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HVAC Design Calculations

Peter S. Curtiss
Kreider & Associates, LLC

Jeffrey S. Haberl
Texas A&M University

Joe Huang
Lawrence Berkeley Laboratory

David Jump
Lawrence Berkeley Laboratory

Jan F. Kreider
Kreider & Associates, LLC

Ari Rabl
École des Mines de Paris and University of Colorado

T. Agami Reddy
Drexel University

Max Sherman
Lawrence Berkeley Laboratory

6.1 Energy Calculations — Building Loads

Ari Rabl and Peter S. Curtiss

Heating and cooling loads are the thermal energy that must be supplied to or removed from the interior of a building in order to maintain the desired comfort conditions. That is the demand side of the building, addressed in this chapter and the next. Once the loads have been established, one can proceed to the supply side and determine the performance of the required heating and cooling equipment, as discussed in Chapters 4.1–4.4.

Of primary concern to the designer are the maximum or peak loads because they determine the capacity of the equipment. They correspond to the extremes of hot and cold weather, called design conditions. But while in the past it was common practice to limit oneself to the consideration of peak loads, examination of annual performance has now become part of the designer's job. The oil crises sharpened our awareness of energy, and the computer revolution has given us the tools to optimize the design of the building and to compute the cost of energy. In this chapter we address the calculation of peak loads. Methods for the determination of annual energy requirements are presented in Chapter 6.2.

A load calculation consists of a careful accounting of all the thermal energy terms in a building. While the basic principle is simple, a serious complication can arise from storage of heat in the mass of the building: In practice, this is very important for peak cooling loads, even in lightweight buildings typical in the U.S. For peak heating loads, the heat capacity can be neglected unless one insists on setting the thermostat back even during the coldest periods. For annual energy consumption, the effect of heat capacity depends on the control of the thermostat: it is negligible if the indoor temperature is constant but can be quite significant with thermostat set back or up.

This chapter begins with models for air exchange in Section 6.1.1. Section 6.1.2 discusses the design conditions, heat loss coefficient, and thermal balance of a building. Section 6.1.3 examines the limitations of a steady state analysis. The need for zoning, i.e., the separate treatment of different parts of a building where the loads are too dissimilar to be lumped together, is discussed in 6.1.4, and a steady-state method for peak heating loads is presented in Section 6.1.5. Peak cooling loads are calculated in Section 6.1.6 by using a modified steady state method, CLF-CLTD. To provide an algorithm for dynamic load calculations, the transfer function method is presented in Section 6.1.7; using this method has become relatively simple, thanks to computers with spreadsheets.

The calculation of loads presented here does not take into account the losses in the distribution system. These losses can be quite significant, especially in the case of uninsulated ducts, and they should be taken into account in the analysis of the HVAC system. Distribution systems are the province of Chapter 4.3.*

6.1.1 Air Exchange

Fresh air in buildings is essential for comfort and health, and the energy for conditioning this air is an important term. Not enough air, and one risks sick-building syndrome; too much air, and one wastes energy. The supply of fresh air, or air exchange, is stated as the flow rate $\dot{V}$ of the outdoor air that crosses the building boundary and needs to be conditioned [ft^3/min (m^3/s or L/s)]. Often it is convenient to divide it by the building volume, as $\dot{V}/V$, expressing it in units of air changes per hour. Even though it is customary to state the air flow as the volumetric rate, the mass flow $\dot{m} = \rho\dot{V}$ would be more relevant for most applications in buildings. The relation between mass flow and volume flow depends on the density ρ, which varies quite significantly with temperature and pressure.

To estimate the air exchange rate, the designer has two sources of information: data from similar buildings and models. The underlying phenomena are complicated, and a simple comparison with other buildings may not be reliable. The modeling approach can be far more precise, but may require a fair amount of effort.

