh/yr)

$$RMC\text{-}adjusted\ AEC\ \frac{kWh}{yr} = 12.67\,\frac{kWh}{yr} + \left[\left(3.80\,\frac{kWh}{cycle}\left(RMC_{User,Input}\right) + 0.25\ \frac{kWh}{cycle}\right) \times \frac{cycles}{yr}\right]$$

Gas Dryer: RMC-adjusted AEC (therms/yr)

$$RMC\text{-}adjusted\ AEC\ \frac{therms}{yr} = \left[0.136\,\frac{therms}{cycle}\left(RMC_{User,Input}\right) + 0.00853\ \frac{therms}{cycle}\right] \times \frac{cycles}{yr}$$

Table 7: Annual clothes dryer cycles estimated based on BR/Unit

BR/Unit	Clothes Dryer Cycles Single-Family	Clothes Dryer Cycles Multi-Family
0	290	227
1	290	241
2	291	341
3	342	335
4	346	405
5+	401	368

Source: California Energy Commission

Load Profiles

Dishwashers and clothes washers loads are specified in the water heating load profiles. Clothes dryers have the same usage assumptions as clothes washers, but shifted one hour later.

The estimated energy use for refrigerators is adjusted for each hour of the year depending on the simulated indoor temperature in the thermal zone where the refrigerator or freezer is installed (user input). Multi-family housing is assuccccmed to have no energy use for non-primary refrigerators or separate freezers.

The following tables summarize the hourly load profiles and seasonal multipliers for the remaining plug load and lighting end uses.

Table 8: Hourly Multiplier – Weekdays

Hour	Oven and Cooktop	Televisions	Set-Top Boxes	Computers and Monitors	Residual MELs	Interior and Garage Lighting	Exterior Lighting
1	0.005	0.035	0.040	0.036	0.037	0.023	0.046
2	0.004	0.026	0.040	0.033	0.035	0.019	0.046
3	0.004	0.023	0.040	0.032	0.034	0.015	0.046
4	0.004	0.022	0.040	0.032	0.034	0.017	0.046
5	0.004	0.021	0.040	0.031	0.032	0.021	0.046
6	0.014	0.021	0.040	0.032	0.036	0.031	0.037
7	0.019	0.025	0.040	0.034	0.042	0.042	0.035
8	0.025	0.032	0.041	0.036	0.044	0.041	0.034
9	0.026	0.038	0.040	0.039	0.037	0.034	0.033
10	0.022	0.040	0.040	0.043	0.032	0.029	0.028
11	0.021	0.038	0.040	0.045	0.033	0.027	0.022
12	0.029	0.038	0.040	0.045	0.033	0.025	0.015
13	0.035	0.041	0.040	0.046	0.032	0.021	0.012
14	0.032	0.042	0.040	0.046	0.033	0.021	0.011
15	0.034	0.042	0.041	0.046	0.035	0.021	0.011
16	0.052	0.041	0.041	0.047	0.037	0.026	0.012
17	0.115	0.044	0.042	0.048	0.044	0.031	0.019
18	0.193	0.049	0.043	0.049	0.053	0.044	0.037
19	0.180	0.056	0.044	0.049	0.058	0.084	0.049
20	0.098	0.064	0.045	0.049	0.060	0.117	0.065
21	0.042	0.070	0.046	0.049	0.062	0.113	0.091
22	0.020	0.074	0.047	0.048	0.060	0.096	0.105
23	0.012	0.067	0.045	0.044	0.052	0.063	0.091
24	0.010	0.051	0.045	0.041	0.045	0.039	0.063

Source: California Energy Commission

Table 8: Hourly Multiplier – Weekends

Hour	Oven and Cooktop	Televisions	Set-Top Boxes	Computers and Monitors	Residual MELs	Interior and Garage Lighting	Exterior Lighting
1	0.005	.035	0.041	0.036	0.037	0.023	0.046
2	0.004	0.027	0.041	0.034	0.035	0.019	0.046
3	0.003	0.022	0.040	0.033	0.034	0.015	0.045
4	0.003	0.021	0.041	0.033	0.034	0.017	0.045
5	0.003	0.020	0.040	0.032	0.032	0.021	0.046
6	0.005	0.020	0.040	0.033	0.036	0.031	0.045

Hour	Oven and Cooktop	Televisions	Set-Top Boxes	Computers and Monitors	Residual MELs	Interior and Garage Lighting	Exterior Lighting
7	0.010	0.022	0.040	0.033	0.042	0.042	0.044
8	0.027	0.029	0.040	0.035	0.044	0.041	0.041
9	0.048	0.037	0.041	0.038	0.037	0.034	0.036
10	0.048	0.043	0.042	0.042	0.032	0.029	0.030
11	0.046	0.042	0.042	0.044	0.033	0.027	0.024
12	0.055	0.039	0.041	0.045	0.033	0.025	0.016
13	0.063	0.040	0.041	0.046	0.032	0.021	0.012
14	0.059	0.042	0.041	0.047	0.033	0.021	0.011
15	0.062	0.045	0.041	0.047	0.035	0.021	0.011
16	0.068	0.048	0.042	0.048	0.037	0.026	0.012
17	0.091	0.051	0.042	0.049	0.044	0.031	0.019
18	0.139	0.052	0.043	0.049	0.053	0.044	0.038
19	0.129	0.056	0.044	0.048	0.058	0.084	0.048
20	0.072	0.061	0.044	0.048	0.060	0.117	0.060
21	0.032	0.065	0.045	0.048	0.062	0.113	0.083
22	0.014	0.069	0.045	0.047	0.060	0.096	0.098
23	0.009	0.064	0.044	0.044	0.052	0.063	0.085
24	0.005	0.050	0.039	0.041	0.045	0.039	0.059

Source: California Energy Commission

Table 9: Seasonal Multipliers

Month	Oven and Cooktop	Televisions	Set-Top Boxes	Computers and Monitors	Residual MELs and Lighting
Jan	1.094	1.032	1.02	0.98	1.19
Feb	1.065	0.991	0.84	0.87	1.11
Mar	1.074	0.986	0.92	0.89	1.02
Apr	0.889	0.990	0.98	1.11	0.93
May	0.891	0.971	0.91	1.14	0.84
Jun	0.935	0.971	0.94	0.99	0.80
Jul	0.993	1.002	1.05	1.05	0.82
Aug	0.920	1.013	1.06	1.01	0.88
Sep	0.923	1.008	1.06	0.96	0.98
Oct	0.920	1.008	1.14	0.97	1.07
Nov	1.128	1.020	1.03	0.99	1.16
Dec	1.168	1.008	1.05	1.04	1.20

Source: California Energy Commission

APPENDIX F – TECHNICAL REFERENCES

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APPENDIX G - ALGORITHMS

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1 California Simulation Engine (CSE)

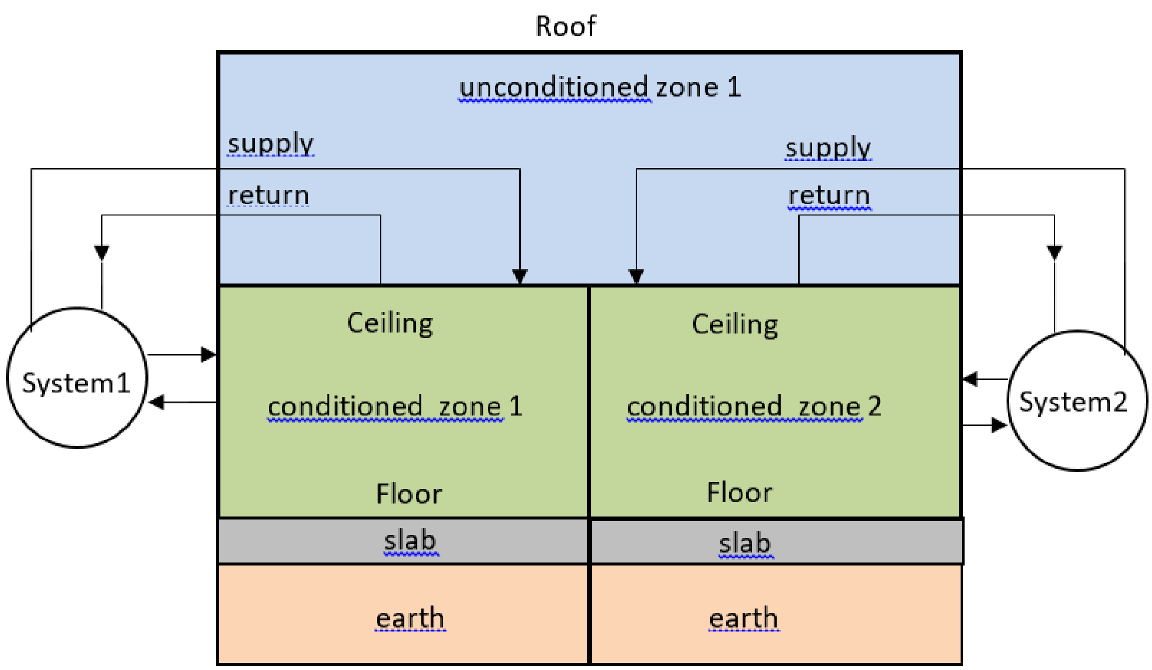
1.1 Overview

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.

Figure 1: Schematic of Zones and Air Handler Systems



Although shown partly outside of the envelope, all ducts are assumed to be in either the conditioned or unconditioned zones only.

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.

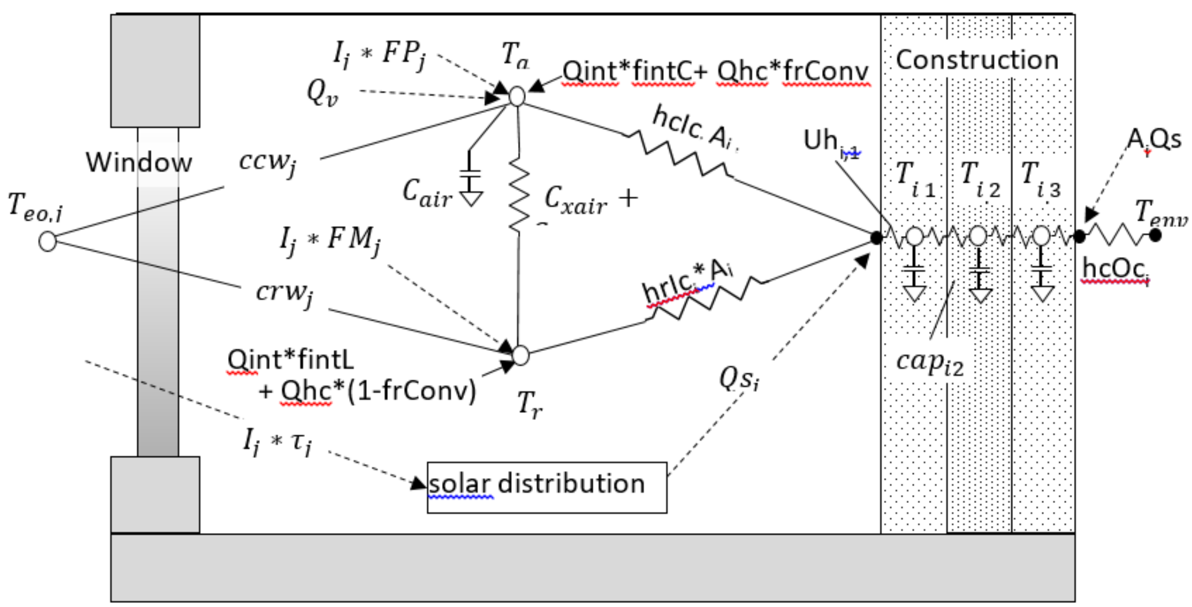
To avoid iteration, a similar use of the last time-step data is necessary is dealing with inter-zone wall heat transfer. For example, heat transfer through the ceiling depends on the conditions in both zones, but these conditions are not known simultaneously. Thus, ceiling masses are treated as belonging 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.

1.1.1 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, 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.

Figure 2: Schematic of Simulation Network



The room air, represented by the mass node Ta, 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 $hcIc_i$ 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: $hrIc_i$ 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, $Qint$, 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 Qhc (+ for heating, - for cooling). If Qhc is heating, a fraction ($frConv$) can be convective with the rest long-wave. The convective parts of $Qint$ and Qhc are shown as added to the air node. The long wave fraction of Qint and Qhc are shown added to the $\mathrm{T_r}$ 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 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, $\mathrm{Qint} * \mathrm{fintSW}$, is distributed diffusely, with the same diffuse targeting as the diffusely distributed solar gains.

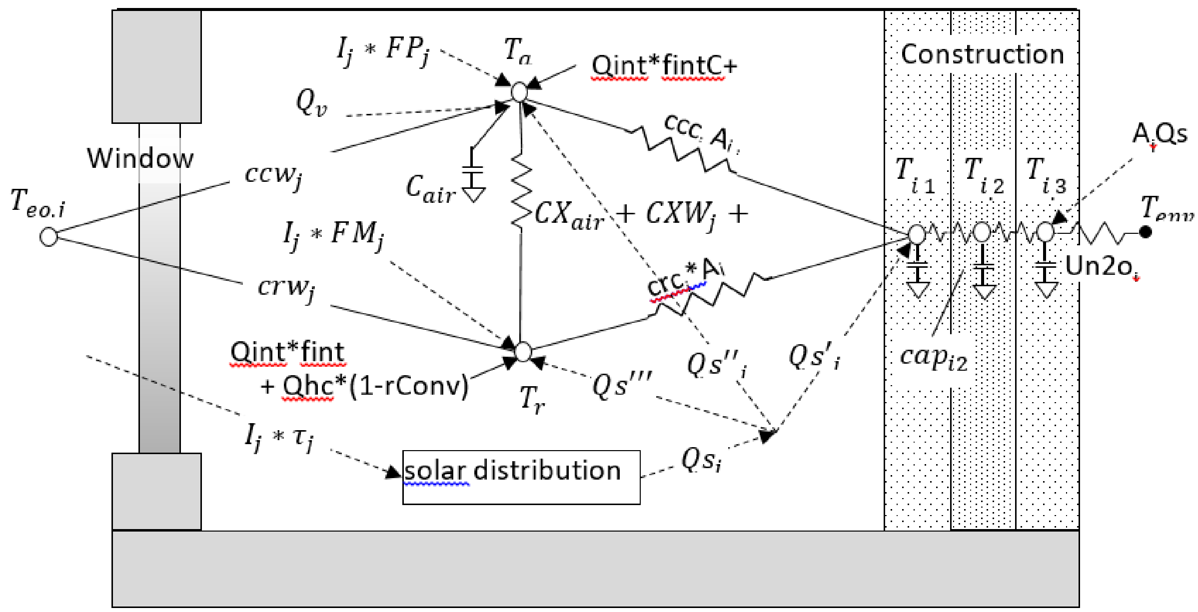
Solar gains absorbed at the outside surface of constructions are represented by Qs_o in Figure 2.

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

1.1.2 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-Δ 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 Qs_i absorbed by the surface node is split into three parts: Qs_i' to the $T_{i,1}$ node, Qs_i'' to the Ta node and Qs_i''' to the Tr node. For example, by current splitting,

$$Qs_i' = Qs_i \frac{Uh_{i,1}}{hcIc_i + hrIc_i + Uh_{i,1}}$$

Equation 1

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,

$$ccc_i = \frac{hcIc_i * Uh_{i,1}}{hcIc_i + hrIc_i + Uh_{i,1}}$$

Equation 2

1.1.3 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 1.2), 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 1.3.1, if the air mass temperature is updated using an implicit-difference method, the effect of the air mass can be duplicated by employing a resistance, *Δt/Cair*, between the Ta node and a fictitious node set at the beginning of the time-step air temperature TaL = Ta(t), and shown as such in Figure 3.

<u>The overall CSE Calculation Sequence is summarized below:</u>

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.

1.2 Updating Layered Mass Temperatures

The heat transfer through the layered constructions is assumed to be one dimensional. The heat conduction equation ($\frac{\partial^2 T^2}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$) is solved by using finite differences (Δt and Δx) to approximate the differential increments in time and distance; α is the thermal diffusivity. The smaller the finite increments, the more accurate the solution. The homogeneous layers are divided into lumps Δx 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 Δx can be taken as the layer thickness. However, at times the actual layer of homogeneous material must be divided into smaller thicknesses. See Section 1.4–Discretization Errors for the criterion used to determine Δx and Δt.

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 $T_{i,1}$:

$$\frac{dT_{i,1}}{dt} = \frac{Tss_{i,1} - T_{i,1}}{\tau}$$ Equation 3

where $T_{i,1}$ is the surface layer mass temperature, and $Tss_{i,1}$ is the temperature $T_{i,1}$ would have if steady state were reached:

$$Tss_{i,1} = \frac{ccc_{i,1}Ta + crc_{i,1}Tr + Ubn_{i,1}T_{i,2} + Qs_i'}{ccc_{i,1} + crc_{i,1} + Ubn_{i,1}}$$

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 τ is the time constant of mass node 1 given by:

$$\tau = \frac{cap_{i,1}}{ccc_{i,1} + crc_{i,1} + Ubn_{i,1}}$$

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 Tss. 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.

1.3 Zone Energy Balance

1.3.1 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:

$$\frac{dT_a}{dt} + \frac{T_a}{\tau_a} = \frac{Tss}{\tau_a}$$

Equation 8

where Tss, the asymptotic steady state temperature of Ta, includes all the sources connected to Ta. 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 Tss is given by:

$$T_{SS} = \left[T_{out}\left(U_{inf} + U_v\right) + ccw_1 Awin_1 T_{out} + ccc_1 Acon_1 T_{1,1} + Acon_1 Qs_1^{"} + Awin_1 Qsw_1^{"} + Qint * fintC + Qhc * frConv + CX * Tr\right]/Usum$$

Equation 9

where

$$CX = CXair + CXW_1 + CXC_1$$

Equation 10

$$Usum = U_{inf} + U_v + ccw_1 Awin_1 + ccc_1 Acon_1 + CX$$

Equation 11

and the air time constant is:

$$\tau_a = \frac{Cair}{Usum}$$

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:

$$T_a(t + \Delta t) = \frac{\frac{T_a(t)\tau_a}{\Delta T} + Tss(t + \Delta t)}{\frac{\tau_a}{\Delta t} + 1}$$

Equation 13

Where the times *t* and *t+Δt* in parenthesis indicate the terms are evaluated at the beginning and end of the time step, respectively. Substituting Equation 12 for τ_a, Equation 13 can be put in the convenient form:

$$T_a(t + \Delta t) = \frac{\frac{T_a(t)Cair}{\Delta T} + Usum * Tss(t + \Delta t)}{\frac{Cair}{\Delta t} + Usum}$$

Equation 14

As this equation shows, with the implicit difference the effect of the air mass can be thought of as a resistance, *Δt/Cair*, 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:

$$Ta = \frac{\frac{TaL * Cair}{\Delta T} + Usum * Tss}{\frac{Cair}{\Delta t} + Usum}$$

Equation 15

where Ta and Tss are evaluated at the end of the time step, and TaL stands for $T_a(t)$ 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.

1.3.2 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.

1.3.2.1 Air Node Balance

The energy balance equation on the Ta node, comparable to Equation 15 above is:

$$Ta = \frac{Qv + Qhc \cdot frConv + Nair + CX \cdot Tr}{Dair + CX}$$

Equation 16

The Equation 16 form, using $\mathrm{Q_v}$, 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, $\mathrm{Q_v}$ is replaced by the essentially equivalent form given by Equation 17, wherein $\mathrm{Q_v}$ is replaced by $\mathrm{Q_v = mC_p\Delta T}$ such that $\mathrm{mdot} * \mathrm{c_p} * \mathrm{T}$ is added to the numerator and $\mathrm{mdot} * \mathrm{c_p}$ is added to the denominator. This was implemented to eliminate oscillations in Ta.

$$Ta = \frac{ST + Qhc \cdot frConv + Nair + CX \cdot Tr}{SB + Dair + CX}$$

Equation 17

where,

$$ST = \sum mdot * c_p * T$$

Equation 18

where T is the temperature of the air in the zone supplying the infiltration or ventilation air.

$$SB = \sum mdot * c_p$$

Equation 19

$$CX = CXair + \sum^{con} Acon_i * cxc_i + \sum^{win} Awin_i * cxw_i$$

Equation 20

with the sum's for all constructions and all windows respectively.

$$Nair = TaL\left(\frac{Cair}{dt}\right) + Qint * fintC + \sum^{con} Acon_i * \left(ccc_i * T_{i1} + \frac{Q_{si} * hcIc_i}{hcIc_i + hrlc_i + Uh_{i1}}\right) + \sum^{win}\left[Awin_i\left(ccw_i * Teo_i + I_j * FP_j\right)\right]$$

Equation 21

$$Dair = \frac{Cair}{dt} + \sum^{con} Acon_i * ccc_i + \sum^{win} Awin_i * ccw_i$$

Equation 22

Qv is the heat transfer to the air node due to infiltration and forced or natural ventilation.

1.3.2.2 Radiant Node Balance

An energy balance on the Tr node gives Equation 23.

$$Tr = \frac{Qhc \cdot (1 - frConv) + N_{rad} + CX \cdot Ta}{Drad + CX}$$

Equation 23

where,

$$Nrad = Qint * fintLW + \sum^{con} Acon_i\left(crc_i * T_{i1} + Qsi_i * \frac{hrIc_i}{hcIc_i + hrIc_i + Uh_{i1}}\right) + \sum^{win} Awin_i\left(crw_i * Teo_i + I_j * FM_j\right)$$

Equation 24

$$Drad = \sum^{con} Acon_i * crc_i + \sum^{win} Awin_i * crw_i$$ Equation 25

1.3.2.3 Simultaneous Solution of Ta and Tr Equations

Equation 16 and Equation 23 can be solved simultaneously to eliminate Tr and give Ta explicitly:

$$Ta = \frac{(Qv + Qhc \cdot frConv + Nair)(Drad + CX) + CX(Nrad + Qhc(1 - frConv)}{(Dair + Drad)CX + Dair \cdot Drad}$$

Equation 26

Similar to Equation 16 and Equation 17), the alternate form of Equation 26 is given by Equation 27.

$$Ta = \frac{(ST + Qhc \cdot frConv + Nair)(Drad + CX) + \ CX(Nrad + Qhc(1 - frConv)}{(SB + Dair + Drad)CX + (SB + Dair)\mathrm{D}rad}$$

Equation 27

Substituting Ta from Equation 26 into Equation 23 gives Tr.

1.3.2.4 Qhc and Qv Equations

When *Ta* is at either the heating or cooling setpoints, Equation 26 is solved to determine the required *Qhc*. In this case *Qv* is set *to QvInf.*

$$Qhc = \frac{Ta\big(Dair * Drad + CX(Dair + Drad)\big) - \ (Nair + Qv)(Drad + CX) - Nrad * CX)}{frConv * Drad + CX}$$

Equation 28

Similarly, when Ta is at the ventilation setpoint, Equation 26 can be solved for Qv to give:

$$Qv \ = \frac{\big(Dair * Drad + CX(Dair + Drad)\big)Ta - CX\big(Nrad + Qhc(1 - frConv)\big)}{Drad + CX} - (Qhc * frConv + Nair)$$

Equation 29

With *Qhc* = 0 this becomes:

$$\mathrm{Qv} \ = \frac{\big(Dair * Drad + CX(Dair + Drad)\big)Ta - Nair(Drad + CX) - CX * Nrad}{Drad + CX}$$

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 TaL; see Section 1.3.1). Although the balance is with contemporary temperatures, many of the heat flows in $Nair$ etc., are based on last time step conditions.

1.3.3 Thermostat Logic

At the end of each time step the program finds the floating temperature of the zone without HVAC ($Qhc = 0$) and with venting $\mathrm{Qv} = \mathrm{QvInf}$. This floating temperature found from Equation 26 is defined as TS1. Next, the venting capacity is determined (see Section 1.9.3.10, Heat Flow), and Equation 26 is solved for Ta at the full venting capacity. This Ta 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 *QvInf* and Ta is set to TC, and Equation 28 is solved for the required cooling, Qhc. If Qhc is smaller than the cooling capacity at this time step then Qhc 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.

1.3.4 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.

1.4 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.

1.4.1 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

$$d_p = \sqrt{2\alpha/\omega}$$

Equation 32

where the angular frequency $\omega = \frac{2\pi}{period}$, α is the thermal diffusivity of the layer material, and ω 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, Δx, be chosen to be thinner than the penetration depth for the layer. That is, select

$$\Delta x \lesssim d_p$$

Equation 33

Substituting Equation 32 into Equation 33 shows that the rule of Equation 33 limits the lump size Δx to about 16% of the wavelength:

$$\Delta x \lesssim dp = \lambda/_{2\pi} = 0.16\lambda$$

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.

1.4.2 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 τ than thick layers. The time constant of a layer scales as $\sim \beta^2$, where β is the a layers dimensionless thickness defined as $\beta = \frac{\Delta x}{d_p}$. 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 β'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

1.5 Surface Heat Transfer Coefficients

The radiation coefficients for surfaces inside the conditioned zone are given in Section 1.6.1 where the long-wave radiant network model is discussed.

1.5.1 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.

1.5.1.1 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):

$$V(z) = SC * V_{met} * \alpha * \left(\frac{z}{32.8}\right)^{\gamma} \qquad \textit{Equation 36}$$

where,

α and γ 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

Class	ϒ	A	Description
I	0.10	1.30	Ocean or other body of water with at least 5 km of unrestricted expanse
II	0.15	1.00	Flat terrain with some isolated obstacles (buildings or trees well separated)

Class	ɣ	A	Description
III	0.20	0.85	Rural areas with low buildings, trees, etc.
IV	0.25	0.67	Urban, industrial, or forest areas
V	0.35	0.47	Center of large city

Source: NORESCO for California Energy Commission

Table 2: Local Shielding Parameters

Class	C'	SC	Description
I	0.324	1.000	No obstructions or local shielding
II	0.285	0.880	Light local shielding and few obstructions
III	0.240	0.741	Moderate local shielding, some obstructions within two house heights
IV	0.185	0.571	Heavy shielding, obstructions around most of the perimeter
V	0.102	0.315	Very heavy shielding, large obstructions surrounding the perimeter within two house heights

Source: NORESCO for California Energy Commission

1.5.1.2 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:

$$V(z) = SC * V_{met} * \alpha * \left(\frac{ze}{32.8}\right)^{\gamma} = 0.571 * V_{met} * 0.67 * \left(\frac{z}{32.8}\right)^{0.25}$$

or,

$$V(z) = 0.16 * z^{0.25} * V_{met}$$

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:

$V(9.8) = 0.16 * 9.8^{0.25} * V_{met} = 0.28\ V_{met}$ for a 1-story building.

$V(19.7) = 0.34\ V_{met}$ for a 2-story building.

$V(29.5) = 0.38\ V_{met}$ for a 3-story building.

(References: Sherman & Grimsrud (1980), Deru & Burns (2003), Burch & Casey (2009), European Convention for Constructional Steelwork (1978).)

1.5.2 Convection Coefficient for Inside and Outside Surfaces of 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 θ ($0 \leq \theta \leq 90$), 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:

1.5.2.1 Inside surfaces

For floors, and either vertical walls, or walls pulled-in-at-the-bottom:

If Tair > Tsurf use Equation 53. (heat flow down)

If Tair < Tsurf use Equation 52. (heat flow up)

For ceilings (horiz or tilted), and walls pulled-in-at-the-top:

If Tair > Tsurf use Equation 52. (heat flow up)

If Tair < Tsurf use *Equation 53*. (heat flow down)

1.5.2.2 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

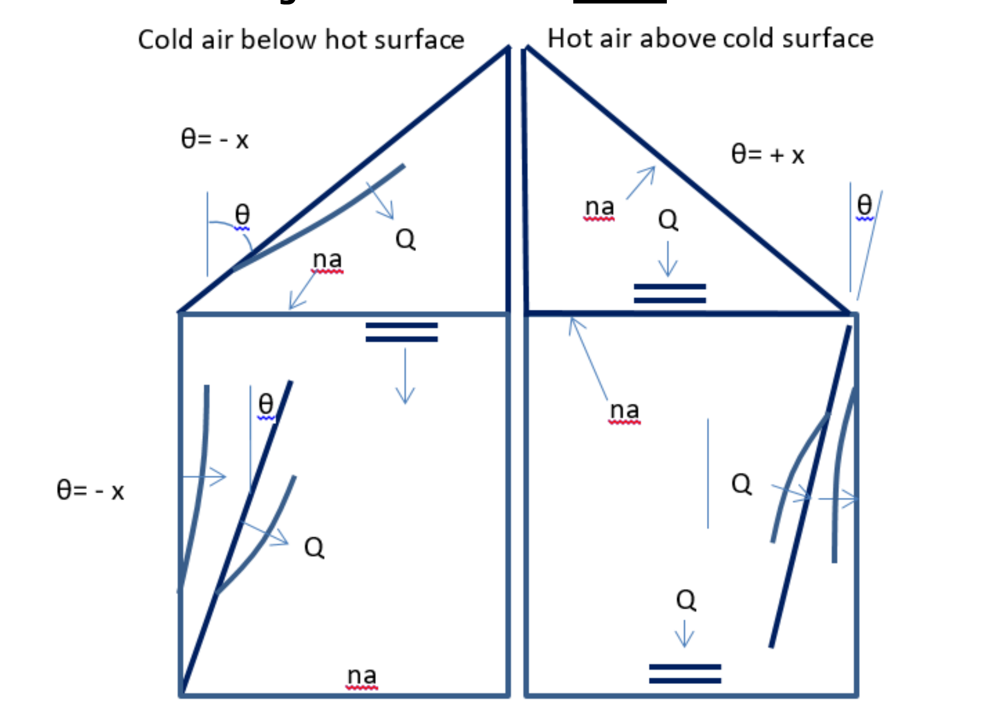
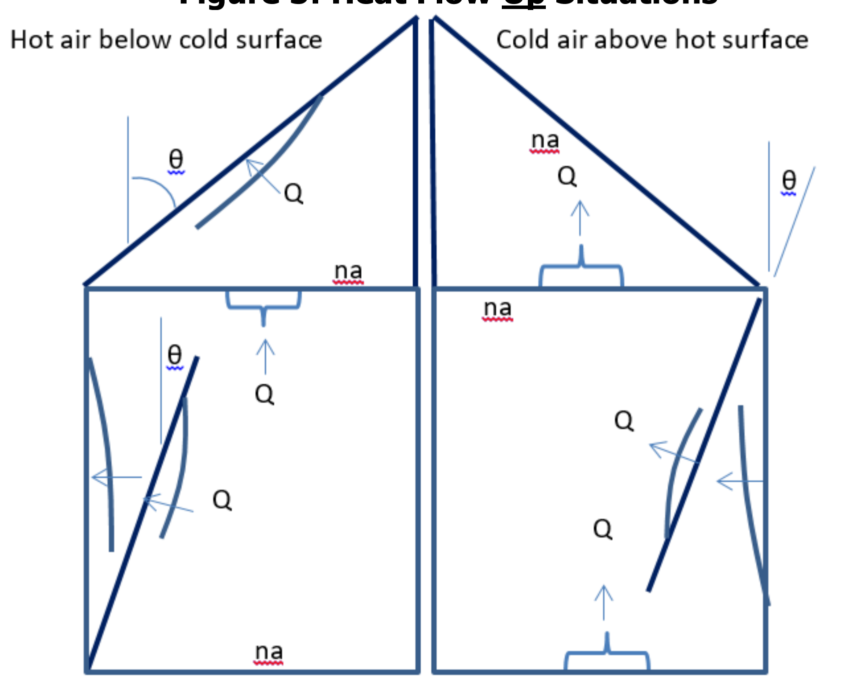


Figure 5: Heat Flow Up Situations



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 figure equations give zero heat flow in this case.

na symbolizes the equations are 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.

1.5.2.3 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 ($10^9 < \mathrm{Ra} < 10^{12}$), expected to be the dominant case in room heat transfer.

Equation 37 applies to either side of a tilted surface for angles $(0 \le \theta \le 88^o)$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 $\theta < 60^o$ if the heat flow has an upward component, or the heat flow is horizontal.

$$Nu = 0.68 + 0.67(Ra \cdot \psi)^{0.25}(1 + 1.6 * 10^{-8} Ra \cdot \psi)^{\frac{1}{12}} \qquad \textit{Equation 37}$$

where,

$Ra =$ the Rayleigh number.

$Nu =$ the Nusselt number.

$Pr =$ the Prandtl number.

$$\psi = \left[1 + \left(\frac{0.492}{Pr}\right)^{-\frac{16}{9}}\right]$$

Using $\psi = 0.349$ for $Pr = 0.72$, *Equation 37* reduces to:

$$Nu = 0.68 + 0.515Ra^{0.25}(1 + 5.58 * 10^{-9}Ra)^{\frac{1}{12}} \qquad \textit{Equation 38}$$

For high Ra [$Ra \approx> 10^9$] , neglecting the additive terms "1" and "0.68" in *Equation 37* gives:

$$Nu = 0.1057Ra^{\frac{1}{3}} \qquad \textit{Equation 39}$$

By the definition of the Nusselt number, the natural convection heat transfer coef, h_n is:

$$h_n \equiv Nu * \frac{k(air)}{L_{char}}$$

At 70F, $Ra = 1.66x10^6 L^3 |\Delta T| \cos(\theta)$*, and* $k = 0.0148$*,*

reduces to:

$$h_n = 0.185(|\Delta T| cos\theta)^{\frac{1}{3}} \qquad \textit{Equation 40}$$

Note that h_n is independent of characteristic length $\mathrm{L_{char}}$.

Downward heat flow

According to Mill's(1992) *Equation 37* doesn't apply to downward heat flow for $\theta > 88^o$. At 70 F, for a 20 ft characteristic length, the 0.68 term predicted by Equation *38* for $\theta = 90^o$ 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), 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:

$$Nu = 0.27Ra^{0.25} \qquad \textit{Equation 41}$$

Clear's equation reduces to:

$$h_n = 0.27(0.0148)(\frac{4}{L})\left[1.642E6\Delta T\left(\frac{L}{4}\right)^3\right]^{0.25}$$

or

$$h_n = 0.202\left|\frac{\Delta T}{L_{char}}\right|^{\frac{1}{4}} \qquad \textit{Equation 42}$$

where, L_{char} is the wall characteristic length; see Equation 51 definitions.

Adding this h to *Equation 40* gives:

$$h_{down} = MAX\left[0.185(|\Delta T|cos\theta)^{\frac{1}{3}}, 0.202\left|\frac{\Delta T}{L_{char}}\right|^{\frac{1}{4}}\right] \quad 0 \le \theta \le 90$$ *Equation 43*

The following simplification is made, where the exponent of the second term is changed to 1/3, so that $|\Delta T|^{\frac{1}{3}}$ can be factored out:

$$h_{down} = |\Delta T|^{\frac{1}{3}} MAX\left[0.185(cos\theta)^{\frac{1}{3}}, 0.202 L_{char}{}^{-\frac{1}{3}}\right] \quad 0 \le \theta \le 90$$

Changing the exponent means *Equation 44* gives same answer as *Equation 43* only when $\frac{\Delta T}{L_{char}} = 1$. But *Equation 44* would have acceptable error for other $\frac{\Delta T}{L_{char}}$ ratios, and gives more or less the right dependence on ΔT. If in addition, one assumes a typical $L_{char} = 15,$ say, then the minimum term becomes: $0.202\mathrm{L}_{\mathrm{char}}^{-\frac{1}{3}} = 0.08$, giving the final reasonable form:

$$h_{down} = |\Delta T|^{\frac{1}{3}} MAX\left[0.185(cos\theta)^{\frac{1}{3}}, 0.08\right] \quad 0 \le \theta \le 90$$ *Equation 45*

Upward heat flow for $\theta \le 60^o$

For the inside & outside of walls where the heat flow has an upward (or horizontal heat flow at the limit $\theta = 0^o$), and the outside of roofs, *Equation 40* applies:

$$h_n = 0.185(|\Delta T|cos\theta)^{\frac{1}{3}}$$

Upward heat flow for $\theta > 60^o$

To handle cases of upward heat flow for $\theta > 60^o$, h_{up} is found by interpolating between *Equation 40*, evaluated at $\theta = 60^o$, and *Equation 47* at 90^o. Equation *46*, for heat transfer from a horizontal surface ($\theta = 90$), 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.

$$Nu = 0.15 Ra^{\frac{1}{3}}$$ *Equation 46*

At 70-F, Equation *46* reduces to

$$h_n = 0.26(\Delta T)^{\frac{1}{3}}$$ *Equation 47*

Interpolating, for upward heat flow cases with $\theta \ge 60^o$:

$$h_{up} = 0.185(\Delta T cos60)^{\frac{1}{3}} + \frac{\left[0.26(\Delta T)^{\frac{1}{3}} - 0.185(\Delta T cos60)^{\frac{1}{3}}\right](\theta - 60)}{30}$$

which reduces to:

$$h_{up} = (0.00377 * \theta - 0.079)|\Delta T|^{\frac{1}{3}} \quad \text{for } 60^o \leq \theta \leq 90 \qquad \textit{Equation 48}$$

where θ is in degrees.

1.5.2.4 Inside forced convection equation

Measured forced convection heat transfer coefficients are frequently correlated using an equation of the form

$$h_{ach} = h_{forcedIN} = C_{ach} * ACH^{0.8} \qquad \textit{Equation 49}$$

The RBH model (Barnaby et al. (2004) suggests using $h_f = 0.88$ 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 $C_{ach} = 0.205$.

1.5.2.5 Outside forced convection equation for all walls and all roofs

From Clear et al. (2001, Eq. (11a)),

$$Nu = W_f R_f 0.037 Re^{0.8} Pr^{\frac{1}{3}} \qquad \textit{Equation 50}$$

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:

$$h_V = k * \frac{Nu}{L} = 0.527 W_f R_f \frac{V^{0.8}}{L^{0.2}} \qquad \textit{Equation 51}$$

where for walls,

$$L = wall\ L_{char} = 4\frac{Wall\ Area}{Wall\ Perimeter} = 4\frac{Height*Width}{2(Height+Width)} \approx height\ of\ square\ wall = Z_{eave}$$

V = wind velocity at eave height at building location, in ft/sec, $= 0.16 * \mathrm{Z}_{\mathrm{eave}}^{0.25} * V_{met}$ from Section 1.5.1.2.

V_{met} = freestream wind velocity, in ft/sec, 10 m (32.8 ft) above the ground at the meteorological station site.

R_f = 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 $h_c \approx 7.5$ averaged over all vertical surfaces, for wind speed $V_{met} = 3$-m/s. Thus, we estimate $W_f = \frac{7.5}{4.7V^{0.84}} = 0.63$.

and for roofs,

$$L = Roof\ L_{char} = 4\frac{Roof\ Plan\ Area}{Roof\ Perimeter} = 4\frac{Length * Width}{2(Length + Width)}$$
$$\approx \sqrt{Roof\ Area}\ for\ square\ roof \approx Z_{eave}$$

V = wind velocity 9.8 ft (3 m) above the eave height at building location, in ft/sec.

$$= 0.16 * (Z_{eave} + 9.8)^{0.25} * V_{met}$$

$W_f = 1$

R_f = 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."

Table 3: Surface Roughness Parameter R_f (Walton 1981)

Roughness Index	**Rf**	**Example**
1 (very rough)	2.1	Stucco
2 (rough)	1.67	Brick
3 (medium rough)	1.52	Concrete
4 (Medium smooth)	1.13	Clear pine
5 (Smooth)	1.11	Smooth plaster
6 (Very Smooth)	1	Glass

Source: NORESCO for California Energy Commission

1.5.2.6 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,

$h_{up} =$ Equation 40 or Equation 48 depending on whether θ is < or > 60°.

$h_{ach} =$ *Equation 49*

For downward heat flow:

$$h_{combined} = h_{down} + h_{ach}$$ *Equation 53*

where,

$h_{down} =$ *Equation 45*

$h_{ach} =$ *Equation 49*

1.5.2.7 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 η given by Equation 56 when forced convection is large ($\eta \rightarrow 0$ as the 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,

$h_n =$ *Equation 40*

$h_V =$ *Equation 51*

$$\eta = 1 \Big/ \left[1 + 1 \Big/ \left(ln\left(1 + \frac{0.06L|\Delta T|}{V^2} \right) \right) \right]$$ (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 η when forced convection is large ($\eta \rightarrow 0$ as the Reynolds number becomes large). Clear gives η as:

$$\eta = 1 \Bigg/ \left[1 + 1 \Bigg/ \left(ln\left(1 + \frac{Gr_L}{{Re_L}^2} \right) \right) \right]$$

Equation 55

At 70F, with $Gr = 2.28x10^6 L^3 |\Delta T|$, $\mathrm{Re}^2 = (6140\mathrm{VL})^2$, and $\mathrm{L} = \mathrm{L_{char}}$ for surface , Equation *55* reduces to:

$$\eta = 1 \Big/ \left[1 + 1 \Big/ \left(ln\left(1 + \frac{0.06L|\Delta T|}{V^2} \right) \right) \right]$$

Equation 56

For roofs:

$$h_{combined} = \eta h_n + h_V$$ *Equation 57*

where,

$h_n =$ Equation *45* for downward heat flow.

$h_n =$ *Equation 47* for upward heat flow.

$h_V =$ *Equation 51* for upward or downward heat flow.

η is from Equation 56

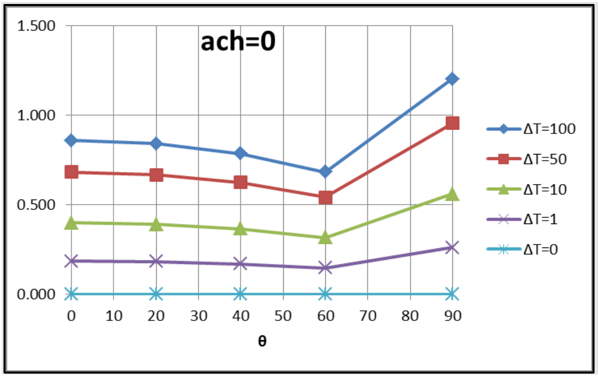
L & V are the same as used in *Equation 51* for roofs.

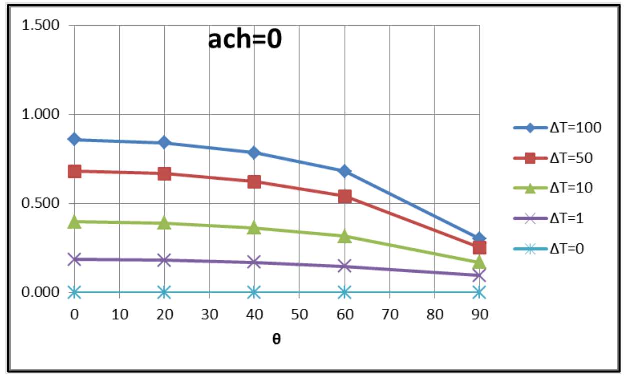
1.5.2.8 Plots of equations

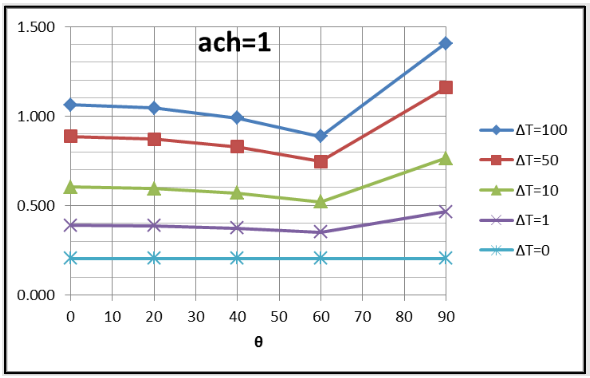
In Figure 6, the left hand column of plots are of *Equation 53*, for the downward heat flow cases shown in Figure 4. The right hand side plots are of *Equation 52*, for upward heat flow cases of Figure 5. All of the plots assume $T_{film} = 70F$, and $L_{char} = Z_{eave} = 20$ ft.

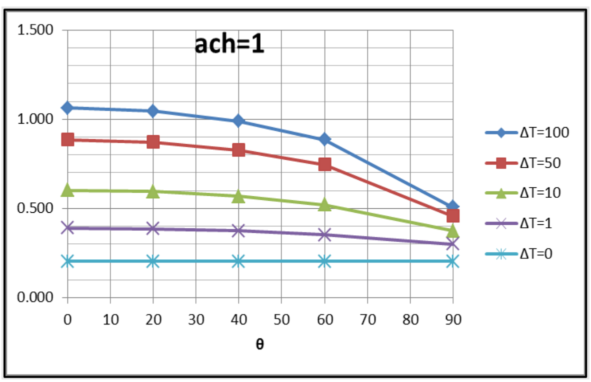
Figure 6: Plots of Equations for Downward and Upward Heat Flow

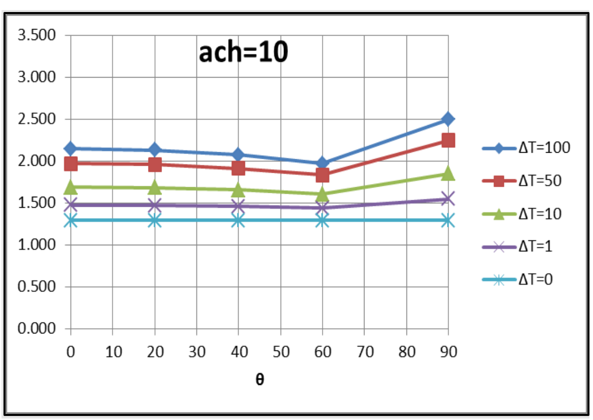
DOWNWARD HEAT FLOW (Equation 53): *UPWARD HEAT FLOW (Equation 52):*

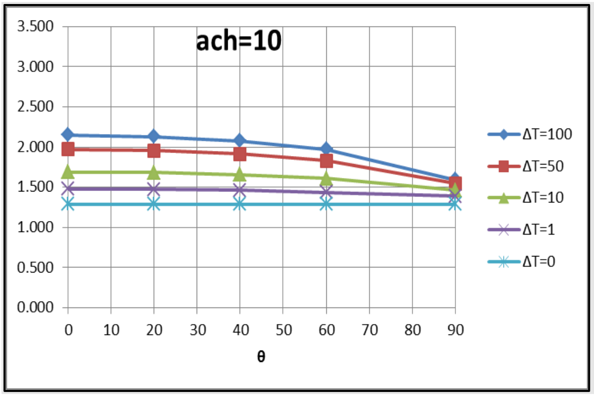

ach=0
1.500
1.000
0.500
0.000
0 10 20 30 40 50 60 70 80 90
θ
ΔT=100
ΔT=50
ΔT=10
ΔT=1
ΔT=0


ach=0
1.500
1.000
0.500
0.000
0 10 20 30 40 50 60 70 80 90
θ
ΔT=100
ΔT=50
ΔT=10
ΔT=1
ΔT=0


ach=1
1.500
1.000
0.500
0.000
0 10 20 30 40 50 60 70 80 90
θ
ΔT=100
ΔT=50
ΔT=10
ΔT=1
ΔT=0


ach=1
1.500
1.000
0.500
0.000
0 10 20 30 40 50 60 70 80 90
θ
ΔT=100
ΔT=50
ΔT=10
ΔT=1
ΔT=0

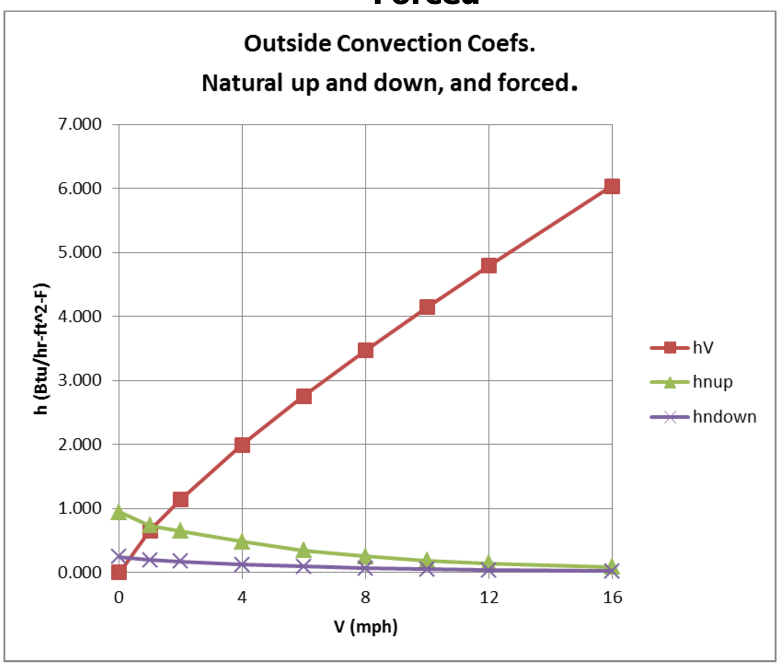

ach=10
3.500
3.000
2.500
2.000
1.500
1.000
0.500
0.000
0 10 20 30 40 50 60 70 80 90
θ
ΔT=100
ΔT=50
ΔT=10
ΔT=1
ΔT=0



OUTSIDE surface convection coefficient Plot for a horizontal roof:

For $\Delta T = 50\ F$, $L_{char} = 20$ ft, $R_f = 1.67$:

Figure 7: Outside Convection Coefficients, Natural Up and Down, and Forced



1.5.3 Outside Radiation Coefficients

1.5.3.1 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 ε and absorptivity α, 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:

$$q_{rad} = \varepsilon\epsilon_g\,\sigma F_{gnd}\left(T_s{}^4 - T_g{}^4\right) + \varepsilon\epsilon_g\,\sigma F_{sky}\beta\left(T_s{}^4 - T_{sky}{}^4\right) + \varepsilon\sigma F_{sky}(1-\beta)\left(T_s{}^4 - T_a{}^4\right)$$

Equation 58

where,

ε = surface emissivity.