It is helpful to distinguish two mechanisms that contribute to the total air exchange:

- *Infiltration* — uncontrolled airflow through all the little cracks and openings in a real building
- *Ventilation* — natural ventilation through open windows or doors and mechanical ventilation by fans

Data for Air Exchange

Air exchange rates can be measured directly by means of a tracer gas. Sulfur hexafluoride (SF_6) has been a favorite because it is inert and harmless, and it can be detected at concentrations above 1 part per billion (ppb). The equipment is relatively expensive but allows determination at hourly or even shorter intervals (Sherman et al., 1980; Grimsrud et al., 1980). More recently a low-cost alternative has been developed that uses passive perfluorocarbon sources and passive samplers (Dietz et al., 1985). Each source can cover up to several hundred cubic meters of building volume, at a cost of about $50, but the method

* For future reference, we note that the loads of each zone, as calculated in this chapter, include the contribution of outdoor air change. However, for the analysis of air-based central distribution systems, it is convenient to exclude the contribution of ventilation air from the zone loads and to count it instead as load at the air handler. Keeping separate the load due to ventilation air is straightforward because this load is instantaneous.

yields only averages over sampling periods of several weeks (in fact, it averages the inverse of the air exchange rate). Carbon dioxide is interesting as a tracer gas because it is produced by the occupants and can be used for monitoring indoor air quality; as a measure of air exchange, it is uncertain to the extent that the number of occupants and their metabolism are not known.

An entirely different method of determining the airtightness of a building is pressurization with a blower door (a special instrumented fan that is mounted in the frame of a door for the duration of the test). To obtain accurate data, one needs fairly high pressures, around 0.2 to 0.3 in WG (50 to 75 Pa), which are higher than natural conditions in most buildings. The extrapolation to lower values requires assumptions about the exponent in the flow-pressure relation, and it is not without problems (see Chapter 23 of ASHRAE, 1989a). In buildings with mechanical ventilation, one could bypass the need for a blower door by using the ventilation system itself, if the pressure is sufficiently high.

In the past, not much attention was paid to airtight construction, and older buildings tend to have rather high infiltration rates, in the range of 1 to 2 air changes per hour. With current conventional construction in the U.S., one finds lower values, around 0.3 to 0.7. These values are seasonal averages; instantaneous values vary with wind and indoor-outdoor temperature difference. When infiltration is insufficient to guarantee adequate indoor air quality, forced ventilation becomes necessary. The required air exchange rate depends, of course, on the density of occupants. In residential buildings, the density is relatively low, and with conventional U.S. construction, infiltration is likely to be sufficient. But it is certainly possible to make buildings much tighter than 0.3 air changes per hour of infiltration. In fact, Swedish houses are standardly built to such high standards that uncontrolled infiltration rates are around 0.1 air changes per hour; mechanical ventilation supplies just the right amount of outdoor air, and an air-to-air heat exchanger minimizes the energy consumption. In the U.S. for buildings with forced ventilation, ASHRAE ventilation Standard 62-99 applies. Good sites for mechanical exhaust are kitchen and bathrooms, to remove indoor air pollution and excessive humidity.

Uncontrolled air exchange is highly dependent on wind and on temperatures. Even with closed windows, it can vary by a factor of 2 or more, being lower in summer than in winter. The variability of air exchange is indicated schematically in Figure 6.1.1 as the relative frequency of occurrence for three types of house: a leaky house and a moderately tight house, both with natural infiltration, and a very tight house with mechanical ventilation. The last guarantees adequate supply of fresh air at all times, without the energy waste of conditioning unnecessary air. With open windows, the air exchange rate is difficult to predict accurately. It varies with the wind, and it is highly dependent on the aerodynamics of the building and its surroundings. The designer needs data on ventilation rates with open windows to assess comfort conditions in buildings with operable windows during the transition season between heating and cooling. Figure 6.1.2 presents data for natural ventilation in a two-story house. Depending on which windows are open and where the ventilation is measured, the air change rate varies between 1 and 20 per hour.

Models for Air Leakage

For a more precise model of air exchange, let us recall from Chapter 2.1 that the flow through an opening is proportional to the area and to some power of the pressure difference:

$$\dot{V} = Ac\Delta p^{n} \tag{6.1.1}$$

where A = area of opening, ft^2 (m^2)
$\Delta p = p_o - p_i$ = pressure difference between outside and inside, inWG (Pa)
c = flow coefficient, ft/(min · inWG^n) [m/(s · Pa^n)]
n = exponent, between 0.4 and 1.0 and usually around 0.65 for buildings

In general, different openings may have different coefficients and exponents. This equation is an approximation, valid only for a certain range of pressures and flows; different n and c may have to be used for other ranges. There is another problem in applying this equation to buildings: the width of an