ϵ_g = ground emissivity is assumed to be 1.

σ = 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 β weighted average of that from $\mathrm{T_{sky}}$ and that from T_a.

1.5.3.2 Fsky, Fgnd, and β

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, ϕ = surface tilt angle, the angle between ground upward normal and window outward normal (0° corresponds to a horizontal skylight, 90° to a vertical surface).

The parameter β accounts for the sky temperature's approach to the air temp near the horizon. β is the fraction of the sky effectively at Tsky; (1-β) is the fraction of the sky effectively at Ta. β is used by Walton (1983), and Energy Plus (2009), but appears to have little theoretical or experimental basis.

Walton (1983) give β as:

$$\beta = cos\left(\frac{\phi}{2}\right)$$

Since $cos\left(\frac{\varphi}{2}\right) = \sqrt{\frac{1+cos\varphi}{2}}$, it is noted that $F_{sky} = \beta^2$, and $F_{sky}\beta = \beta^3$.

1.5.3.3 Net radiant heat loss from a unit area

Equation 58 can be written as

$$q_{rad} = h_{rg}(T_s - T_g) + h_{rsky}(T_s - T_{sky}) + h_{rair}(T_s - T_a) \qquad \textit{Equation 59}$$

where,

$$h_{rg} = \varepsilon\epsilon_g\, \sigma F_{gnd}({T_s}^2 + {T_g}^2)(T_s + T_g)$$

$$h_{rsky} = \epsilon\sigma F_{sky}\beta({T_s}^2 + {T_{sky}}^2)(T_s + T_{sky})$$

$$h_{rair} = \varepsilon\sigma\, F_{sky}(1-\beta)(T_s^2 + T_a^2)(T_s + T_a).$$

T_g is assumed to be equal to *Ta*, so *Equation 59* becomes

$$q_{rad} = h_{rsky}(T_s - T_{sky}) + h_{ra}(T_s - T_a) \qquad \textit{Equation 60}$$

where,

$$h_{rsky} = \epsilon\sigma F_{sky}\beta({T_s}^2 + {T_{sky}}^2)(T_s + T_{sky}) \qquad \textit{Equation 61}$$

$$h_{rair} = \varepsilon\sigma\left(F_{sky}(1-\beta) + F_{gnd}\right)(T_s^2 + T_a^2)(T_s + T_a). \qquad \textit{Equation 62}$$

For a vertical surface, $F_{sky}\beta = 0.354$, and $F_{sky}(1-\beta) + F_{gnd} = 0.646$, so

$$h_{rsky} = 0.354\epsilon_s\sigma(T_s^2 + T_{sky}^2)(T_s + T_{sky}) \approx 4(0.354)\, \epsilon_s\sigma\overline{T^3}$$

$$h_{rair} = (0.146 + 0.5)\epsilon_s\sigma(T_s^2 + T_a^2)(T_s + T_a) \approx 4(0.646)\, \epsilon_s\sigma\overline{T}^3$$

1.5.3.4 Total effective conductance and outside effective temperature, T_{env}, for walls

Adding the exterior convection coefficient, hco, of *Equation 40* to *Equation 60* gives the total net heat transfer from the outside surface :

$$q_{rad+conv} = h_{rsky}(T_s - T_{sky}) + (h_{rair} + h_{co})(T_s - T_a) \qquad \textit{Equation 63}$$

This can be written as,

$$q_{rad+conv} = h_o(T_s - T_{env}) \qquad \textit{Equation 64}$$

where h_o is the effective exterior conductance to the conductance weighted average temperature, T_{env}.

$$h_o = h_{rsky} + h_{rair} + h_{co} \qquad \textit{Equation 65}$$

$$T_{env} = \frac{h_{rsky}T_{sky}+(h_{rair}+h_{co})T_a}{h_{rsky}+ h_{rair}+h_{co}} \qquad \textit{Equation 66}$$

1.5.3.5 Outside window surfaces

The ASHWAT window algorithm of Section 1.7 utilizes the irradiation intercepted by the window. From Equation 58 this can be deduced to be:

$$G = F_{gnd}\sigma T_{gnd}^4 + F_{sky}\beta\sigma T_{sky}^4 + F_{sky}(1-\beta)\sigma T_{air}^4 \qquad \textit{Equation 67}$$

1.5.4 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 ε_{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,

$$T_{sky} = \varepsilon_{sky}^{0.25}T_a, \qquad \textit{Equation 68}$$

where T_{sky} and T_a are in degrees Rankine.

The value of ε_{sky} depends on the dewpoint temperature, cloud cover, and cloud height data. Martin and Berdahl (1984) give the ε_{sky} for clear skies as ε_o:

$$\varepsilon_0 = 0.711 + 0.56\frac{T_{dew}}{100} + 0.73\left(\frac{T_{dew}}{100}\right)^2 + 0.13cos\left(\pi\frac{hr}{12}\right) + 0.00023(P_{atm} - 1000)$$

Equation 69

where,

T_{dew}= the dewpoint temperature in Celsius.

hr = hour of day (1 to 24).

P_{atm}= atmospheric pressure in millibars.

1.5.4.1 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.

$$\epsilon_{sky} = \varepsilon_0 + (1-\varepsilon_0)(n_{op}\varepsilon_{op}\Gamma_{op} + n_{th}\varepsilon_{th}\Gamma_{th})$$ *Equation 70*

where,

n_{op} = the opaque cloud fraction

n_{th} = the thin cloud fraction: $n_{th} = n - n_{op}$

n = the total sky cover fraction

ε_{op} = the opaque cloud emittance is assumed to be 1.

ε_{th} = the thin cloud emittance; assumed to be 0.4.

The cloud factor Γ 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, Γ 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, Γ_{th} is determined using an assumed cloud height of 8000-m, so,

$$\Gamma_{th} = e^{-\frac{8000}{8200}} = 0.377$$ *Equation 71*

For opaque clouds,

$$\Gamma_{op} = e^{-\frac{h}{8200}}$$ *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:

$$\epsilon_{sky} = \epsilon_0 + (1-\epsilon_0)\left[n_0\Gamma_{op} + (n-n_0) * 0.4 * 0.377\right]$$

$$\epsilon_{sky} = \epsilon_0 + (1-\epsilon_0)\left[n_0 e^{-\frac{h}{8200}} + 0.151(n-n_0)\right]$$ *Equation 73*

1.5.4.2 When opaque cloud cover data, $\mathrm{n_o}$, 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 $n_o = n$):

$$\epsilon_{sky} = \epsilon_0 + (1 - \epsilon_0)ne^{-\frac{h}{8200}}$$ *Equation 74*

For $h \geq 8000\ m$ (from Equation 73 with $n_{op} = n_{th} = \frac{n}{-}$):

$$\epsilon_{sky} = \epsilon_0 + (1 - \epsilon_0)n\left[\frac{1}{2}e^{-\frac{h}{8200}} + 0.0754\right]$$ *Equation 75*

1.5.4.3 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*

1.6 Distribution of SW and LW Radiation inside the Zone

1.6.1 Long Wave Radiation Distribution

1.6.1.1 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 (seeC) by using a mean radiant temperature node, Tr, 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.

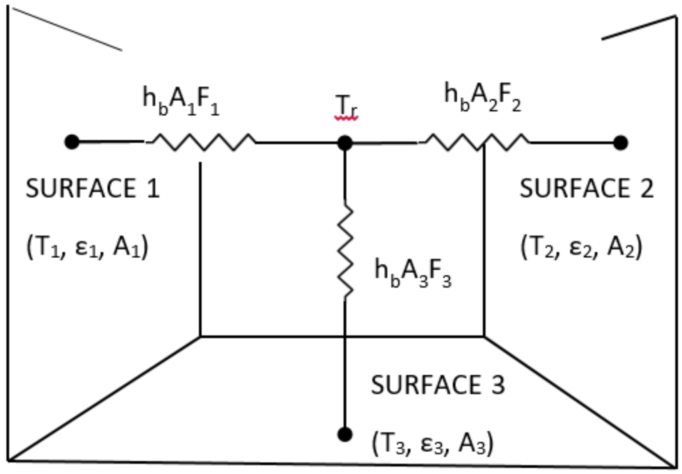
For black surfaces the radiant network is shown in Figure 8. For n surfaces, T_r floats at the conductance, A_iF_i, weighted average surface temperature:

$$T_r = \frac{\sum_1^n A_iF_iT_i}{\sum_1^n A_iF_i}$$

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 (seeD) of $\mathrm{T_I}$ in the temperature $\mathrm{T_r}$. The $\mathrm{F_I}$ factors are obtained from the set of n nonlinear equations for n surfaces:

$$F_i = \frac{1}{1 - \frac{A_i F_i}{\sum_1^n A_j F_j}}$$

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 $|\mathrm{T_r} - \mathrm{T_I}|$ being smaller than it would be had T_I not been part of the conductance weighted average T_r. The $\mathrm{F_I}$ 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-Δ transformation, the Figure 8 circuit can put in the form of the exact solution network of Figure C-1 in 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 Aj 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 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 ε_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:

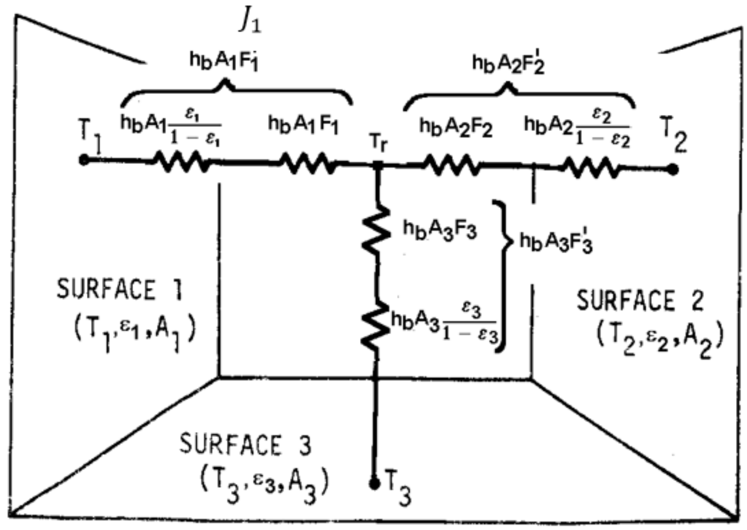
$$T_r = \frac{\sum_1^n A_i F_i' T_i}{\sum_1^n A_i F_i'}$$

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 1.6.1.3). 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 $A_i F_i'$.

Conversion to delta

Using a Y-Δ transformation, the radiant network of Figure 9 can be converted to the C, Figure C-3 circuit form, eliciting the F_{ij}' interchange factors implicit in Carroll's algorithm. Similar in form to Equation 80,

$$A_i F_{ij}' = \frac{A_i F_i' A_j F_j'}{\sum_{k=1}^{n} A_k F_k'}$$

Equation 84

Using these $A_i F_{ij}'$ values, q_{ij} can be obtained from

$$q_{ij} = h_b A_i F_{ij}' (T_i - T_j)$$

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:

$$q_i = \sum_{j=1}^{n} h_b A_i F_{ij}' (T_i - T_j)$$

Equation 86

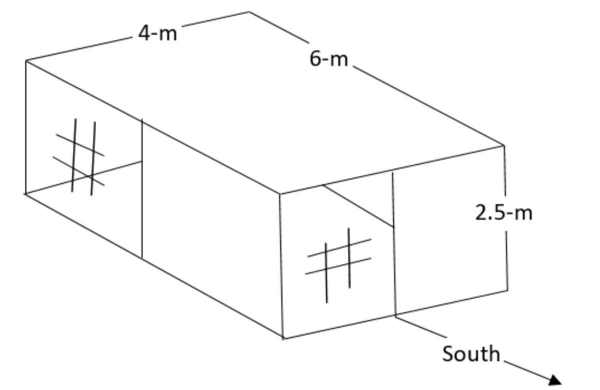
which will agree with the result of Equation 82.

1.6.1.2 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 ε = 0.84, and the rest of the interior surfaces have ε = 0.9.

Figure 10: Test Room of Walton (1980)



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, $\mathrm{q_{int}} + \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{q_i} = 0$.

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, compared to the q_i values found using the exact $A_i F'_{ij}$ values (obtainable from Figure C-3 of 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:

$$Err = \left(\frac{\frac{1}{n} \sum_{i=1}^{n} \Delta q_i^2}{\frac{1}{n} \sum_{i=1}^{n} \overline{q}_i^2} \right)^{\frac{1}{2}} * 100$$

Equation 87

where

$\Delta q_i = q_i - \overline{q}_i$, is the error in q_i.

$q_i = \sum_{j=1}^{n} h_b A_i F'_{ij} (T_i - T_j)$, using F'_{ij} values from Carroll's model, Equation 87.

$\overline{q}_i = \sum_{j=1}^{n} h_b A_i F'_{ij} (T_i - T_j)$, using the exact F'_{ij} values of Figure C-3 of C

$T_i - T_j = 1^0 F$ assumed in all cases.

n = 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.

$$ERR = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{\Delta q_i}{q_i} \right)^2 * 100$$

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.

Table 4: Err = % rms Error in q_i from Equation 87 and Equation 88 in Parenthesis

	Figure 10 room 2.5:4:6 ε = 0.9 (.84 wdws)	Corridor 10:1:1 ε = 0.9	Warehouse 10:10:1 ε = 0.9
Carroll	0.11 (0.19)	0.06(0.05)	0.07 (0.04)
Walton(1980)	1.9 (1.30)	0.6 (0.6)	4.4 (3.0)
NBSLD, BLAST	3.2 (2.1)	3.2 (2.6)	7.5 (4.4)

Source: NORESCO for California Energy Commission

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 C.

Carroll gives two percentage error results.

By the first method, for each surface i, the rms of the error, Δq_{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_i, of all the surfaces gives the final distribution error in percent:

$$ERR = \frac{\sqrt{\sum_{i=1}^{n}\left[\frac{\sum_{j=1}^{n}\Delta q_{ij}^2}{n(n-1)}\right]}}{\sqrt{\sum_{i=1}^{n}\left(\frac{\overline{q}_i^2}{n}\right)}} * 100$$

Equation 89

where

$$\Delta q_{ij} = q_{ij} - \overline{q}_{ij}$$

$q_{ij} = h_b A_i F'_{ij}(T_i - T_j)$ with F'_{ij} values from Equation 84.

$\overline{q}_{ij} = h_b A_i F'_{ij}(T_i - T_j)$ with the exact F'_{ij} values of Figure C-3 of 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, $\overline{q}_i$, is obtained.

$$Err = 100 * \sqrt{\sum_{i=1}^{n}\left[\frac{\sum_{j=1}^{n}\left(\frac{\Delta q_{ij}}{\overline{q}_i}\right)^2}{n(n-1)}\right]}$$

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

	Figure 10 room 2.5:4:6 ε = 0.9 (.84 wdws)	**Corridor 1:10:1 ε = 0.9**	**Warehouse 1:10:10 ε = 0.9**
Carroll	2.1 (3.9)	3.3 (2.8)	0.6 (1.9)
Walton(1980)	2.4 (3.7)	3.3 (2.8)	2.8 (3.0)
BLAST	2.8 (4.4)	3.4 (4.4)	3.4 (15)
NBSLD	1.7 (3.5)	1 (0.83)	3.3(1.9)

(Equation *91* was used for the results in parenthesis.)

Source: NORESCO for California Energy Commission

Carroll's model is seen to give very respectable results, despite giving no special treatment to coplanar surfaces.

1.6.1.3 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):

$$\varepsilon_a = 0.08\varepsilon_s ln\left[1+\left(\frac{4v}{\varepsilon_s A}RP_{atm}\right)e^{\frac{TaF-32}{30.6}}\right] \textit{Equation 91}$$

The logarithm is natural, and,

ε_s = the area-weighted average long-wave emissivity for room surfaces, excluding air.

V/A = the room volume to surface area ratio, in meters.

R = the relative humidity in the zone. (0 ☐ R ☐ 1).

Patm = atmospheric pressure in atmospheres.

☐a = zone air temperature, in ☐F.

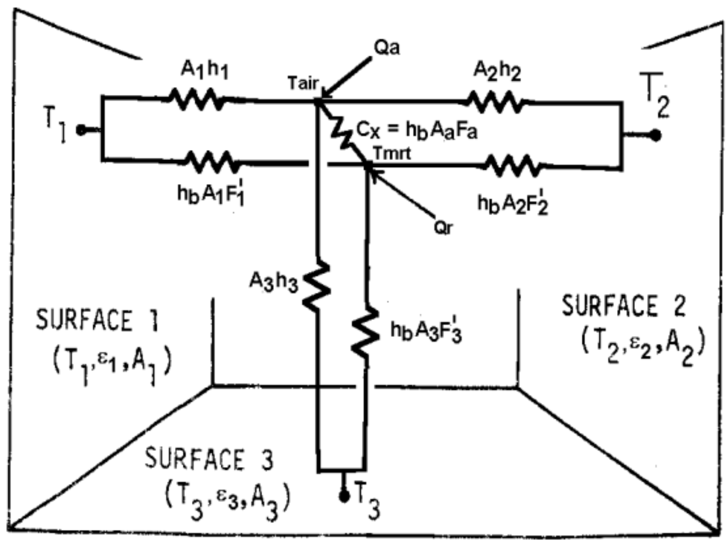
Following a heuristic argument Carroll assigns an effective area A_a to the air that is the product of $\square_a$ and the sum of all of the zone surface areas, as if the absorbing part of the air were consolidated into a surface of area A_a.

$$A_a = \varepsilon_a \sum A_i \qquad \text{Equation 92}$$

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:

$$C_x = h_b A_a F_a \qquad \text{Equation 93}$$

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:

$$F_i = 1 \Big/ \left[1 - \frac{A_i F_i / N_i}{S(A_i F_i)}\right] \qquad \text{Equation 94}$$

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.

1.6.1.4 Radiation removed at each surface of a zone by a single source of targeted insolation

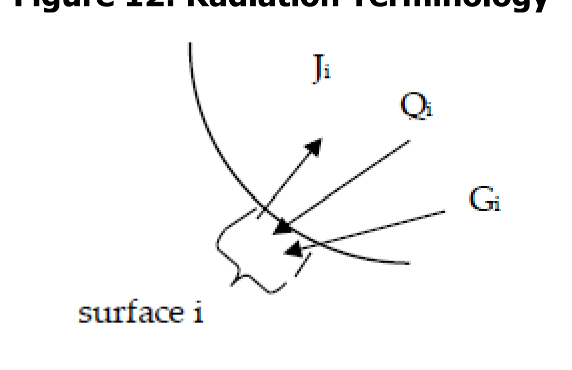
Assume a spherical zone with total insolation S(Btu/hr) admitted into the zone through one window. Assume that the portion $a_i Q_i$ (ft^2*Btu/(hr-ft^2)) of S(Btu/hr) is targeted to surface i with area a_i such that,

$$\sum_i a_i Q_i = S \qquad \textit{Equation 95}$$

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 Gi and Ji is developed:

Since G_i is composed only of reflected radiation,

$$a_i G_i = \sum_k J_k a_k F_{ik} \qquad \textit{Equation 96}$$

where the sum is over all surfaces n of the sphere of area a_S.

Using the view-factor reciprocity principle,

$$a_k F_{ki} = a_i F_{ik}$$

G_i becomes

$$G_i = \sum_k J_k F_{ik}$$

For spherical geometry, the view factor is $F_{ik} = \frac{a_k}{a_S}$, where $a_S = \sum a_k$, so G_i can be written

$$G_i = \frac{1}{a_S} \sum_k J_k a_k \qquad \textit{Equation 97}$$

The right hand side is the area-weighted average radiosity, showing that G_i is independent of i,

$$G_i = \bar{J} \qquad \textit{Equation 98}$$

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

$$J_i = \rho_i (G_i + Q_i) \qquad \textit{Equation 99}$$

Substituting *Equation 97* for G_i gives

$$\frac{J_i}{\rho_i} = \frac{1}{a_S} \sum_k J_k a_k + Q_i \qquad \textit{Equation 100}$$

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

$$\frac{J_i}{\rho_i} = \frac{1}{a_s} \sum_k \left[a_k \rho_k \left(\frac{J_i}{\rho_i} + Q_k - Q_i \right) \right] + Q_i$$

This can be solved explicitly for J_i:

$$J_i = \frac{\frac{1}{a_s} \rho_i}{1 - \bar{\rho}} \left(\sum_k a_k \rho_k Q_k \right) + Q_i \rho_i \qquad \textit{Equation 101}$$

From Equation 101, the area weighted average *J* is

$$J_i = \frac{\frac{1}{a_s}\overline{\rho}}{1-\overline{\rho}}\left(\sum_k a_k \rho_k Q_k\right) + \frac{1}{a_s}\sum_i a_i Q_i \rho_i$$

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:

$$Qnet_i = (G_i + Q_i - J_i)a_i = (\bar{J} - J_i + Q_i)a_i$$

Equation 103

Substituting Equation 101 and Equation 102 into this gives

$$Qnet_i = \frac{a_i}{a_s}\left(\frac{1-\rho_i}{1-\overline{\rho}}\right)\sum_k a_k \rho_k Q_k + a_i Q_i (1-\rho_i)$$

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 $Qnet_i$ for isotropically distributed insolation:

$$Qnet_i = \frac{a_i}{a_s}\left(\frac{1-\rho_i}{1-\overline{\rho}}\right)S$$

Equation 106

1.6.1.5 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}.

$$Qnet_i = \frac{a_i}{a_s}\left(\frac{1-\rho_i}{1-\overline{\rho}}\right)\sum_k a_k \rho_k Q_k + a_i Q_{ji}(1-\rho_i)$$

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

$$Qnet_{ji} = a_i S_j (1 - \rho_i) \left[\frac{H_{ji}}{a_i} + \frac{1}{a_s(1 - \overline{\rho})} \sum_k \rho_k H_{jk} \right]$$

Equation 109

The effective absorptivity of the targeted surfaces is defined as

$$\alpha effT_{ji} = \frac{Qnet_{ji}}{S_j}$$

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:

$$aeffT_{ji} = A_i F_i (1 - \rho_i) \left[\frac{H_{ji}}{A_i F_i} + \frac{1}{(1 - \overline{\rho}) \sum_i A_i F_i} \sum_k \rho_k H_{jk} \right]$$ *Equation 111*

If $\sum_k H_{jk} < 1$ then it is assumed that the remaining insolation $S_j(1 - \sum_k H_{jk})$is distributed isotropically. From Equation 105 it is

$$isotropic\ Qnet_{ji} = \frac{a_i}{a_s} \left(\frac{1-\rho_i}{1-\overline{\rho}} \right) S_j \left(1 - \sum_k H_{jk} \right)$$ Equation 112

The definition of the effective absorptivity for isotropic insolation is:

$$\alpha effI_{ji} = \frac{Qnet_{ji}}{S_j}$$

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.

$$aeffI_{ji} = \frac{A_i F_i}{\sum_k A_k F_k} \left(\frac{1-\rho_i}{1-\overline{\rho}} \right) S_j \left(1 - \sum_k H_{jk} \right)$$ 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:

$$\alpha eff_{ji} = A_i F_i (1-\rho_i)\left(\frac{1}{(1-\bar{\rho})\sum_k A_k F_k}\left[1-\sum_k (1-\rho_k) H_{jk}\right]+\frac{H_{ji}}{A_i F_i}\right)$$

Equation 115

The net radiation absorbed in surface i from window j is thus

$$Qnet_{ji} = A_i F_i (1-\rho_i) S_j \left(\frac{1}{(1-\bar{\rho})\sum_k A_k F_k}\left[1-\sum_k (1-\rho_k) H_{jk}\right]+\frac{H_{ji}}{A_i F_i}\right)$$

Equation 116

Summing this over all windows gives the total SW radiation absorbed and/or transmitted by surface i as:

$$Qnet_i = A_i F_i (1-\rho_i) \sum_j \left[S_j \left(\frac{1}{(1-\bar{\rho})\sum_k A_k F_k}\left[1-\sum_k (1-\rho_k) H_{jk}\right]+\frac{H_{ji}}{A_i F_i}\right)\right]$$

Equation 117

1.7 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.

1.7.1 Inputs

Each time step, for each window, ASHWAT is given the environmental inputs:

I = insolation incident on window system.

I_{refl} =insolation reflected diffusely from the other room surfaces.

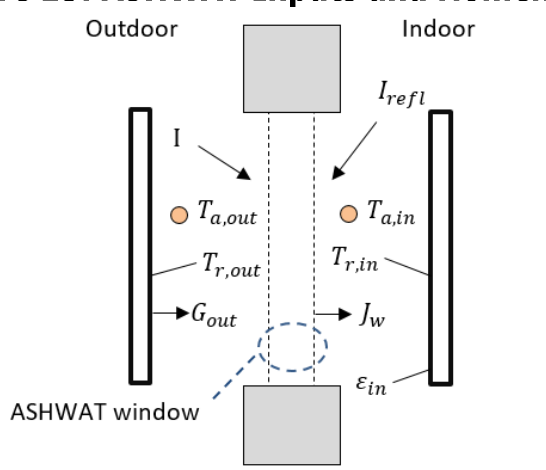
$T_{a,out}$ = outside dry bulb air temperature.

$T_{a,in}$ = inside dry bulb air temperature.

$T_{r,in}$ = the temperature of the indoor plate.

$T_{r,out}$ = the temperature of the outdoor plate.

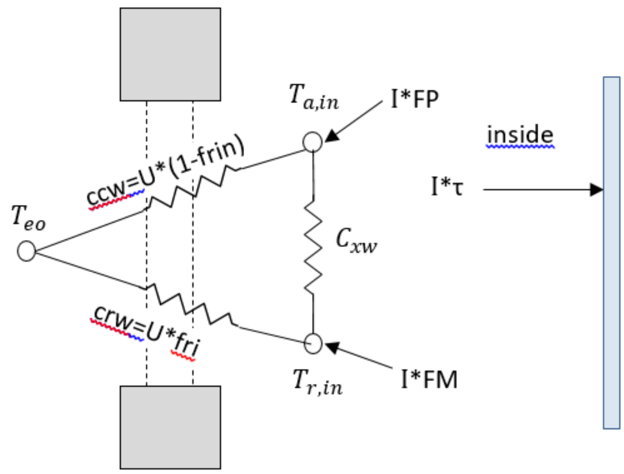
Figure 13: ASHWAT Inputs and Nomenclature



1.7.2 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).

Figure 14: Window System Representation in CSE



In Figure 14,

FP = fraction of the heat from Insolation absorbed in the various window layers that ends up being transferred to the inside radiant node.

FM = fraction of the heat from Insolation absorbed in the various window layers that ends up being convected to the inside air node.

$frin$ = fraction of total non-solar heat transfer that goes to the inside radiant node; dimensionless.

frout = fraction of non-solar heat transfer to the outside that goes to the outside radiant node.

U = conductance between the inside and outside effective temperatures T_{ei} and T_{eo}; Btu/(hr-sf-F), where $T_{ei} = T_{a,in}(1 - frin) + T_{r,in}frin$.

$T_{eo} = T_{a,out} * (1 - frout) + T_{r,out} * frout$ = the effective outdoor temperature; F.

C_{xw} = the cross coupling term; Btu/(hr-sf-F).

τ = 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 = $+ I\ (\tau + FP + FM) - I_{refl} + U(T_{eo} - T_{ei})$

1.7.3 Matching ASHWAT to CSE Radiant Network

1.7.3.1 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*.

1.7.3.2 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

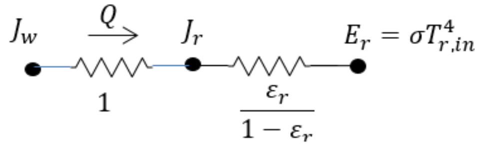
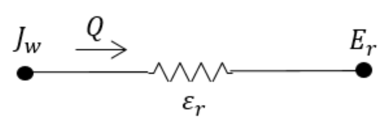


Figure 15 reduces to:

Figure 16: Reduced Figure 15



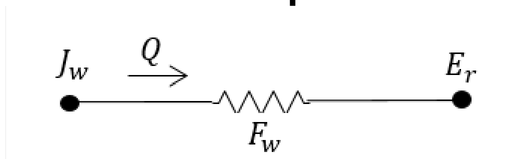
Thus the heat transfer rate per unit area, with Q positive from window to room, is:

$$Q = \varepsilon_r(J_w - E_r)$$

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



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 1.6.1. 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.

1.8 Slab Model

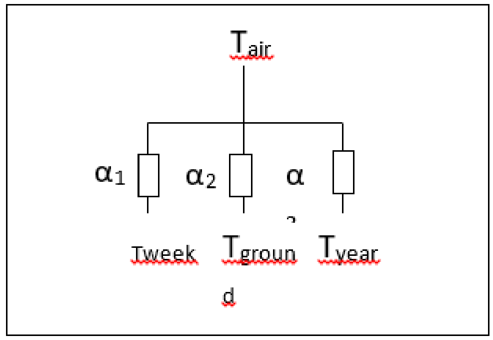
1.8.1 Bajanac Simplified Model

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.

1.8.1.1 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 α_1, α_2, and α_3 to three environmental temperatures: $\mathrm{T_{week}}$, , $\mathrm{T_{ground}}$, *and* $\mathrm{T_{year}}$:

Figure 18: Perimeter Coupling



Thus the instantaneous heat flow from the room Temp node to perimeter slab, in Btu/hr-sf-F, is given by:

$$Qperim = [\alpha_1(T_{air} - T_{week}) + \alpha_2(T_{air} - T_{ground}) + \alpha_3(T_{air} - T_{year})]$$

Equation 122

where,

T_{air} = the current interior-space effective temperature (involving both Ta and Tr).

T_{week} = the average outside air temperature of the preceding two-weeks.

T_{ground} = the current average temperature of the earth from the surface to a 10 ft depth.

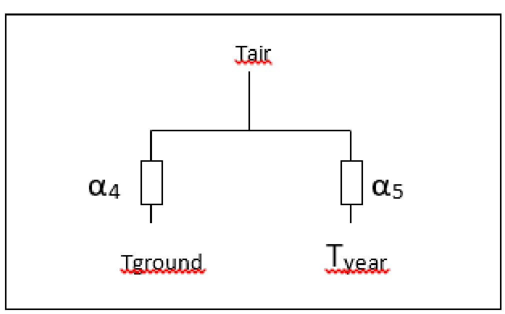
T_{year} = the average yearly dry bulb temperature.

α*'s =* conductances from Table 3 of Bazjanac et al; Btu/sf-hr-F.

1.8.1.2 Core region

The core region couples *T* to T_{ground} and T_{year}, via conductances α_4 and α_5.

Figure 19: Core Coupling



$$Qcore = [\alpha_4(T_{air} - T_{ground}) + \alpha_5(T_{air} - T_{year})]$$ Equation 123

Bazjanac et al. determined the conductances α_1, through α_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.

1.8.1.3 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.

1.8.1.4 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:

$$\mathrm{T_{ground}} = \mathrm{T_{yrAve}} - \mathrm{GM}\left(\frac{\mathrm{TyrMax}-\mathrm{TyrMin}}{2}\right) cos\left(\left(\frac{2\pi}{8760}\right)\theta - PO - \phi\right) \quad \text{Equation 124}$$

where,

$\mathrm{T_{yrAve}}$ = average outdoor temperature over year; F.

$\mathrm{T_{yrMax}}$ = highest average monthly outdoor temperature for the year; F.

$\mathrm{T_{yrMin}}$ = lowest average monthly outdoor temperature for the year; F.

$\mathrm{GM} = \sqrt{\frac{e^{-2\beta}-2e^{-\beta} cos\,\beta+1}{2\beta^2}}$ = dimensionless amplitude for integrated depth average.

$\beta = \mathrm{L}\sqrt{\frac{\pi}{\mathrm{D*PY}}}$ = dimensionless depth.

L = 10 ft, the depth over which average is taken.

D = thermal diffusivity of soil, ft^2/hr.

$\mathrm{PY} = 8760$ hr = period of 1 year.

$\theta = 24\left(\frac{365\mathrm{M}}{12} - 15\right)$ ≈ elapsed time from Jan-1 to middle of month M; hours.

M = month, 1à12.

$\phi = atan\left(\frac{1-e^{-\beta}(cos\beta+sin\beta)}{1-e^{-\beta}(cos\beta-sin\beta)}\right)$ = phase angle for depth averaged $\mathrm{T_{ground}}$; radians.

$\mathrm{PO} = 0.6$ *radians* = phase lag of ground surface temperature (assumed equal to air temperature) relative to January 1. From measured data, see Fig. 7 in Kusuda and Achenbach.

1.8.2 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:

$$Q = A * U_g\left(T_{air} - T_{geff}\right)$$

Equation 125

where T_{geff} is the α-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,

$$T_{geff} = \frac{\alpha_4 T_{ground} + \alpha_5 T_{yrAve}}{\alpha_4 + \alpha_4}$$

Equation 128

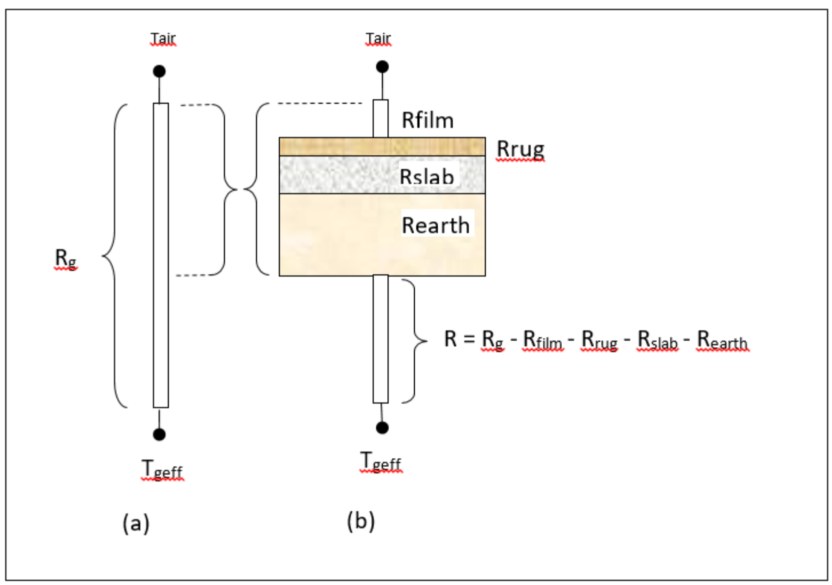
$$R_g = \frac{1}{\alpha_4 + \alpha_5}$$

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.

Figure 20: Addition of Film, Rug, Slab, and Earth



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 Q_{air} per degree amplitude of 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 Q_{air} per degreee amplitude of T_{geff}. [The same value of transfer admittance applies to the T_{geff} node, even if the circuit is not symmetrical, being the contribution to the T_{geff} node per degree amplitude of T_{air}]

Q_{air} = the amplitude (Btu/hr-ft^2-F) and phase of the heat transfer rate leaving T_{air}, and is composed of the contribution from all of the frequencies that may be extant in the driving temperatures T_{air} and 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 1.4; but this subdivision is irrelevant to the slab model discussion in this section.

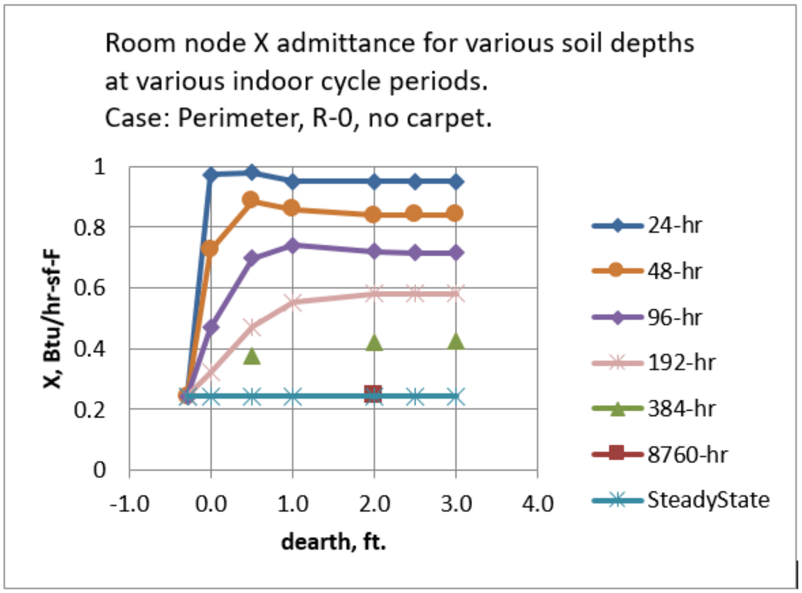
The maximum possible thickness of the earth layer is limited by the need for R to be positive. The limiting maximum possible thickness value, dmax, occurs in the perimeter case, when the foundation is uninsulated (i.e., the foundation insulation value R-0 in Bazjanac et al), and the slab is uncarpeted. In this case, dmax = 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.

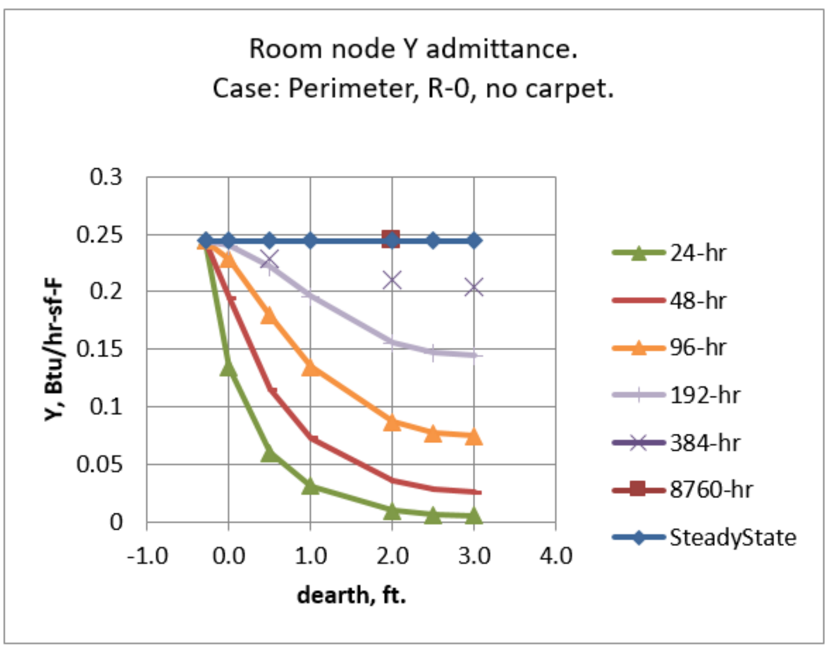
This is the case for all indoor driving frequencies periods of up to at least 384-hr = 16-days. Thus 2 ft of earth is able to portray the dynamics resulting from a cycle of 8-cloudy days followed by 8 sunny days.

Figure 21: Room Node X Admittance



The transfer admittance Y shown in Figure 22 also contributes to Q_{air} according to the frequencies extant in the driving temperature T_{geff}.

Figure 22: Room Node Y Admittance



As seen in Equation 128, for the slab core region, T_{geff} has the same frequency content as T_{ground} and T_{year}. T_{year} is a constant, i.e., zero frequency, steady-state.

As seen in Equation 124, T_{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 T_{geff} values. For a 2 ft earth layer the lag is ~40-hours. A 22-day lag is already included by φ 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, T_{geff} has the additional frequency content of the T_{week}, the two-week running average outdoor temperature. T_{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.

1.8.2.1 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.

1.8.2.2 Input properties

Strictly speaking, the same properties assumed in the Bazjanac model in Section 1.8.1.3 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 a1, a2...) obtained for the carpeted slabs were sensitive to the Rrug value used. While inputting a different value than Rrug = 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 Rrug = 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 Rfilm; its value is calculated each time-step and is used instead of 0.77, even though 0.77 is still the value subtracted from Rg 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.

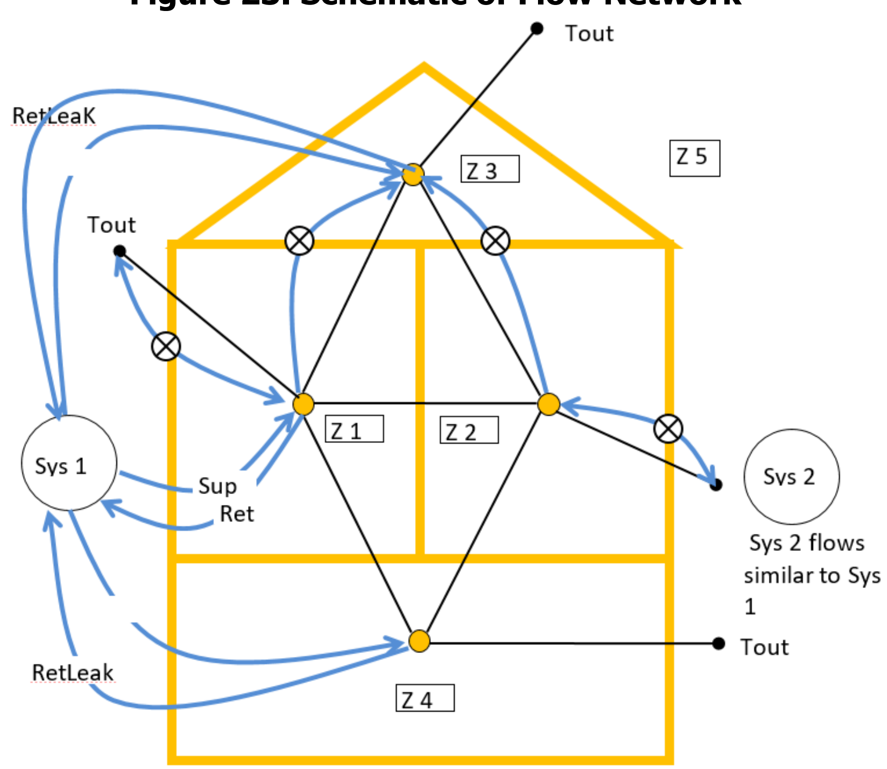
1.9 Ventilation and Infiltration Air Network

1.9.1 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



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 1.9.3 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 1.9.5– 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 1.9.4. This type of opening would typically be between zones Z1 and Z2 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.

1.9.1.1 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 ¼ 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.

1.9.2 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:

$$p_i = Pz_i - \rho_i g z_i$$

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. Pz_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 Pz_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 Pz_i for the outdoor side of a flow element is given by (*i* is 5 if there are 4 conditioned and unconditioned zones):

$$Pz_i = patm + CP * Pu$$

Equation 132

The weather tape atmospheric pressure, patm, is assumed to exist at the elevation z = 0 far from the building. 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:

$$Pu = \frac{\rho_{out}(S * U)^2}{2}$$

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.

ρ_{out} is the outside air density.

CP is the orientation sensitive pressure coefficient.

1.9.2.1 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 = ½ 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

Pressure Coefficient Upwind Wall	Pressure Coefficient Side walls	Pressure Coefficient Downwind Wall
+0.6	-0.65	-0.3

Source: NORESCO for California Energy Commission

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^o 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^o . 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

Roof Pitch ψ	Upwind Roof	Side Hip Roof	Downwind Roof	Ridge
$\psi < 10^o$	-0.8	-0.5	-0.3	-0.5
$10 \leq \psi < 15$	-0.5	-0.5	-0.5	-0.8
$15 \leq \psi < 25$	-0.3	-0.5	-0.5	-0.5
$25 \leq \psi < 35$	+0.1(pos)	-0.5	-0.5	-0.3
$35 \leq \psi < 50$	+0.3 (pos)	-0.5	-0.5	-0.2

Source: NORESCO for California Energy Commission

1.9.2.2 Density

Zone *i*'s air density ρ_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°F is $\frac{\partial\rho}{\partial T} / \frac{\partial\rho}{\partial p} = -\rho R_{air}$, 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 patm. (This has been changed in code so that ρ_i depends on both T_i and Pz_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

$$\Delta p_{ij} = p_i - p_j = Pz_i - Pz_j - gz_i(\rho_i - \rho_j)$$

Equation 135

1.9.3 Power Law Flow Equation

1.9.3.1 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:

$$m = C_D A\sqrt{2\rho_{in} g_c}\,(\Delta p)^{\frac{1}{2}}$$

Equation 136

where

C_D is the dimensionless orifice contraction coefficient.

$C_D = \frac{\pi}{\pi+2}$ = Kirchoff's irrotational flow value for a sharp edge orifice.

$C_D = 0.6$ default for CSE windows

$C_D = 1$ for rounded inlet orifice as used in ELA definition, and consistent with no vena contracta due to rounded inlet.

A = Orifice throat area, ft^2.

ρ_{in} = density of air entering the orifice; $\frac{lb_m}{ft^3}$.

$g_c = 32.2\,\frac{lb_m ft}{lb_f\,sec^2}$

1.9.3.2 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 = volume flow in ft^3/sec.

m = mass flow in lb_m/sec.