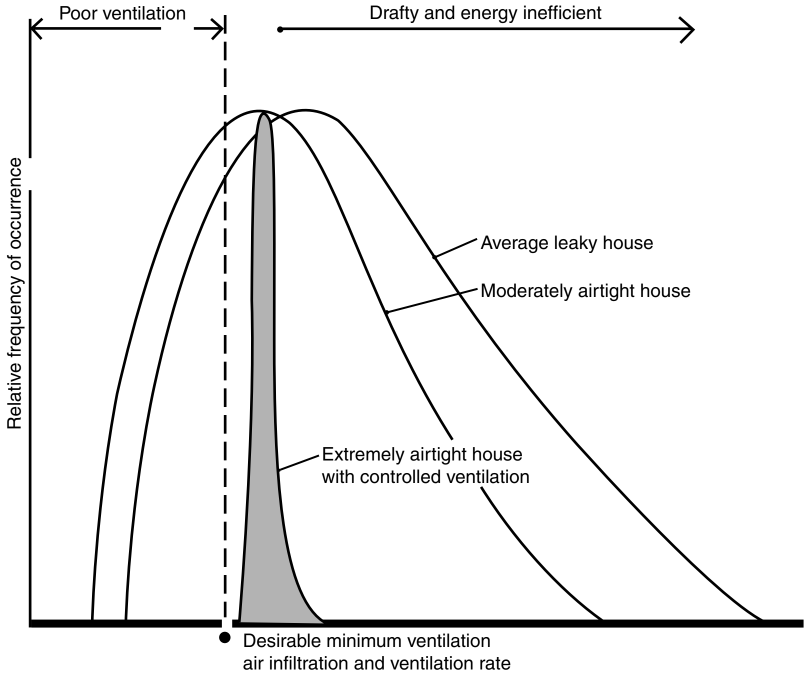
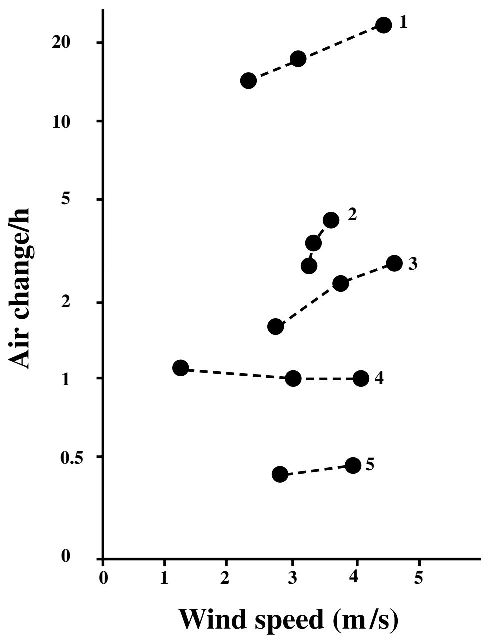


FIGURE 6.1.1 Variability of air exchange for three types of houses, plotted as relative frequency of occurrence versus air change rate (from Nisson and Duff, 1985).

FIGURE 6.1.2 Measured ventilation rates, as a function of wind speed, in a two-story house with windows open on lower floor (from Achard and Gicquel, 1986). The curves are labeled according to the location of open windows and measuring point as follows:

Open Windows	Measuring Point
1. All upper floor	Upper floor
2. Upper floor windward	Upper floor
3. All upper floor	Lower floor
4. Upper floor leeward	Upper floor
5. None	Whole house



opening can change with pressure. Blower door tests have shown that the apparent leakage area can be significantly higher for overpressurization than for underpressurization; external pressure tends to compress the cracks of a building (Lydberg and Honarbakhsh, 1989). In buildings without mechanical ventilation, the pressure differences under natural conditions are positive over part of the building and negative over the rest; here it is appropriate to average the blower door data over positive and negative