ρ_{in} = entering air density, $\frac{lb_m}{ft^3}$

ΔP = pressure difference in $\frac{lb_f}{ft^2} = psf$.

n= measured exponent, assumed to be n = 0.65 if measured value is unavailable.

κ = measured proportionality constant.

Equation 137 and Equation 138 are dimensional equations. Thus κ is not a dimensionless number but implicitly has the dimensions $ft^{3+2n}/(sec*lb_f^n)$. See Section 1.9.3.8–Converting Units of κ.

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 ΔP 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 κ, 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 ΔP:

$$m = ELA\sqrt{2\rho_{in}g_c}P_r^{\frac{1}{2}-n}\Delta P^n$$

Equation 142

(Note that substituting Equation 140 into Equation 142 recovers the empirical Equation 137).

1.9.3.3 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*.

$$m_{i,j} = SP * A_e\sqrt{2\rho_{in}\,g_c}\left|\Delta p_{i,j}\right|^{n_g}$$

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:

- $A_e = \left(P_r^{\frac{1}{2}-n}\right) ELA$, where n here is the measured exponent.
- $n_g = n$
- $P_r = 0.08354 \frac{lb_f}{ft^2}$

[Although C_D is dimensionless in Equation 136, the generalization to Equation 143 requires C_D to implicitly have the units of$(lb_m)^{\frac{1}{2}-n_g}(ft)^{2n_g-1}$].

1.9.3.4 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:

$$\frac{\partial m_{i,j}}{\partial p_i} = A_e n_g \sqrt{2\rho_{in}} |\Delta p_{i,j}|^{n_g - 1}$$

Equation 144

Since $n_g < 1$ this derivative à∞ as ΔPà zero, 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, ΔP_L, the power law is extended to the origin by a linear power law ($n_g = 1$),

$$m_{i,j} = SP * A_{elinear} \sqrt{2\rho_{in}\, g_c} \left|\Delta p_{i,j}\right|^1$$

Equation 145

as shown in Figure 24.

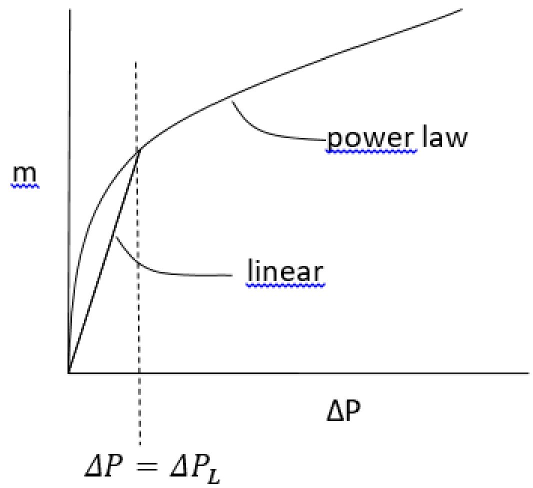
So that the flow rates match when $\Delta P = \Delta P_L,\ A_{elinear}$ is determined by equating Equation 145 to Equation 143 with $\Delta p = \Delta P_L$, giving:

$$A_{elinear} = A_e \Delta P_L{}^{ng-1}$$

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.

Figure 24: Mass Flow m versus Pressure Drop ΔP



1.9.3.5 Summary of inputs to the generalized flow equation

The generalized flow equation, Equation 143,

$$m_{i,j} = SP * A_e\sqrt{2\rho_{in}\, g_c}\,|\Delta p_{i,j}|^{ng}$$

is used with the following parameter values, depending on element type and pressure drop ΔP.

1.9.3.6 For windows, doors, and vents

If $\Delta P > \Delta P_L$:

- $A_e = A * C_D$
- A = area of flow element; ft^2.
- $C_D = 0.6$.
- $n_g = \frac{1}{2}$

If $\Delta P < \Delta P_L$:

- $Ae = C_D\, A * \Delta {P_L}^{0.5-1} = C_D \frac{A}{\sqrt{\Delta P_L}}$
- A = area of flow element; ft^2.
- $C_D = 0.6$
- $n_g = 1$
- ΔP_L = determined by computational experiment.

1.9.3.7 For infiltration leakage elements

If $\Delta P > \Delta P_L$:

- $A_e = \left(P_r^{\frac{1}{2}-n}\right) ELA$, *n* here is the measured exponent, or 0.65 if not known. (Note that if $n = 0.65$, $A_e = 1.45 * ELA$, 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 κ and n using Equation 140. See Section 1.9.3.8–Converting units of κ.
  - code regulations, in which case $n = 0.65$ is assumed.

If $\Delta P < \Delta P_L$:

- $A_e = \Delta {P_L}^{n-1}\left(P_r^{\frac{1}{2}-n}\right) ELA$, where n here is the measured value, or 0.65.
- $n_g = 1$
- $P_r = 0.08354 \frac{lb_f}{ft^2}$

1.9.3.8 Converting units of κ

The κ in Equation 137 is not dimensionless, so κ changes value depending on the units of Q and ΔP in Equation 137. The analysis herein (Section 1.9) assumes Q in $\frac{ft^3}{sec}$d ΔP in $\frac{lb_f}{ft^2}$.

However, conventionally κ is obtained from measured data with $Q \text{ in } \left(\frac{ft^3}{\min}\right)$ and $\Delta P \text{ in } Pascals$. With these units Equation 137 takes the form:

$$Q[cfm] = \kappa'(\Delta P(Pa))^n$$

Equation 147

Using dimensional analysis the value of κ to be used in Equation 137 with Q in $(\mathrm{ft}^3/\sec)$ and $\Delta \mathrm{P} \text{ in } \left(\frac{\mathrm{lb_f}}{\mathrm{ft}^2}\right)$ is:

$$\kappa = \left(\frac{47.88^n}{60}\right)\kappa'$$

Equation 148

where the numbers are from the conversion factors $47.88\frac{\mathrm{Pa}}{\frac{\mathrm{lb_f}}{\mathrm{ft}^3}}$ and 60 sec/min. $\kappa = 0.206\kappa'$ for $\mathrm{n} = 0.65$.

κ' = the measured value from data with $Q \text{ in } \left(\frac{ft^3}{\min}\right)$ and $\Delta P \text{ in } Pascals$.

1.9.3.9 ACM Manual relationship between CFM50 and ELA

Using Equation 142 (in volume flow form) the infiltration volume flow, CFS50, with 50 Pa pressurization is:

$$\text{CFS50} = \text{ELA}\sqrt{\frac{2g_c}{\rho}}P_r^{\frac{1}{2}-n}\Delta P^n = ELA\sqrt{\frac{64.4}{0.075}}0.08354^{-0.15}\,1.04428^{0.65} = 43.738 * ELA$$

Equation 149

where

ΔP = 50 Pa = 1.04428 psf

CFS50 = flow in units of $\frac{ft^3}{sec}$or cfm units, and ELA in square inches,

CFM50 = (60/144)CFS50 = 18.224*ELA

Equation 150

or alternately,

ELA [in^2] = 0.055*CFM50

Equation 151

This is the equation used to get ELA from blower door data at 50 Pa pressure difference.

1.9.3.10 Heat Flow

When the flow $m_{i,j}$ is positive, the heat delivered to zone j by this flow is given by

$$Q_j = m_{i,j} C_p (T_i - T_j)$$

Equation 152

while the heat delivered to zone *i* by the flow $m_{i,j}$ is zero:

$$\mathrm{Q_i} = 0$$

Equation 153

When the flow $m_{i,j}$ is negative, the heat delivered to zone j is zero,

$$Q_j = 0$$

Equation 154

while the heat delivered to zone *i* by the flow $m_{i,j}$ is:

$$Q_i = m_{i,j} C_p (T_i - T_j)$$

Equation 155

1.9.4 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 1.9.3.3 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 is the lower zone, i.e., $T_{upper-zone} < T_{lower-zone}$. 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.

1.9.4.1 Pressure driven flow

The pressure forced flow is modeled as orifice flow using Equation 143, except the area A in the Section 1.9.3.5 is replaced by:

$$Aeff = L1 * L2 * sin(StairAngle) * (1 + cos(StairAngle))$$

Equation 156

L1 and *L2* are the dimensions of the horizontal rectangular hole. To include the effect of stairs, a $StairAngle$ can be set, where $StairAngle = 90 \text{ deg}$ 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 *Aeff* in place of A.

1.9.4.2 Buoyancy flow

When the zone on top has a higher density than the zone on the bottom, the maximum possible buoyancy flow, mbm, occurs when the pressure difference across the hole is zero:

$$mbm = 0.055\sqrt{g\bar{\rho}|\Delta\rho|Dhyd^5}$$

Equation 157

The 0.055 factor is dimensionless ; g = 32.2 ft/s^2.

The hydraulic diameter of the hole is defined as:

$$Dhyd = 2 * \frac{Aeff}{L1 + L2}$$

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:

$$mb = mbm * \left(1 - \frac{|\Delta p|}{\Delta pF}\right)$$

Equation 159

The flooding pressure difference ΔpF is defined as:

$$\Delta pF = \frac{C_s^2 g|\Delta\rho|Dhyd^5}{2\mathrm{A}_{\mathrm{eff}}^2}$$

Equation 160

The shape factor C_s is

$$C_s = 0.942\left(minimum\left(\frac{L1}{L2},\frac{L2}{L1}\right)\right)$$

Equation 161

If the top zone density is lower than the bottom zones, or if $|\Delta p| > \Delta pF$ 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 exists, the heat transfer due to the buoyancy flow to the upper zone, *i* say, is

$$\mathrm{Q_i} = \mathrm{mb} * \mathrm{C_p}(\mathrm{T_j} - \mathrm{T_i})$$

Equation 162

and to the lower zone is

$$\mathrm{Q_j} = \mathrm{mb} * \mathrm{C_p}(\mathrm{T_i} - \mathrm{T_j})$$

Equation 163

1.9.5 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 Δp equal to the pressure difference ¾ the way up the opening (the midpoint of the top half of the opening area). Similarly, the flow through the bottom half uses the Δp at ¼ 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 *Δp* à *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 ELA/2, located at the ¼ and ¾ heights. These holes are then modeled using Equation 138, Equation 141, Equation 144, and Equation 145.

1.9.5.1 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 ELA/2, is placed at the height that is above ¼ of the area of the triangle. This can be shown to be a height of:

$$H_{lower\ hole} = Z_{soffit} + \left(1 - \frac{\sqrt{3}}{2}\right)\left(Z_{ridge} - Z_{soffit}\right)$$

Equation 164

Similarly, the top hole is placed at the height above ¾ of the area of the triangle:

$$H_{upper\ hole} = Z_{soffit} + \left(\frac{1}{2}\right)\left(Z_{ridge} - Z_{soffit}\right)$$

Equation 165

1.9.6 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).

$$m_{i,j} = \sum_{k=1}^{K_{i,j}} m_{i,j,k}$$

Equation 166

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

$$\mathrm{m_{I,j}} \ = -\ \mathrm{m_{j,i}}$$

Equation 168

From Equation 167, $\mathrm{m}_{\mathrm{I,j},k}$ values are functions of the zone pressure difference $(P_i - P_j)$.

$$\mathrm{m_{i,j,k}} = +\ \mathrm{A_e}\sqrt{2\rho_{in}}\left(\mathrm{P_i} - \mathrm{P_j}\right)^{\mathrm{n}}$$ for positive ΔP

$$\mathrm{m_{i,j,k}} = -\mathrm{A_e}\sqrt{2\rho_{in}}\left(\mathrm{P_j} - \mathrm{P_i}\right)^{\mathrm{n}}$$ for negative ΔP

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 *ri*:

$$r_i = \sum_{j=1,j\neq i}^{nout} m_{i,j} = \sum_{j=1,j\neq i}^{j=nout} \sum_{k=1}^{K_{i,j}} m_{i,j,k}$$

Equation 171

The $j \neq i$ criterion on the sums eliminates summing $m_{i,i}$ terms which are zero by definition. The zone pressures $\mathrm{P_I}$ are to be determined such that the residuals $\mathrm{r_I}$ all become zero.

Equation 169 and Equation 171 constitute a set of n = nuc nonlinear equations with n = 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:

$$r_i' = r_i + \sum_{j=1}^{nuc} \frac{\partial r_i}{\partial P_j} \left(P_j{}' - P_j\right)$$

Equation 172

In matrix form this is written:

$$\boldsymbol{r}' = \boldsymbol{r} + \boldsymbol{J}(\boldsymbol{P}' - \boldsymbol{P})$$

Equation 173

where $\boldsymbol{r}'$ is the vector with elements r_i', and $\boldsymbol{r}$ is the vector with elements r_i.

$\boldsymbol{J}$ is the nuc-by-nuc Jocobian matrix with elements:

$$J_{i,l} = \frac{\partial r_i}{\partial P_l} = \sum_{j=1}^{nout} \frac{\partial m_{i,j}}{\partial P_l} = \sum_{j=1,j\neq i}^{j=nout} \sum_{k=1}^{k=K_{i,j}} \frac{\partial m_{i,j,k}}{\partial P_l}$$

Equation 174

where $i = 1\ to\ nuc, and\ l = 1\ to\ nuc$.

Setting $r_i' = 0$ and solving for $P_j{}'$, Equation 173 becomes

$$\boldsymbol{P}' = \boldsymbol{P} - \boldsymbol{J}^{-1}\boldsymbol{r}$$

Equation 175

$$\boldsymbol{P}' = \boldsymbol{P} - \boldsymbol{C}$$

Equation 176

where ***C*** is the correction vector:

$$\boldsymbol{C} = -\boldsymbol{J}^{-1}\boldsymbol{r}$$

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.

1.9.6.1 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)).

1.9.6.2 Relaxation

Equation 178 is more generally written as

$$P_i' = P_i - relax * C_i$$

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 $\frac{C_i}{C_i^{last}}$. 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:

$$relax = \frac{1}{1 - \frac{C_i}{C_i^{last}}}$$

Equation 183

Thus, whenever, during an iteration for zone *i*,

$$\frac{C_i}{C_i^{last}} < -0.5$$

Equation 184

then Equation 178 is replaced by

$$P_i' = P_i - \frac{1}{1 - \frac{C_i}{C_i^{last}}} * C_i$$

Equation 185

Insofar as the extrapolation is warranted, this should give a better prediction of the pressure P_i' than would using *relax* = 1 for this iteration. For the iteration following that using Equation 185, *relax* = 1 is reverted to (i.e., Equation 178) so that only unrelaxed correction values are used to evaluate $\frac{C_i}{C_i^{last}}$. The following iteration, if any, is then again tested by Equation 184. The first iteration is always done with *relax = 0.75* since at this point there is no value available for C_i^{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.

1.9.6.3 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:

$$J_{i,l,i\neq l} = \sum_{k=1}^{K_{i,l}} \frac{\partial m_{i,l,k}}{\partial P_l}$$

Equation 186

where $i = 1\ to\ nuc, and\ l =\ 1\ to\ nuc$.

Equation 186, along with Equation 170, shows that all off diagonal terms have a negative magnitude. Since $m_{i,l,k} = -\ m_{l,i,k}$,

$$J_{i,l,i\neq l} = \sum_{k=1}^{K_{i,l}} \frac{\partial m_{i,l,k}}{\partial P_l} = -\sum_{k=1}^{K_{i,l}} \frac{\partial m_{l,i,k}}{\partial P_l}$$

Equation 187

Using Equation 170, Equation 187 becomes:

$$J_{i,l,i\neq l} = \sum_{k=1}^{K_{i,l}} \frac{\partial m_{l,i,k}}{\partial P_i} = J_{l,i,i\neq l}$$

Equation 188

Thus the Jacobian matrix is symmetric:

$$J_{i,l} = J_{l,i}$$

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.

1.9.6.4 Diagonal terms

For *i = j* Equation 174 gives:

$$J_{i,i} = \frac{\partial r_i}{\partial P_i} = \sum_{j=1}^{nout} \frac{\partial m_{i,j}}{\partial P_i} = \sum_{j=1}^{j=nout} \sum_{k=1}^{k=K_{i,j}} \frac{\partial m_{i,j,k}}{\partial P_i}$$

Equation 190

where $i = 1\ to\ nuc$.

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:

$$J_{i,i} = \frac{\partial m_{i,nout}}{\partial P_i} - \sum_{k=1,k\neq i}^{k=nuc} J_{k,i}$$

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 $\frac{\partial m_{i,nout}}{\partial P_i} = 0$, so that at least one connection to outdoors is necessary.

1.10 Duct System Model

1.10.1 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, $Qdel$, 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 $\frac{Qload}{}Qdel$ of the time step. The needed capacity, $Qneed$, 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 Qneed summarized in the hourly output.

The above steps are presented in detail in the following sections, in the same sequence as described above.

1.10.2 Duct System Inputs

1.10.2.1 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.

1.10.2.2 Annual run inputs

The following data is input to model the duct/air handler system(s):

Duct inside areas

$Asd_{c,u}$ = supply duct inside area for air handler c in unconditioned zone u.

$Ard_{c,u}$ = return duct inside area for airhandler c in unconditioned zone u.

Duct insulation rated R values

$Rsd_{c,u}$ = supply duct rated R for air handler c in unconditioned zone u; hr-ft^2-F/Btu.

$Rrd_{c,u}$ = 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-ft2-F/Btu).

Layed flat, the thickness the insulation layer is:

$$t = Rrate * k$$

Equation 192

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:

$$d_o = d_i + 2 * Rrate * k$$

so,

$$\frac{d_o}{d_i} = 1 + \frac{2kR_{rate}}{d_i}$$

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:

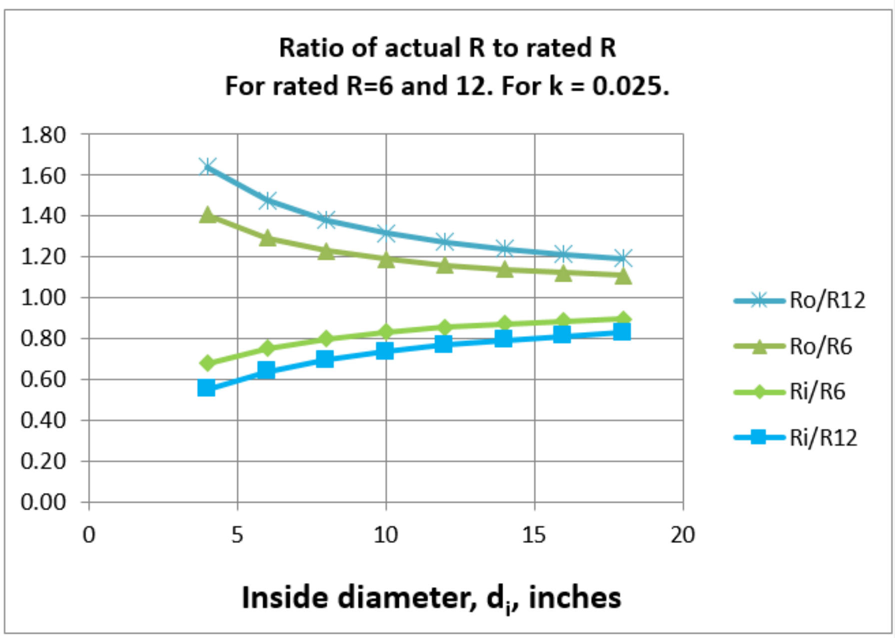
$$R_o = \frac{d_o}{d_i} R_i$$

Equation 197

$$A_o = \frac{d_o}{d_i} A_i$$

The R values of Equation 195 and Equation 197, divided by R_{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



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 Rrate, 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=1à 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:

$$'UA' = \sum_{j=1 \to n} \left(\frac{A_i(j)}{R_i(j)} \right)$$

Equation 198

where R_i for each branch segment j is given by Equation 196 as

$$R_i(j) = \frac{A_i(j) ln \left(\frac{A_o(j)}{A_i(j)} \right)}{2\pi k(j) L(j)}$$

Equation 199

With $A_i(j) = \pi d_i(j) L(j)$, and using Equation 193, this can be written as

$$R_i(j) = \frac{d_i(j) ln \left(1 + \frac{2k(j) R_{rate}(j)}{d_i(j)} \right)}{2k(j)}$$

Equation 200

The total branch inside area is:

$$A_i = \sum_{j=1 \to n} A_i(j)$$

Equation 201

The effective overall resistance of the branched duct, based on inside area A_i, is thus:

$$R_i = \frac{A_i}{'UA'} = \frac{A_i}{\sum_{j=1 \to n} \left(\frac{A_i(j)}{R_i(j)} \right)} = \frac{A_i}{\sum_{j=1 \to n} \left[\frac{A_i(j)}{\frac{d_i(j) ln \left(1 + \frac{2k(j) R_{rate}(j)}{d_i(j)} \right)}{2k(j)}} \right]}$$

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:

$$"R" = \frac{A_i}{\sum_{j=1 \to n} \frac{A_i(j)}{R_{rate}(j)}}$$

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:

$$A_o = \sum_{j=1 \to n} A_o(j)$$

Equation 204

Based on outside area, the effective duct system resistance would be:

$$R_o = \frac{A_o}{A_i} R_i$$

Equation 205

1.10.2.3 Emissivities

$epss_{c,u}$ = supply duct emissivity for air handler c in unconditioned zone u.

$epsr_{c,u}$ = return duct emissivity for air handler c in unconditioned zone u.

1.10.2.4 Duct leakage

$Ls_{c,u}$ = the fraction of the flow through the system c 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.

$Lr_{c,u}$ = the fraction of the flow through the system c 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.

1.10.2.5 System flow

$Flow_{m,c}$ = the flow rate in cfm (at standard conditions) through the air handler for the cooling and heating modes, for of each system.

1.10.2.6 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:

$Fmr_{c,u}$ = fraction of flow of system c in the return duct located in unconditioned zone u.

$Fms_{c,u}$ = fraction of flow of system c in the supply duct located in unconditioned zone u.

$Fmrc_c$ = fraction of flow of system c in the return duct located in conditioned zone c.

$Fmsc_c$ = fraction of flow of system c 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: $Fmr_{c,1}$ + $Fmr_{c,2}$ + $Fmrc_c$ = 1. Similarly for the supply duct fractions.

1.10.3 Return Duct Air Temperatures

Following the procedure indicated in Section 1.10.1, the return duct air temperatures are determined first. Utilizing the heat exchanger effectiveness approach (see Mills (1992), andA), 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:

$$Tout_{c,u} = Er_{m,c,u}Teqr_{c,u} + \left(1 - Er_{m,c,u}\right) \cdot Tmix_{c,u}$$

where $Er_{m,c,u}$ is the effectiveness of the return duct of system c in unconditioned zone u when operating in mode m:

$$Er_{m.c.u} = 1 - e^{\frac{-Urtot_{c,u}}{Mcpr_{m,c,u}}}$$

where $Urtot_{c,u}$ is the total conductance between the return duct air and the equivalent surroundings temperature $Teqr_{c,u}$:

$$Teqr_{c,u} = \left(Frda_{c,u} \cdot Tair_u + Frdr_{c,u} \cdot Tmrt_u\right)$$

$Frda_{c,u}$ is the fraction of return duct (dissolved surface node) conductance that goes to the $Tair_u$ node.

$$Frda_{c,u} = \frac{Urc_{c,u}}{(Urc_{c,u} + Urr_{c,u}}$$

$Frdr_{c,u}$ is the fraction of the conductance from the c,u return duct air that goes to the $Tmrt_u$ radiant node.

$$Frdr_{c,u} = \frac{Urr_{c,u}}{Urc_{c,u} + Urr_{c,u}}$$

The U terms are the conductances from the duct air to the mrt and air nodes, determined as described inA. These conductance values, and the similar supply duct values of Section 1.10.6 are used in the energy balance of the unconditioned zone(s) containing ducts.

Urr_{cu} = conductance from return duct air to Tmrt.

$Urc_{c,u}$ = conductance from return duct air to Tair.

$$Urtot_{c,u} = Urc_{c,u} + Urr_{c,u}$$

The term $Mcpr_{m,c,u}$ is the flow conductance (see below) for the return duct flow:

$$Mcpr_{m,c,u} = Mcp_{m,c}Fmr_{c,u}$$

The total system flow, $Mcp_{m,c}$ is in the "flow conductance" form with the units Btu/hr-F:

$$Mcp_{m,c} \quad = \quad Flow_{m,c} \cdot c_p$$

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 lb_m/ft^3 and c_p = 0.24 Btu/lb_m-F.

The term $Tmix_{c,u}$ is the mixed air just downstream of the return duct leakage, given by:

$$Tmix_{c,u} = Lr_{c,u}Tair_u + \left(1 - Lr_{c,u}\right)Temp_c$$

where $Temp_c$ is the temperature of conditioned zone c's air, assumed to be well-mixed.

1.10.4 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:

$$qlr_{c,u} \; = \; Mcpr_{m,c,u} \; \cdot \; \left(Tmix_{c,u} - \; Tout_{c,u}\right)$$

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,

$$Trp_c = \; Fmrc_c \; \cdot Temp_c \; + \sum_{all\, u} Fmr_{c,u} \; \cdot Tout_{c,u}$$

1.10.5 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.

1.10.6 Supply Plenum and Supply Register Temperatures

The supply plenum temperature is given by:

$$Tsp_c \; = \; Trp_c \; + \; dte_c$$

Equation 207

The supply register temperature for the supply duct of system c in unconditioned space u is:

$$Tsr_{c,U} = Teqs_{c,u} + \left(1 - Es_{m,c,u}\right) \cdot \left(Tsp_c - Teqs_{c,u}\right)$$

Equation 208

where $Es_{m,c,u}$ is the effectiveness of the supply duct of system c in unconditioned zone u when operating in mode m:

$$Es_{m,c,u} = 1 - e^{\frac{-Ustot_{c,u}}{Mcps_{m,c,u}}}$$

Substituting the Tsp_c equation above into Equation 208and rearranging gives:

$$Tsr_{c,u} = \left(1 - Es_{m,c,u}\right)dte_c + Tsrhx_{m,c,u}$$

Equation 209

Where

$$Tsrhx_{m,c,u} = \left(1 - Es_{m,c,u}\right)Trp_c + Es_{m,c,u}Teqs_{c,u}$$

$Tsrhx$ is the temperature that would be delivered to the supply register with the current mode's flow rate but with zero capacity such that $dte_c = 0$. The duct system is then acting as a heat exchanger (thus the 'hx') between the connected conditioned and unconditioned zones.

The term $s_{c,u}$, similar to $Teqr_{c,u}$ of Section 1.10.3, is an equivalent environmental temperature defined by

$$Teqs_{c,u} = \left(Fsda_{c,u} \cdot Tair_u + Fsdr_{c,u} \cdot Tmrt_u\right)$$

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.

$$Ustot_{c,u} = Usc_{c,u} + Usr_{c,u}$$

The supply duct flow rate is:

$$Mcps_{m,c,u} = Mcp_{m,c} \cdot Fms_{c,u}$$

1.10.7 Heating/Cooling Delivered and Supply Duct Conductive Heat Loss

Given $Tsr_{c,u}$, 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:

$$\text{Q delivered from ducts} = \sum_u Mcpsr_{m,c,u} \cdot \left(Tsr_{c,u} - Temp_c\right)$$

Equation 210

where $Mcpsr_{m,c,u}$, the flow out the supply register after the supply leakage is removed, is given by:

$$Mcpsr_{m,c,u} = \left(1 - Ls_{c,u}\right) \cdot Mcps_{m,c,u}$$

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:

$$\text{Q delivered directly to conditioned zone} = Fmsc_c \cdot Cap_c$$

Equation 211

Adding the Q's of Equation 210 and Equation 211 gives the net heating (+), or cooling (-), delivered by the system c as:

$$Qdel_c = Fmsc_c \cdot Cap_c + \sum_{\text{over } u}[Mcpsr_{m,c,u} \cdot (Tsr_{c,u} - Temp_c)]$$

Substituting the expression for $Tsr_{c,u}$ from Equation 209 into this, $Qdel_c$ can be put in the form:

$$Qdel_c = Qdel1_c + Qdel2_c,$$

where $Qdel1_c$ is the part of Qdel 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:

$$Qdel1_c = \sum_{all\,u}\left[Mcpsr_{m,c,u}\left(Tsrhx_{m,c,u} - Temp_c\right)\right]$$

$Qdel2_c$ is the part of $Qdel$ that is linearly dependent on the air handler capacity:

$$Qdel2_c = Fmsc_c \cdot Cap_c + \sum_{over\,u}\left[Mcpsr_{m,c,u} \cdot \left(1 - Es_{m,c,u}\right) \cdot dte_c\right]$$

The rate of supply duct conduction losses this time step is given by:

$$qls_{c,u} = Mcps_{m,c,u} \cdot \left(Tsp_c - Tsr_{c,u}\right)$$

1.10.8 Duct System Performance when the Load is Less than the Heat Delivered at Full Capacity

If Qld_c is smaller than the capacity $Qdel_c$, then the system runs only part of the time step. In this case the run time fraction is:

$$Frun_c = \frac{Qld_c}{Qdel_c}$$

The capacity required to meet the load is $Qneed_c$:

$$Qneed_c \ = \ Frun_c \cdot Cap_c$$

The duct conductive and leakage losses are also reduced by the same $Frun_c$ fraction.

1.10.9 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 η=Qload/Qneed] 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 $Qdel1$ and $Qdel2$ equations it can be seen that the capacity needed in this case is:

$$Qneed_c = \frac{Qld_c - Qdel1_c}{Qdel2_c} Cap_c$$

Thus, the temperature rise through the air handler needs to be:

$$dte_c = \frac{Qneed_c}{Mcp_{m,c}}$$

The supply plenum temperature becomes:

$$Tsp_c = Trp_c + dte_c$$

The supply register temperatures is determined reusing Equation 208:

$$Tsr_{c,u} = Teqs_u + \left(1 - Es_{m,c,u}\right) \cdot \left(Tsp_c - Teqs_{c,u}\right)$$

The supply duct losses now become:

$$qls_{c,u} = Mcps_{m,c,u} \cdot \left(Tsp_c - Tsr_{c,u}\right)$$

The $Qneed_c$'s from each of the time steps during the hour are summed over the hour and reported in the output as $Qneed_c$. 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.

1.11Variable 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:

$$k = (kn) \cdot \left(1 + 0.00418(T_{insul} - 70)\right)$$; temperatures in ^{o}F.

where,

k = insulation conductivity (Btu/hr-ft-R) at the average insulation temperature, T_{insul}(F).

kn = nominal insulation conductivity (Btu/hr-ft-R) for insulation at 70 F

1.12 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 $Tair_c > Tair_u$, the attic air temperature:

$$qbp = U(Tair_c - Tair_u)$$

where, the conductance follows a simple power law dependence on the temperature difference:

$$U = U_{bp}(Temp_1 - Tair_u)^{nbp}$$

Ubp 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 $U = 0.02Aceil$ were implemented, then nbp would be chosen as zero.

1.13 Zone Humidity Balance

1.13.1 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:

$$\frac{dMw}{dt} = \sum_j m_j(w_j - w) + m_{sched}$$

Equation 212

which can be written as:

$$M\frac{dw}{dt} = \sum_j m_j(w_j - w) + m_{sched} - w\frac{dM}{dt}$$

Equation 213

where,

M = mass of dry air in the zone; lbm of dry air.

$\frac{dw}{dt}$ = the rate of change of humidity ratio in zone.

m_j = air flow rate from source j into zone; lbm-dry-air/unit-time. Source j can be outdoors, a supply register, adjacent zone, etc.

w_j = humidity ratio of air coming from source j; lbm H_2O/lbm dry air.

w = humidity ratio of air in zone; lbm H_2O/lbm dry air.

m_{sched} = scheduled rate of moisture addition to zone; lbm H_2O/unit time.

Using the air perfect gas equation the last term in Equation 213 can be written

$$w\frac{dM}{dt} = -w\frac{M}{T}\frac{dT}{dt}$$

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 δt is the time step, using a forward difference, gives:

$$w(t+\delta t) = \left(m_{sched}(t) + \sum_j m_j(t)w_j(t)\right)\frac{\delta t}{M(t)} + w(t)\left(1 - \frac{\delta t}{M(t)}\sum_j m_j(t) - \frac{T(t+\delta t) - T(t)}{T(t)[\deg R]}\right)$$

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 1.3). The term $\frac{T(t+\delta t)-T(t)}{T(t)[\deg R]}$ is assumed to be negligible and not included in the CSE code.

1.13.2 Stability of Solution

The time series solution of Equation 215 will become unstable unless the second term is positive. That is, stability requires

$$\left(\frac{\delta t}{M(t)}\sum_j m_j(t) + \frac{T(t+\delta t)-T(t)}{T(t)[\deg R]}\right) < 1$$

Equation 216

Solving for δt, stability requires

$$\delta t < \frac{M(t)}{\sum_j m_j(t)}\left(1 - \frac{T(t+\delta t)-T(t)}{T(t)[\deg R]}\right)$$

Equation 217

Since the zone air changes per unit time is $AC = \frac{\sum_j m_j(t)}{M(t)}$ then the stability requirement can be written in terms of air changes as:

$$AC < \frac{1}{\delta t}\left(1 - \frac{T(t+\delta t)-T(t)}{T(t)[\deg R]}\right)$$

Equation 218

If the solution is unstable at the given δt, the zone air mass M(t) can be temporarily boosted up such that:

$$M(t) > \frac{\delta t \sum_j m_j(t)}{\left(1 - \frac{T(t+\delta t)-T(t)}{T(t)[\deg R]}\right)}$$

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.

1.13.3 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 determination of the moisture buffer potential of room enclosures, Journal of Building Physics, 34(3): 223-246.]

1.14 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.

1.15HVAC Equipment Models

Air conditioning systems shall be sized, installed, tested and modeled according to the provisions of this section.

1.15.1 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.

$$AC_{kWh} = \frac{Fan_{Wh} + Comp_{Wh}}{1{,}000}$$

Equation 219

Where:

AC_{kWh} = 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} = Indoor fan electrical energy for a particular hour of the simulation, Wh.

$Comp_{Wh}$ = 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:

Cap95 = AHRI rated total cooling capacity at 95 °F, Btuh

$CFM_{per\ ton}$ = Air flow rate per ton of cooling capacity, cfm/ton.

$$= \frac{\text{Operating air flow rate, cfm}}{\text{Cap95} — 12000}$$

EFan = Fan operating electrical power, W/cfm. Default = 0.365.

SEER = 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 = AHRI rated energy efficiency ratio at 95 °F, Btuh/W. If EER is not available, it is derived from SEER as follows:

SEER >=16 EER = 13

SEER >= 13 and <16 EER = 11.3 + 0.57 x (SEER - 13)

SEER < 13EER = 10 + 0.84 x (SEER – 11.5)

F_{chg} = Refrigerant charge factor, default = 0.9. For systems with a verified refrigerant charge (Reference Residential Appendix RA3), the factor shall be 0.96.

F_{size} = Compressor sizing factor, default = 0.95. 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 = Nominal cooling capacity defined as Cap95 / 12000

$QFan_{rat}$ = Assumed fan heat included at AHRI test conditions, Btuh

Fan motor type	$QFan_{rat}$
PSC	500 x Cap95 / 12000
BPM	283 x Cap95 / 12000

Source: NORESCO for California Energy Commission

$QFan_{op}$ = Fan heat assumed during operation (i.e., during simulation), Btuh

$$QFan_{op} = \frac{CFM_{per\ ton} \times Cap95 \times EFan \times 3.413}{12000}$$

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 = Dry bulb temperature of air at the condensing unit, °F (typically outdoor air temperature).

WB_{ec} = Coil entering air wet bulb temperature, °F (return air temperature adjusted for blow-through fan heat if any)

DB_{ec} = Coil entering air dry bulb temperature, °F (return air temperature adjusted for blow through fan heat if any)

Qneed = Cooling system sensible cooling output, Btuh. Qneed 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.

$$Comp_{wh} = \frac{QFan_{op} + Qneed}{CE_t}$$

Equation 221

Where:

Fan_{wh} = Fan power for this time step, Wh.

CE_t = Sensible energy efficiency at current conditions, Btuh/W. This is calculated using Equation 222 below.

$$CE_t = EER_t \times SHR$$

Equation 222

Where:

EER_t = Energy efficiency ratio at current conditions, Btuh/W. EER_t is calculated using Equation 226 below.

SHR = Sensible Heat Ratio (sensible capacity / total capacity), derived as follows:

$$
\begin{aligned}
SHR = \text{minimum}(1,\ & A_{SHR} \times DB_{ec} + \\
& B_{SHR} \times WB_{ec} + \\
& C_{SHR} \times DB_t + \\
& D_{SHR} \times CFM_{per\ ton} + \\
& E_{SHR} \times DB_{ec} \times DB_t + \\
& F_{SHR} \times DB_{ec} \times CFM_{per\ ton} + \\
& G_{SHR} \times WB_{ec} \times DB_t + \\
& H_{SHR} \times WB_{ec} \times CFM_{per\ ton} + \\
& I_{SHR} \times DB_t \times CFM_{per\ ton} + \\
& J_{SHR} \times WB_{ec}^2 + \\
& K_{SHR} / CFM_{per\ ton} + \\
& L_{SHR})
\end{aligned}
$$

SHR coefficients:

A_{SHR}	0.0242020
B_{SHR}	-0.0592153
C_{SHR}	0.0012651
D_{SHR}	0.0016375
E_{SHR}	0
F_{SHR}	0
G_{SHR}	0
H_{SHR}	-0.0000165
I_{SHR}	0
J_{SHR}	0.0002021
K_{SHR}	0
L_{SHR}	1.5085285

CAP_{nf} = Total cooling capacity across coil (that is, without fan heat) at current conditions, Btuh

$$CAP_{nf} = (Cap95 + QFan_{rat}) \times F_{chg} \times F_{size} \times F_{cond_{cap}}$$

Equation 223

$$
\begin{aligned}
F_{cond\_cap} = \ & A_{CAP} \times DB_{ec} + \\
& B_{CAP} \times WB_{ec} + \\
& C_{CAP} \times DB_t +
\end{aligned}
$$

$D_{CAP} \times CFM_{per\ ton}$ +
$E_{CAP} \times DB_{ec} \times DB_t$ +
$F_{CAP} \times DB_{ec} \times CFM_{per\ ton}$ +
$G_{CAP} \times WB_{ec} \times DB_t$ +
$H_{CAP} \times WB_{ec} \times CFM_{per\ ton}$ +
$I_{CAP} \times DB_t \times CFM_{per\ ton}$ +
$J_{CAP} \times WB_{ec}^2$ +
$K_{CAP} / CFM_{per\ ton}$ +
L_{CAP}

Coefficients as follows:

SHR Condition	SHR < 1	SHR = 1
A_{CAP}	0	0.009483100
B_{CAP}	0.009645900	0
C_{CAP}	0.002536900	-0.000600600
D_{CAP}	0.000171500	-0.000148900
E_{CAP}	0	-0.000032600
F_{CAP}	0	0.000011900
G_{CAP}	-0.000095900	0
H_{CAP}	0.000008180	0
I_{CAP}	-0.000007550	-0.000005050
J_{CAP}	0.000105700	0
K_{CAP}	-53.542300000	-52.561740000
L_{CAP}	0.381567150	0.430751600

Source: NORESCO for California Energy Commission

CAP_{sen} = Sensible capacity including fan heat, Btuh

$$CAP_{sen} = CAP_{nf} \times SHR - QFan_{op}$$

Equation 224

CAP_{lat} = Latent capacity, Btuh

$$CAP_{lat} = CAP_{nf} - CAP_{sen}$$

Equation 225

Note: The air leaving the AC unit is limited to 95% relative humidity. If that limit is invoked, CAP_{lat} is reduced and CAP_{sen} is increase.

EER_t is calculated as follows:

When

DB_t £ 82 ºF	$EER_t = SEER_{nf}$
82 < DB_t < 95 °F	$EER_t = SEER_{nf} + ((DB_t - 82)*(EER_{nf} – SEER_{nf}) / 13)$
DB_t ³ 95 °F	$EER_t = EER_{nf}$

Equation 226

Where:

$SEER_{nf}$ = Seasonal energy efficiency ratio at current conditions without distribution fan consumption ("nf" = no fans). This is calculated using Equation 227.

EER_{nf} = 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.

$$SEER_{nf} = \frac{F_{chg} \times F_{size} \times F_{cond_{SEER}} \times (1.09 \times Cap95 + QFan_{rat})}{1.09 \times Cap95/SEER - QFan_{rat}/3.413}$$

Equation 227

$$\begin{aligned} F_{cond\_SEER} = F_{cond\_cap} / \quad (&A_{SEER} \times DB_{ec} + \\ &B_{SEER} \times WB_{ec} + \\ &C_{SEER} \times DB_t + \\ &D_{SEER} \times CFM_{per\ ton} + \\ &E_{SEER} \times DB_{ec} \times DB_t + \\ &F_{SEER} \times DB_{ec} \times CFM_{per\ ton} + \\ &G_{SEER} \times WB_{ec} \times DB_t + \\ &H_{SEER} \times WB_{ec} \times CFM_{per\ ton} + \\ &I_{SEER} \times DB_t \times CFM_{per\ ton} + \\ &J_{SEER} \times WB_{ec}^2 + \\ &K_{SEER} / CFM_{per\ ton} + \\ &L_{SEER}) \end{aligned}$$

Coefficients as follows:

SHR Condition	SHR < 1	SHR = 1
A_{SEER}	0	0.0046103
B_{SEER}	-0.0202256	0
C_{SEER}	0.0236703	0.0125598
D_{SEER}	-0.0006638	-0.000512
E_{SEER}	0	-0.0000357
F_{SEER}	0	0.0000105
G_{SEER}	-0.0001841	0
H_{SEER}	0.0000214	0
I_{SEER}	-0.00000812	0
J_{SEER}	0.0002971	0
K_{SEER}	-27.95672	0
L_{SEER}	0.209951063	-0.316172311

Source: NORESCO for California Energy Commission

$$EER_{nf} = \frac{Cap_{nf}}{F_{cond_{EER}} \times (Cap95/EER - QFan_{rat}/3.413)}$$

Equation 228

Where:

$$\begin{aligned} F_{cond\_EER} = \quad & (A_{EER} \times DB_{ec} + \\ & B_{EER} \times WB_{ec} + \\ & C_{EER} \times DB_t + \\ & D_{EER} \times CFM_{per\ ton} + \\ & E_{EER} \times DB_{ec} \times DB_t + \\ & F_{EER} \times DB_{ec} \times CFM_{per\ ton} + \\ & G_{EER} \times WB_{ec} \times DB_t + \\ & H_{EER} \times WB_{ec} \times CFM_{per\ ton} + \\ & I_{EER} \times DB_t \times CFM_{per\ ton} + \\ & J_{EER} \times WB_{ec}^2 + \\ & K_{EER} / CFM_{per\ ton} + \end{aligned}$$

L_{EER})

Coefficients as follows:

SHR Condition	SHR < 1	SHR = 1
A_{EER}	0	0.004610300
B_{EER}	-0.020225600	0
C_{EER}	0.023670300	0.012559800
D_{EER}	-0.000663800	-0.000512000
E_{EER}	0	-0.000035700
F_{EER}	0	0.000010500
G_{EER}	-0.000184100	0
H_{EER}	0.000021400	0
I_{EER}	-0.000008120	0
J_{EER}	0.000297100	0
K_{EER}	-27.956720000	0
L_{EER}	0.015003100	-0.475306500

Source: NORESCO for California Energy Commission

1.15.2 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

Fchgheat = Heating refrigerant charge factor, default = 0.92. For systems with verified charge indicator light (Reference Residential Appendix RA3.4) or verified refrigerant charge (Reference Residential Appendix RA3), the factor shall be 0.96

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.

$$COP47 = \left(0.3038073 \times HSPF - 1.884475 \times \frac{Cap17}{Cap47} + 2.360116\right) \times Fchgheat$$

$$COP17 = \left(0.2359355 \times HSPF + 1.205568 \times \frac{Cap17}{Cap47} - 0.1660746\right) \times Fchgheat$$

$$Cap35 = 0.9 \times [Cap17 + 0.6 \times (Cap47 - Cap17)]$$

$$Inp35 = 0.985 \times [Inp17 + 0.6 \times (Inp47 - Inp17)]$$

$$COP35 = \frac{Cap35}{Inp35}$$

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)

$$Cap(T) = Cap17 + \frac{(Cap35 - Cap17) \times (T - 17)}{35 - 17}$$

$$Inp(T) = Inp17 + \frac{(Inp35 - Inp17) \times (T - 17)}{35 - 17}$$

Else

$$Cap(T) = Cap17 + \frac{(Cap47 - Cap17) \times (T - 17)}{47 - 17}$$

$$Inp(T) = Inp17 + \frac{(Inp47 - Inp17) \times (T - 17)}{47 - 17}$$

Resistance heat.

Load in excess of Cap(T) is met with backup heating at COPbu.

1.15.3 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.

2 Compliance Manager

2.1 Overview

2.2 One-dimensional Roof Edge Heat Transfer Model

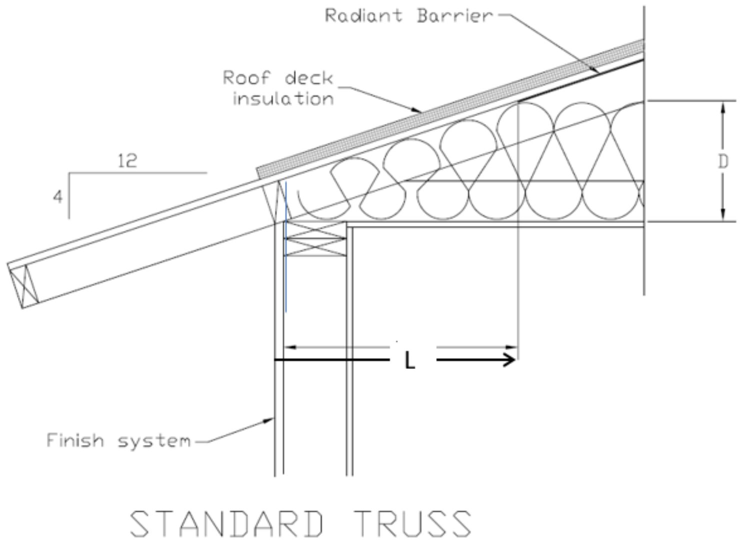
2.2.1 Construction Practice

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.

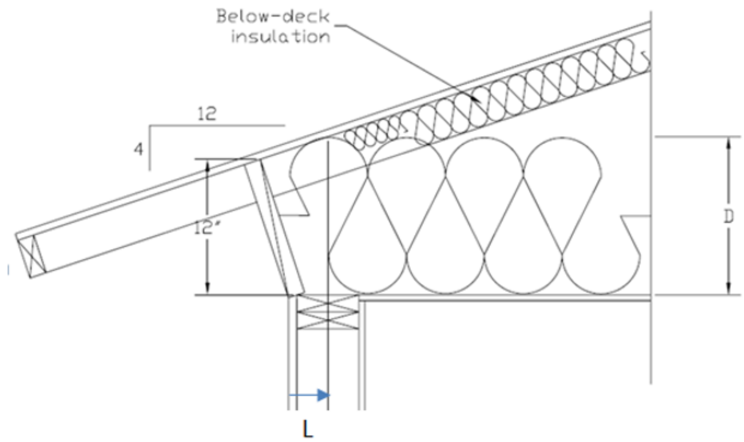
The 1-D model is developed in order to simplify the heat transfer calculation for roof edges, while preserving the steady state and transient characteristics (layer mass) of the typical roof constructions addressed. The 1-D model produces the dimensions of the construction layers needed to represent 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.

2.2.2 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.

2.2.2.1 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

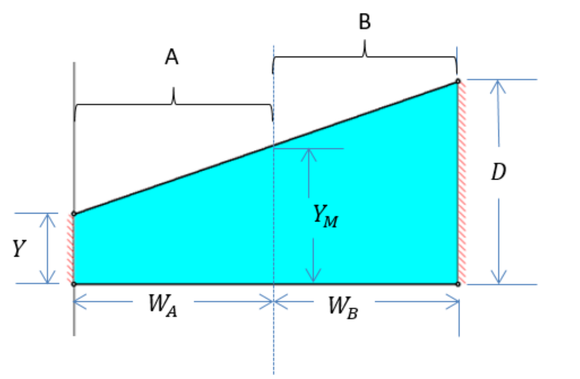
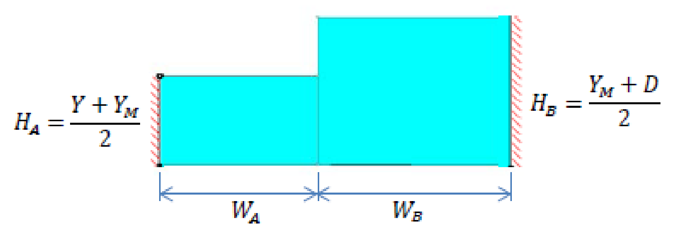


Figure 28 is then reduced to the 1-D form shown in Figure 29, where the layer thicknesses are taken as the average height of the layer in Figure 28.

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.

2.2.2.2 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. $\mathrm{H_{B1}}$, and $\mathrm{H_{B3}}$ are the vertical thickness of the 2x4's and $\mathrm{H_{B2}}$ is the average thickness of insulation.

Figure 30: Standard-Heel Simplified Geometry for Framing Path

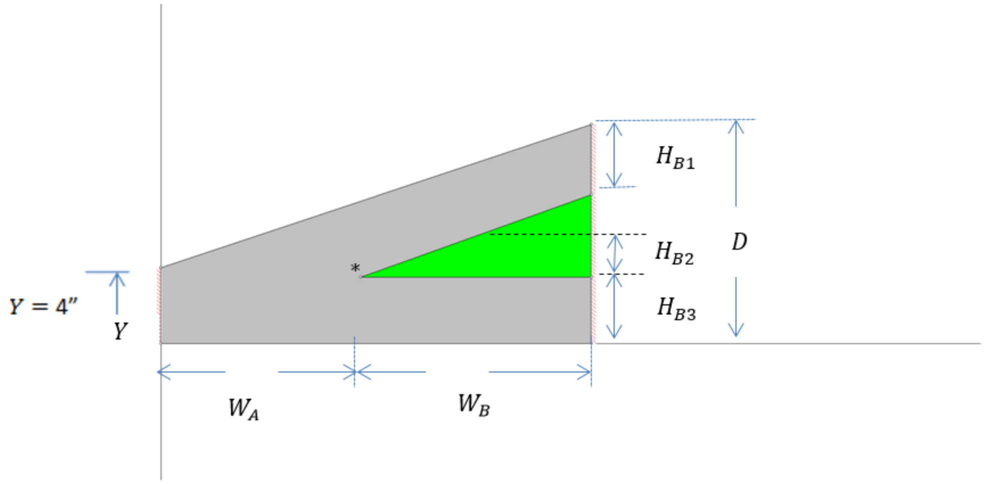
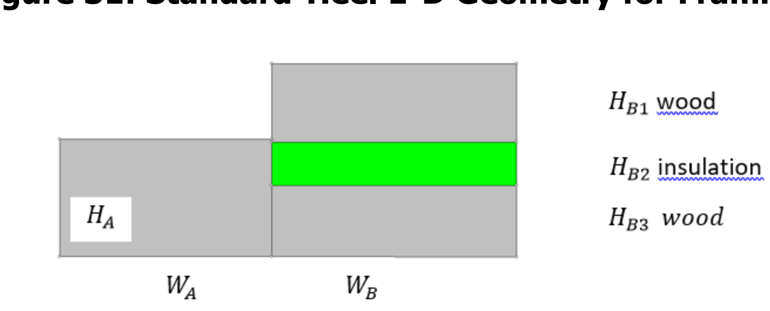


Figure 31: Standard-Heel 1-D Geometry for Framing Path



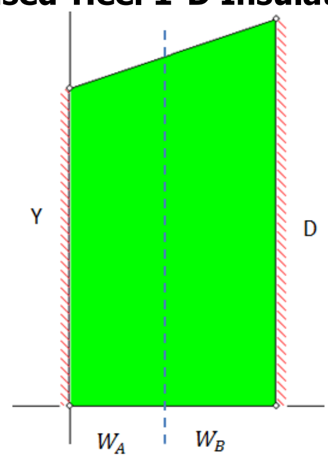
2.2.2.3 Raised heel

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.

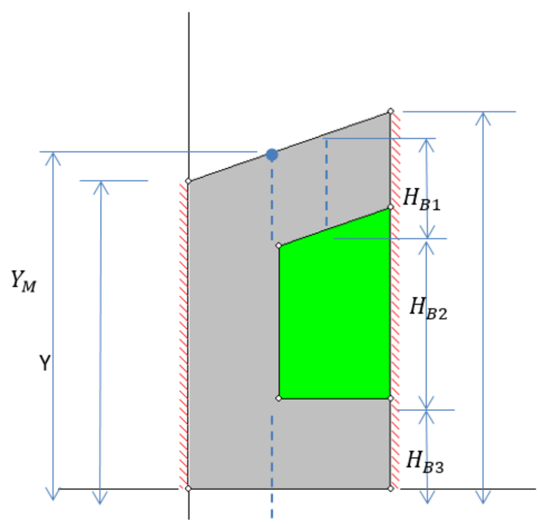
2.2.2.4 Raised heel insulation path

Figure 32: Raised-Heel 1-D Insulation Path Geometry



2.2.2.5 Raised heel frame path

Figure 33: 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.

2.2.2.6 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]

$Rtot$ = total R value of ceiling insulation, hr-ft^2-F/Btu.

R_{perin} = R value of the ceiling insulation for one inch thickness, hr-ft^2-F/Btu.

P = pitch = rise/12

Calculation of $\mathbf{W_A, W_B, H_A, H_B, H_{B1},\ H_{B2}, and\ H_{B3}}$:

$D = \frac{Rtot}{12 * R_{perin}}$ 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 ≤ Y)

$W_A = H_A = 0$

$W_B = H_B = H_{B1} = H_{B2} = H_{B3} = 0$

END IF

PRINT OUTPUT: $W_A, W_B, H_A, H_B, H_{B1}, H_{B2}, H_{B3}$

2.2.3 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.

2.2.3.1 1-D model, Rtot = 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

$R_{tot} = 30$ hr-ft^2-F/Btu.

$P = \frac{4}{12}$

Y = 0.3333 ft

w = 0.2917 ft

R_{perin} = 2.6 hr-ft^2-F/Btu.

Output of Roof Edge Algorithm

W_A =0.797 ft

$W_B = 1.087$ ft

H_A =0.466 ft

H_B =0.780 ft

$H_{B1} = 0.292$ ft

$H_{B2} = 0.182$ ft

$H_{B3} = 0.307$ ft

Insulation Path Results

The insulation conductivity is $k = \frac{1}{12R_{perin}} = 0.03205$ 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:

$$Q_A = \frac{W_A * \Delta T}{R_A} = \frac{0.797 * 100}{14.546} = 5.48 \text{ Btu/hr-ft}$$

$$Q_B = \frac{W_B * \Delta T}{R_B} = \frac{1.087 * 100}{24.346} = 4.465 \text{ Btu/hr-ft}$$

The total is:

$Q_{insulpath} = Q_A + Q_B =$ 9.944 Btu/hr-ft

Framing Path Results

Assume wood framing conductivity k = 0.084 hr-ft-F/Btu.

The thermal resistance of A, per foot of roof edge perpendicular to the section:

$R_A = \frac{H_A}{k_{wood}} = 5.55$ hr-ft^2-F/Btu

The thermal resistance of path B; sum of layer resistances:

$R_B = \frac{H_{B1}}{k_{wood}} + \frac{H_{B2}}{k_{insul}} + \frac{H_{B3}}{k_{wood}}$= 3.66+5.654+3.473=12.786 hr-ft^2-F/Btu

The sum of the heat transfers in this case is (from CathedralWorksheet.xlsx).

$Q_A = \frac{W_A * \Delta T}{R_A} = \frac{0.797*100}{5.550} = 14.36$

$Q_B = \frac{W_B * \Delta T}{R_B} = \frac{1.087*100}{12.786} = 8.50$

$Q_{framingpath} = Q_A + Q_B =$ 22.86 Btu/hr-ft

2.2.3.2 1-D model, Rtot = 60, Y = 4-inches

Input to Roof Edge Algorithm

Rtot = 60; other inputs the same as in Rtot = 30 case above.

Output of Roof Edge Algorithm

$\mathrm{W_A} =$ 0.797 ft

$\mathrm{W_B} =$ 3.972 ft

$\mathrm{H_A} =$ 0.466 ft

$\mathrm{H_B} =$ 1.261 ft

$\mathrm{H_{B1}} = 0.292$ ft

$H_{B2} =$ 0.662 ft

$H_{B3} =$ 0.307 ft

Insulation Path Results

Similar to the Rtot = 30 case, the thermal resistance of A and B are:

$R_A = \frac{H_A}{k_{insul}} = 14.546$ hr-ft^2-F/Btu

$R_B = \frac{H_B}{k_{insul}} = 39.346$ hr-ft^2-F/Btu

The heat transfer rates are:

$$Q_A = \frac{W_A * \Delta T}{R_A} = \frac{0.797 * 100}{14.546} = 5.48$$

$$Q_B = \frac{W_B * \Delta T}{R_B} = \frac{3.972 * 100}{39.346} = 10.095$$

$Q_{framingpath} = Q_A + Q_B =$ 15.57 Btu/hr-ft

Framing path results

The thermal resistance of A, per foot of roof edge perpendicular to the section:

$R_A = \frac{H_A}{k_{wood}} = 5.55$ hr-ft^2-F/Btu

The thermal resistance of path B is the sum of layer resistances. k = 0.084 hr-ft-F/Btu is assumed.

$R_B = \frac{H_{B1}}{k_{wood}} + \frac{H_{B2}}{k_{insul}} + \frac{H_{B3}}{k_{wood}} =$hr-ft^2-F/Btu

$= 3.472$ + 20.66 + 3.66 = 27.79

The sum of the heat transfers in this case is:

$$Q_A = \frac{W_A * \Delta T}{R_A} = \frac{0.797 * 100}{5.55} = 14.36$$

$$Q_B = \frac{W_B * \Delta T}{R_B} = \frac{3.972 * 100}{27.79} = 14.29$$

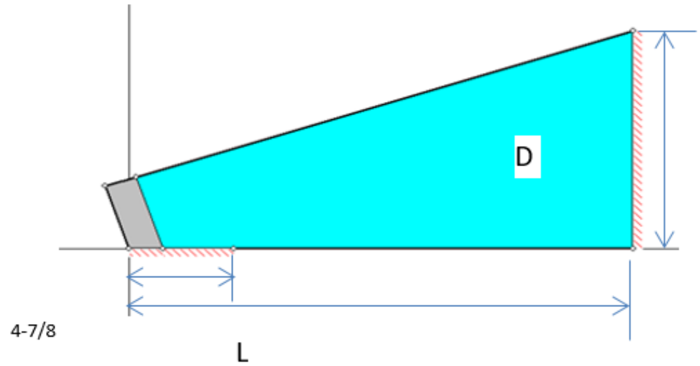
$Q_{framingpath} = Q_A + Q_B =$ 28.65 Btu/hr-ft

2.2.3.3 2-D Model, Rtot = 30, Y = 4-inches

Insulation Path

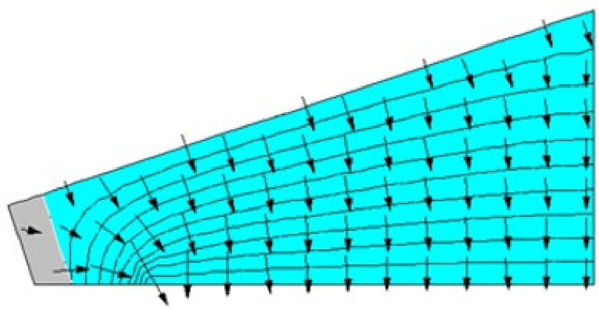
The Figure 26 case is modeled with the simplified geometry of Figure 34, shown for a ceiling insulation of R30. The top of the plate capping the vertical wall is assumed to be adiabatic. The tilted block assumed to be wood, exposed to ambient conditions on its outside sides. The outside of the wood and insulation assumed to be at a uniform 100F. 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.

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:

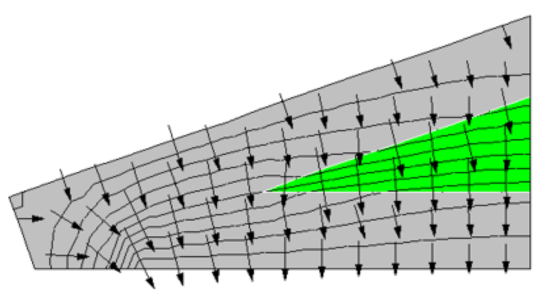
Q = 9.67 Btu/hr-ft

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:

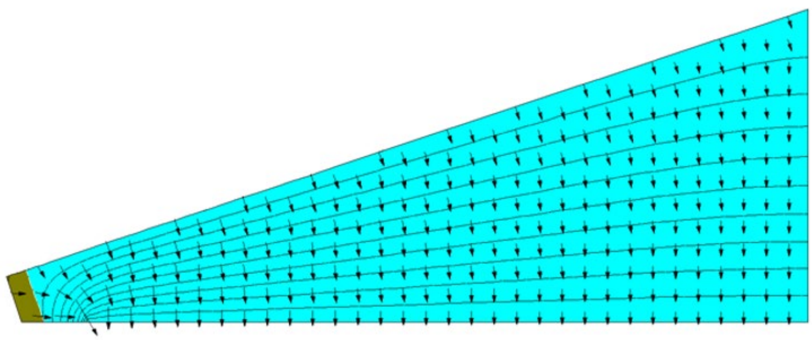
Q = 21.94 Btu/hr-ft

Equation 230

2.2.3.4 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.

Figure 37: 2-D Results for Insulation Path of R-60 Standard-Heel

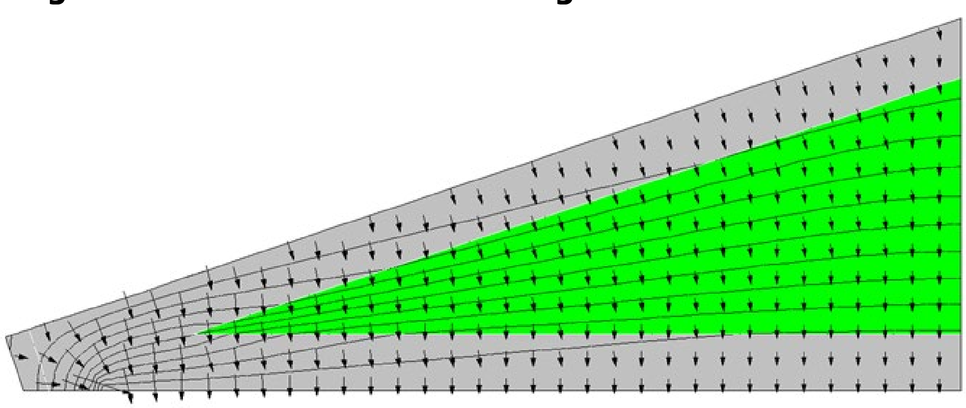


The overall heat transfer, per foot of perimeter, for this case was determined (RUN: std60.fet) to be:

Q = 16.342 Btu/hr-ft

Equation 231

Figure 38: 2-D Results for Framing Path of R-60 Standard-Heel



The overall heat transfer, per foot of perimeter, for this case was determined (RUN: std60F.FET) to be:

Q = 31.543 Btu/hr-ft

Equation 232

2.2.3.5 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 8: Comparison of 1-D and 2-D Results

	R-30 Ceiling Insulation Path	R-30 Ceiling Framing Path	R-60 Ceiling Insulation Path	R-30 Ceiling Framing Path
Q_{1D}	9.94	22.86	15.57	28.65
Q_{2D}	9.67	21.94	16.34	31.543
Q_{1D} is	$3\% > Q_{2d}$	$4\% > Q_{2d}$	$5\% < Q_{2d}$	$9\% < Q_{2d}$

Source: NORESCO for California Energy Commission

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.

2.3 How to Build an Airnet

2.3.1 Background

2.3.2 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:

Input	Description
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

2.3.2.1 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.

2.3.3 Inputs

Input	Description
ACH50	7.6 (Air Changes per Hour at 50 Pascals pressure difference that leak through the envelope of the conditioned zones)
Avent	1/300 (ratio of "free area of attic vents to AceilGross)
Fraction High	0.3 (fraction of the attic vent area located in the upper part of the attic, check precise definition)

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 ELAtot = CFA*ACH50/(2*10000) (CFA is conditioned floor area)
   b. Determine Envelope Areas
      1. ExCeiltotSF =sum (AceilGross + 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. ExWalltotSF =sum (Gross Area of Exterior Walls) (walls in conditioned zones whose outside condition is Ambient)
      3. ExFloortotSF =sum (Gross Area of Exterior floors) (floors in conditioned zones whose outside condition is Ambient, Crawl or GROUND)
      4. ExFloorSlabSF =sum (Gross Area of Exterior slab on grade floors) (slab on grade floors in conditioned zones)
      5. SlabRatio =ExFloorSlabSF/ExFloortotSF
      6. GaragetotSF =sum (Gross Area of Surfaces to Garage) (walls and floors in conditioned zones whose outside condition is Garage)
   c. Determine leakage distribution:
      1. ELAceilsf = ELAtot* (.4+.1*SlabRatio)/(AceilGross + area of exterior ceilings)
      2. ELAraisedFloorsf = ELAtot* (.2* 1-SlabRatio)/(ExFloortotSF-ExFloorSlabSF)

   #If there is a garage zone

      1. ELAGaragesf = ELAtot* 0.1/GaragetotSF
      2. ELAwallsf = ELAtot* (.3 + .1*SlabRatio)/ExWalltotSF

      #Else

      3. ELAGaragesf = 0
      4. ELAwallsf = ELAtot* (.4 + .1*SlabRatio)/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 NightBreeeze Windows are on year round

    #reDefine Windowmode 1.//Always available

    #Define VentDiff 0 // Differential. No differential for windows or WWF

    // 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

ELA_Aceil(zone)	= ELAceilsf * AceilGross(zone)
ELA_Xceil(zone)	= ELAceilsf * (AEdge(zone) + area of exterior ceilings(zone)) //AEdge is determined in the Ceiling Surface setup BAW 120517
ELAXwall(zone)	= ELAwallsf * Gross Area of Exterior Walls(zone)
ELAGwall(zone)	= ELAGaragesf * Gross Area of walls and floors next to the Garage(zone)
ELAfloor(zone)	= ELAraisedFloorsf * AreaExtfloor(zone) (gross area of floors whose outside condition is Ambient, Crawl)
ZoneBotZ	= Bottom(zone) - height of the lowest floor in the zone
ZoneTopZ	= ZoneBotZ + FloortoFloor(zone)*NumofStories(zone)
ZoneHeightZ	= ZoneTopZ - ZoneBotZ
WinHHTop	= ZoneBotZ + FloortoFloor(zone)*(NumofStories(zone)-1) + Window head height

b. Exteror 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 Downwind Wall -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 WlLU stands for Wall Low Upwind etc.

IZXFER (ZoneName)WlLU izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = WH izHD = ZoneBotZ + (0.25 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=0.6

IZXFER (ZoneName)WlLS izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = 2*WH izHD = ZoneBotZ + (0.25 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=-.65

IZXFER (ZoneName)WlLD izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = WH izHD = ZoneBotZ + (0.25 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=-0.3

IZXFER (ZoneName)WlHU izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = WH izHD = ZoneBotZ + (0.75 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=0.6

IZXFER (ZoneName)WlHS izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = 2*WH izHD = ZoneBotZ + (0.75 * ZoneHeightZ)izNVEff = 1 izExp=0.65 izCpr=-.65

IZXFER (ZoneName)WlHD izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = WH izHD = ZoneBotZ + (0.75 * ZoneHeightZ) izNVEff = 1 izExp=0.65 izCpr=-0.3

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.

IZXFER (ZoneName)WnHU izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo=.00001 izAHi = WnHole izHD = (WinHHTop-1) izNVEff =.5 izCpr=0.6

IZXFER (ZoneName)WnHS izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo=.00001 izAHi = 2*WnHole izHD = (WinHHTop-1) izNVEff =.5 izCpr=-.65

IZXFER (ZoneName)WnHD izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo=.00001 izAHi = WnHole izHD = (WinHHTop-1) izNVEff =.5 izCpr=-0.3

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 Ceil 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:

ELAfloor(Name) = ELAraisedFloorsf * AreaExtfloor * 1.45 (floors whose outside condition is Ambiant)

Write Airnet Object to CSE Input

IZXFER (Name) izNVTYPE = AirNetExt izZN1 = (ZoneName) izALo = ELAfloor(Name) izHD = Floor Height izNVEff = 1 izExp=0.65 izCpr=0. // located at the Extfloor elevation, no wind effect

f. Floor over Crawl

For each floor over outside calculate:

ELAfloor(Name) = ELAraisedFloorsf * AreaCrawlfloor * 1.45 (floors whose outside condition is Crawl)

Write Airnet Object to CSE Input

IZXFER (Name)xCrawl izNVTYPE = AirNetIZ izZN1=(ZoneName) izALo=ELAfloor(Name) izHD = Floor Height izNVEff=1. izExp=0.65 izZN2 = Crawl

g. Floor over Garage

For each floor over garage calculate:

ELAfloor(Name) = ELAGaragesf * AreaGarfloor * 1.45 (floors whose outside condition is Garage)

Write Airnet Object to CSE Input

IZXFER (Name)xGarage izNVTYPE = AirNetIZ izZN1=(ZoneName) izALo=ELAfloor(Name) izHD = Floor Height izNVEff=1. izExp=0.65 izZN2 = Garage

h. Garage wall

Calculate:

GWH	= ELAGaragesf * Gross Area of walls next to the Garage(zone)/2 // size of the 2 holes (high and low) betwen zone and garage
GWalltopZ	= Min(ZoneTopZ(zone),(ZoneTopZ(Garage)) //The top of the shared wall
GWallBotZ	= Max(ZoneBotZ(zone),(ZoneBotZ(Garage)) //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=-0.3

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,-.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,-.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 conditoned zone)

Door calculation for each pair of zones with a common wall surface (zoneA<>zoneB, zoneB<>zoneC, zoneA<>zoneC, etc)

DoortopZ = Min(ZoneTopZ(zone A),(ZoneTopZ(zone B)) //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 = DHlZ 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 conditoned zone where it is located

Calculate

Relief = CoolVentCFM/750 // 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/750 // 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/750 // 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/750 // 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

AtticRelief = Sum(CoolVentCFM)/750 // 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 http://www.tamtech.com/userfiles/Fan%20size%20and%20venting%20requirements(3).pdf

7. *Duct system leaks and pressurization.*

These are generated automatically by CSE based on the duct system inputs.

2.4 How to Create CSE Conditioned Zone Internal Mass Inputs

2.4.1 Background

2.4.2 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)

2.4.3 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. Xflr = sum of the area of floors to ground, crawl space, exterior or other zones
   b. IntFlr = Floor Area-Xflr

2. Interior Wall Setup. Input for inside the conditioned zone interior walls as mass elements.

   Calculate:

   a. IZwall = sum of the area of interior walls to other conditioned zones
   b. Intwall(zone) floor area - .5 * IZwall

3. Write objects to the CSE input

Light stuff

1. znCAir=floor area * 2
2. Interior wall if Intwall(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

Interior Floor if IntFlr(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

CONSTRUCTION IntwallCav // 2x4 Revised Layers

Layer lrMat="Gypsum Board"

Layer lrMat="Gypsum Board"

CONSTRUCTION IntwallFrm // 2x4 Revised Layers

Layer lrMat="Gypsum Board"

Layer lrMat="SoftWood" lrThk=3.5/12.

Layer lrMat="Gypsum Board"

CONSTRUCTION IntFFrm2x10 // 9.25" (2x10)

Layer lrMat="Carpet"

Layer lrMat="Wood layer"

Layer lrMat="SoftWood" lrThk=9.25/12.

Layer lrMat="Gypsum Board"

CONSTRUCTION IntFCav2x10 // 9.25" (2x10)

Layer lrMat="Carpet"

Layer lrMat="Wood layer"

Layer lrMat="Carpet" // Air space with 1 psf of stuff (cross bracing wiring, plumbing etc) approximated as 1" of carpet

Layer lrMat="Carpet" // Air space with 1 psf of stuff (cross bracing wiring, plumbing etc) approximated as 1" of carpet

Layer lrMat="Gypsum Board"

2.5 Appliances, Miscellaneous Energy Use, and Internal Gains

2.5.1 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.

2.5.2 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.

2.5.2.1 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 do not work 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.

2.5.3 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):

Input	Description
Refrigerator/Freezer	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 additons and alterations when we get to them.
Dishwasher	Efficiency (Choice of Default, no other choices at this time), Location (Choice of zones if multiple conditioned zones). // HTM assumes all Dwelling units have refrigerators. Different for additons and alterations when we get to them.
Clothes Dryer	Location (Choice of zones if multiple zones, No Dryer space or hookup provided) Dryer power (Choice Electric, Gas or other) //Assuming gas for now
Clothes Washer	Location (Choice of zones if multiple zones), No Washer space or hookup provided)
Range/Oven	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.

Assumes CSE Meters are set up elsewhere:

Mtr_Elec

Mtr_NatGas

Mtr_Othewr //PropaNE

Write Constants to the CSE input:

#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,\

0.021,0.021,0.021,0.026,0.031,0.044,0.084,0.118,0.113,0.096,0.063,0.038) // Changed 0.117 to 0.118 to add to 1

#redefine OutdoorLights_hr hourval(0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0.25,0.25,0.25,0.25) //

#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,\

0.014,0.014,0.019,0.027,0.041,0.055,0.068,0.082,0.082,0.070,0.053,0.035)

#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,\

0.032,0.033,0.035,0.037,0.044,0.053,0.058,0.060,0.062,0.060,0.052,0.045)

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+ 0.601×CFA)×(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 electonic 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

#Redefine WasherGain ((-64 + 0.108 * CFAperUnit) * DwellingUnits * 3413. / 365.)

e. Clothes Dryer - Assumes gas with electonic 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

#Redefine 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 gnFrLat=0.25 gnEndUse=Dish gnMeter= Mtr_Elec //

GAIN Cooking gnPower= CookGain*Equipment_hr*Intgain_mo gnFrRad=0 gnFrLat=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 //

2.6 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
hourval(65,65,65,65,65,65,65,68,68,68,68,68,68,68,68,68,68,68,68,68,68,68,68,65)

#redefine Liv_Heat_hr
hourval(65,65,65,65,65,65,65,68,68,68,68,68,68,68,68,68,68,68,68,68,68,68,68,65)

#redefine Slp_Heat_hr
hourval(65,65,65,65,65,65,65,68,65,65,65,65,65,65,65,65,65,65,65,65,65,68,68,65)

#redefine Winter_Vent 77

#redefine Winter_Cool 78

//Cool Mode

#redefine SZ_Cool_hr
hourval(78,78,78,78,78,78,78,83,83,83,83,83,83,82,81,80,79,78,78,78,78,78,78,78)

#redefine Liv_Cool_hr
hourval(83,83,83,83,83,83,83,83,83,83,83,83,83,82,81,80,79,78,78,78,78,78,78,83)

```
#redefine Slp_Cool_hr
hourval(78,78,78,78,78,78,78,83,83,83,83,83,83,83,83,83,83,83,83,83,83,78,78,78)

#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%?
```

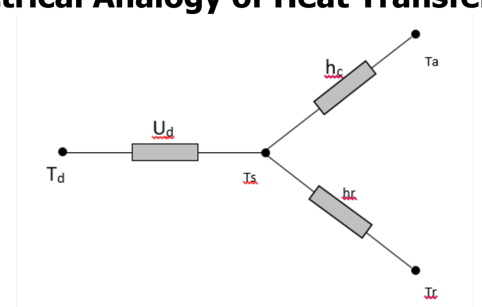
TECHNICAL APPENDICES

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 (T_d) and is connected to the temperate on the surface of the duct (T_s) by the conductance through the duct wall (U_d). The convective heat transfer coefficient (h_c) connects the surface temperature to the duct zone air temperature (T_a). The radiation heat transfer coefficient (h_r) connects the surface temperature to the duct zone radiant temperature (T_r).

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.

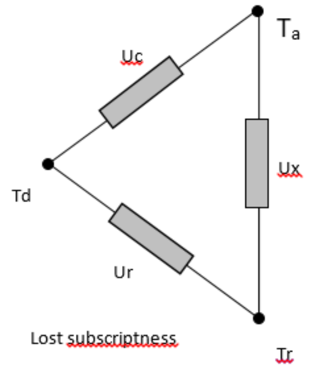
$$U_r = \frac{U_d h_r}{D} \qquad U_c = \frac{U_d h_c}{D} \qquad U_x = \frac{h_c h_r}{D}$$

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

$$\ln y(L) - \ln y(0) = -\frac{(U_c + U_r)PL}{mc_p}$$

Equation A- 11

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- 12

Let

$$\beta = \exp\left(-\frac{(U_c + U_r)A}{mc_p}\right)$$

Equation A- 13

Then

$$\frac{T_d(L) - T_{amb}}{T_d(0) - T_{amb}} = \beta$$

Equation A- 14

Solving for the exit temperature gives

$$T_d(L) = \beta(T_d(0) - T_{amb}) + T_{amb}$$

Equation A- 15

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- 16

This can be rewritten as

$$T_d(0) - T_d(L) = (1 - \beta)(T_d(0) - T_{amb})$$

Equation A- 17

Let ε be the sensible heat exchanger effectiveness

$$\varepsilon = (1 - \beta)$$

Equation A- 18

Then the conduction loss from the duct to the duct zone can then be written as

$$Q_{loss} = mc_p(T_d(0) - T_d(L)) = \varepsilon\, mc_p(T_d(0) - T_{amb})$$

Equation A- 19

Appendix B. Screen Pressure Drop

NOTE: 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,

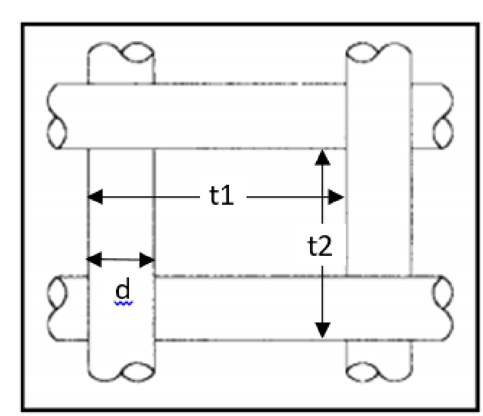
$$K = \left(\frac{1}{\beta^2} - 1\right)\left[\frac{18}{Re} + \frac{0.75}{log(Re+1.25)} + 0.055\,log(Re)\right]$$

Equation B- 2

and,

β = screen porosity = open area/total area perpendicular to flow direction.

$$\beta = \left(1 - \frac{d}{t1}\right)\left(1 - \frac{d}{t2}\right)$$



$Re = \frac{wd}{\nu} = \frac{md}{\rho A\nu}$ = Renolds number.

w = face velocity = $\frac{m}{\rho A}$, ft/sec.

m = mass flow rate, lb_m/sec.

d = wire diameter, ft.

ν = viscosity ≈ 1.25E-4 + 5.54E-07T(degF); ft^2/sec. = 1/6100 ft2/sec at 70-F.

ρ = air density, lb_m/ft^3.

g_c = 32.2 $lb_m ft/lb_f\text{-}sec^2$.

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 $Re = \frac{wd}{\nu}$ is roughly 5 times the face velocity in ft/sec. For a velocity of 1 ft/sec, Re ~ 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

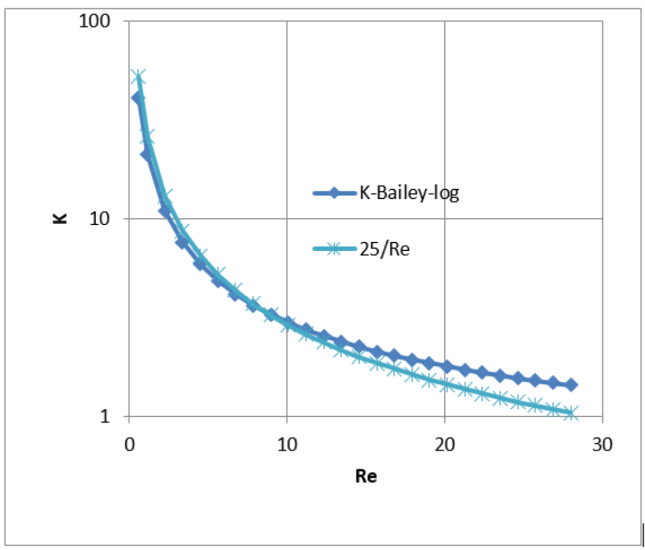
$$K = \left(\frac{1}{\beta^2} - 1\right)\frac{25}{Re}$$

Equation B- 3

[note #1: California CZ12 ave yearly Vmet ≈ 11 ft/sec. Correcting for height and shielding gives Vlocal ≈ 11*0.5*0.32 ≈ 1.8 ft/sec. For max flow case of windows on windward and leeward walls, with typical wall wind pressure coefficients, w ≈ 0.5*Vlocal. Thus, the maximum window velocity expected for the annual average wind velocity of 11 ft/sec is w ≈ 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, $w(fpm) = 9\sqrt{H[ft](\Delta T[F])} =$ $9 * \frac{\sqrt{10*10}}{60} = 1.5\frac{ft}{sec}$ 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 $w_c = 21\psi\nu C_d^2$, defined below. As discussed there, at this velocity the pressure drop through the screen is equal to that through the window orifice.

Figure B-1: Screen Pressure Drop



Equation B- 3 can be written as

$$K = \frac{25\psi\nu}{w}, \text{or alternately} \frac{25\psi\rho A\nu}{m}$$

Equation B- 4

where, as a result of the approximation *Equation B- 3*, the screen inputs can be combined into one characteristic screen parameter ψ (of dimension ft^{-1}):

$$\psi = \frac{1}{d}\left(\frac{1}{\beta^2} - 1\right)$$

Equation B- 5

ψ 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 $\mathrm{Re_{wdw}} = (\mathrm{D_h/d})25\psi \mathrm{d}\mathrm{C_d^2}$.

$\mathrm{w_c}$ =1.89 ft/sec for std 14x18x0.011 screen &Cd=0.6; 14&18 are wires/inch.

Re_c = 10.6 for std 14x18x0.011 screen &Cd=0.6

Re_{wdw}= (~1.5*12/0.011)*(10.6)=1,7345 >10^4.

Thus Re is not > 10^4 when w < ~1 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 Δp,

$$\Delta \mathrm{p} = \frac{1}{\mathrm{C_d^2}}\frac{\rho \mathrm{w}^2}{2\mathrm{g_c}} = \frac{1}{\mathrm{C_d^2}}\frac{\mathrm{m}^2}{2\mathrm{g_c}\rho \mathrm{A}^2}$$

Equation B- 7

Adding Equation B- 1 and Equation B- 7 gives the total pressure drop for a window and screen in series:

$$\Delta p = \left(K + \frac{1}{C_d^2}\right)\frac{m^2}{2g_c \rho A^2}$$

Equation B- 8

Solving for mass flow rate,

$$\mathrm{m} = \mathrm{AC_d}\left(\frac{1}{1 + \mathrm{C_d^2 K}}\right)^{\frac{1}{2}}(2\rho \mathrm{g_c} \Delta \mathrm{p})^{\frac{1}{2}}$$

Equation B- 9

or,

$$m = AC_d S(2\rho g_c \Delta p)^{\frac{1}{2}}$$

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.

$$S = \left(\frac{1}{1 + C_d^2 K}\right)^{\frac{1}{2}} = \left(\frac{1}{1 + C_d^2 \frac{25\psi\nu}{w}}\right)^{\frac{1}{2}}$$

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:

$$w_c = 25\psi\nu C_d^2$$

Equation B- 12

The corresponding Reynolds number is $Re_c = 25\psi d C_d^2$.

Substituting Equation B- 12 into Equation B- 11shows that for this condition,

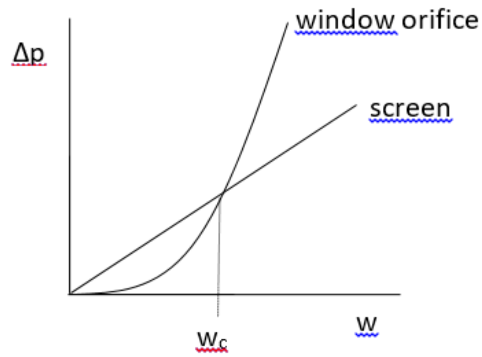
$$S_c = \frac{1}{\sqrt{2}} = 0.707$$

Equation B- 13

Equation B- 12 and Equation B- 13 show that w_c, which, besides viscosity, only depends on the screen constant ψ and window-orifice coefficient C_d, can be considered a "characteristic" velocity, the velocity at which the flow is reduced by (1 - 0.707) ~ 29.3% by the addition of a screen to the window.

Figure B-2 shows that the typical Δp 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.

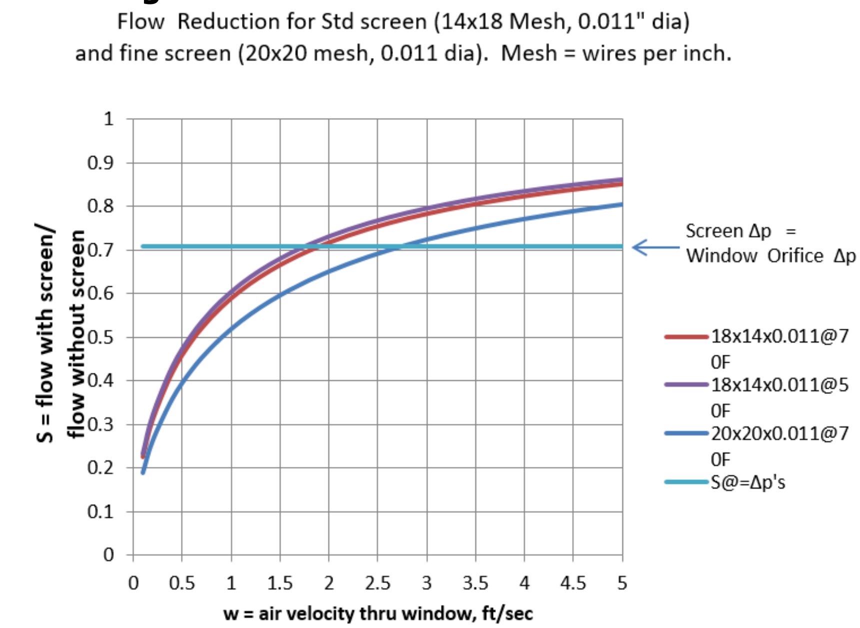
Figure B-2: Pressure vs. Flow Characteristics



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 = ~ 1-ft/sec taken as typical according to note #1, S = 0.6, corresponding to a 40% reduction in flow].

Figure B-3: Standard Screen Flow Reduction



Partial Derivatives for use in Airnet:

From Equation B- 4 and Equation B- 8,

$$\Delta p = \left(\frac{25\psi\rho A\nu}{m} + \frac{1}{C_d^2}\right)\frac{m^2}{2g_c\rho A^2}$$

Equation B- 14

This can be written in the quadratic form for m:

$$m^2 + bm - a\Delta p = 0$$

Equation B- 15

Where,

$$a = 2g_c\rho C_d^2 A^2$$

$$b = 25\psi\rho\nu C_d^2 A$$

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:

$$m = \frac{b}{2}\left\{\left(1 + \frac{4a\Delta p}{b^2}\right)^{\frac{1}{2}} - 1\right\}$$

Equation B- 16

If Δp 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 Δp as shown in Figure B-4 and Figure B-5. The value of $\frac{a}{b} \approx 25$, and $\frac{4a}{b^2} \approx 88$ for thse 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 Δp

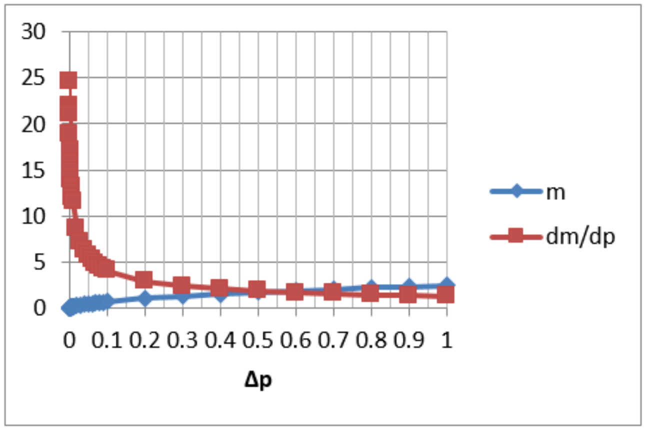
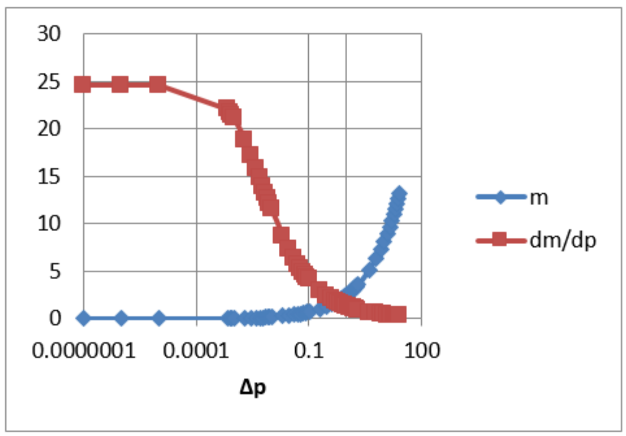


Figure B-5: For Large Δp



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 1.6. 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 $\frac{q_{ij}}{A_i}$, 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:

$$q_{ij} = h_b A_i F_{ij}(T_i - T_j)$$

Equation C- 1

where,

$h_b = 4\sigma\bar{T}^3$ = black body radiation coefficient; Btu/(hr-ft^2-F).

$\sigma = 0.1714x10^{-8}$ Btu/hr-ft^2-R^4, the Stefan-Boltzmann constant.

$\bar{T}^3 \approx \frac{T_i+T_j}{2}$; 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-1: View-Factor Method's Radiant Network for Black-Body Surfaces

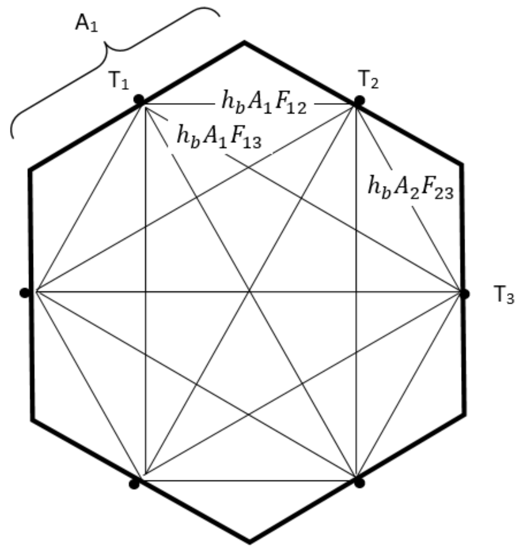
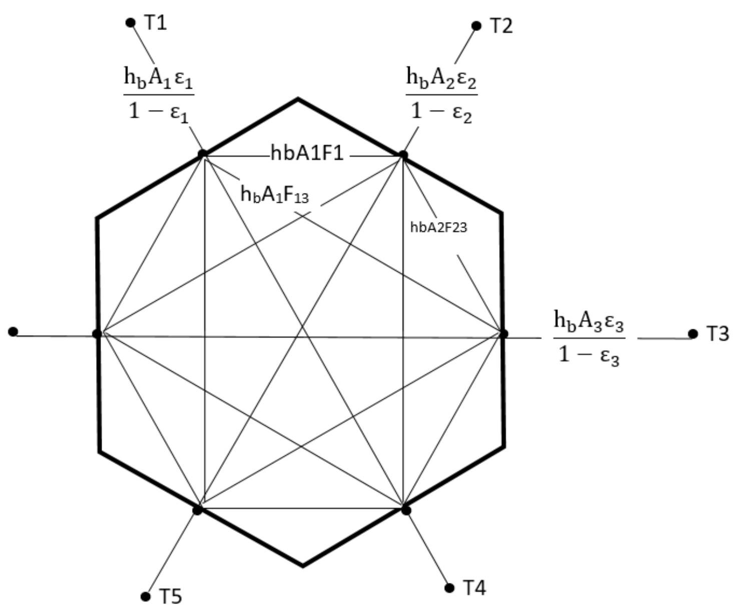


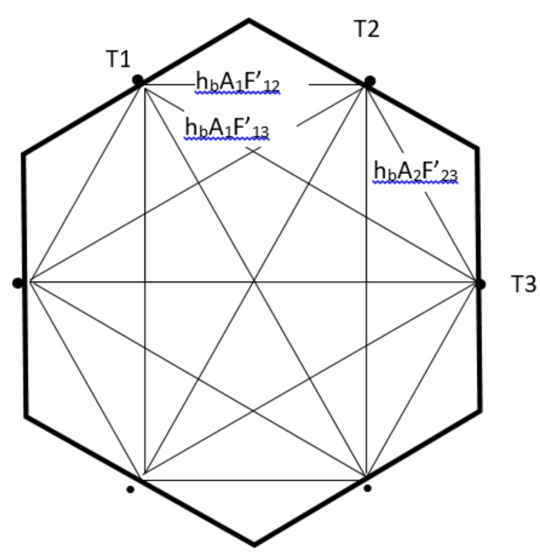
Figure C-2 shows the Figure C-1 black surface case extended to handle diffuse gray surfaces (ε = α = constant over temperature range of interest) with emissivities ε_i, by adding the Oppenheim radiant surface conductances $\frac{A_i \varepsilon_i}{1-\varepsilon_i}$ between the surface temperature nodes 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 $A_i F'_{ij}$ implicit in the conductances of Figure C-2.

Figure C-3: View-Factor Method's Network for Grey Surfaces Reduced to Star Network



F'_{ij} are the 'radiant interchange factors'. As with the black surfaces view factors, reciprocity holds: $A_i F'_{ij} = A_j F'_{ji}$. 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≠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 1.6.1. 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} q'[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 $q'_{ij}q'$ will be higher than the average $\frac{q_{ij}}{A_i}$, 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 $\mathrm{F_i}$

Consider a flat black surface of area $A_1$and temperature T_1viewing 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 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 Section1.6.1.

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