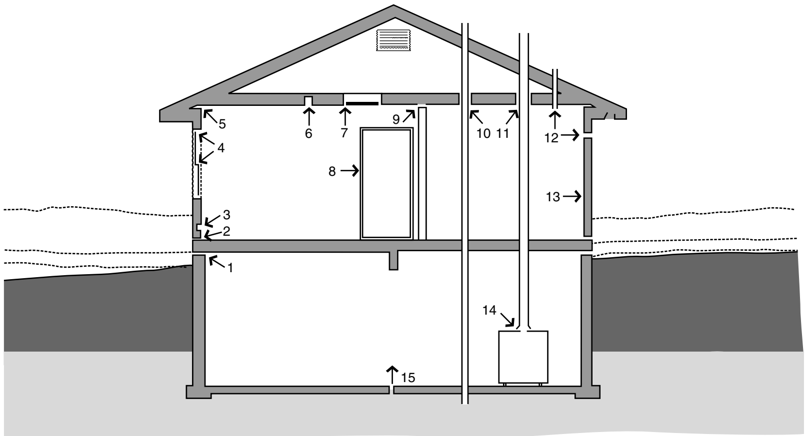


FIGURE 6.1.3 Typical air leakage sites in a house. (1) Joints between joists and foundation; (2) joints between sill and floor; (3) electrical boxes; (4) joints at windows; (5) joints between wall and ceiling; (6) ceiling light fixtures; (7) joints at attic hatch; (8) cracks at doors; (9) joints at interior partitions; (10) plumbing-stack penetration of ceiling; (11) chimney penetration of ceiling; (12) bathroom and kitchen ventilation fans; (13) air/vapor barrier tears; (14) chimney draft air leaks; (15) floor drain (air enters through drain tile) (from Nisson and Duff, 1985).

pressure differences. In buildings where over- or underpressure is maintained, the leakage area data should correspond to those conditions.

The total flow is obtained by summing over all openings k as

$$\dot{V} = \sum_k A_k c_k \Delta p_k^n \qquad \text{(include only terms with } \Delta p_k > 0\text{)} \tag{6.1.2}$$

where A_k = leakage area
c_k = flow coefficient
n_k = exponent
$\Delta p_k = p_o - p_i$ = local pressure difference

If one sums naively over all openings of a building, the result (averaged over momentary fluctuations) is zero because the quantity of air in a building does not change. The flow into the building must equal the flow out; the former corresponds to positive terms in the sum, the latter to negative terms. What interests us here is the energy needed for conditioning the air that flows into the building. Therefore, the sum includes only the terms with $p_o > p_i$.

As indicated by the subscript k, all the terms can vary from one point to another in the building. Therefore, a fairly detailed calculation may be required. Typical air leakage sites in houses are shown in Figure 6.1.3, and data for leakage areas can be found in Table 6.1.1 for a wide variety of building components.

Actually, in many applications, one need not worry about this. For relatively small buildings without mechanical ventilation, the LBL model can be used; this model, discussed shortly, bypasses Equation 6.1.2 by correlating the flow directly with wind speed, temperature difference, and total leakage area. In many (if not most) buildings with mechanical ventilation, one maintains a significant pressure difference between the interior and exterior*. If this pressure difference is larger than the pressures induced by wind and temperature, the latter can be neglected and all terms in Equation 6.1.2 have the same sign. Before proceeding to these applications, we have to discuss the origin of the pressure differences.

* Overpressure in the building allows better control and comfort. Underpressure can be maintained with smaller ducts and lower cost, but at the risk of condensation, freezing, and possibly draft.

TABLE 6.1.1 Data for Effective Leakage Areas of Building Components at 0.016 in WG (4 Pa), cm^2

Component	Best Estimate	Maximum	Minimum
Sill foundation-Wall			
Caulked, in^2/ft of perimeter	0.04	0.06	0.02
Not caulked, in^2/ft of perimeter	0.19	0.19	0.05
Joints between ceiling and walls			
Joints, in^2/ft of wall			
(only if not taped or plastered and no vapor barrier)	0.07	0.12	0.02
Windows			
Casement			
Weather-stripped, in^2/ft^2 of window	0.011	0.017	0.006
Not weather-stripped, in^2/ft^2 of window	0.023	0.034	0.011
Awning			
Weather-stripped, in^2/ft^2 of window	0.011	0.017	0.006
Not weather-stripped, in^2/ft^2 of window	0.023	0.034	0.011
Single-hung			
Weather-stripped, in^2/ft^2 of window	0.032	0.042	0.026
Not weather-stripped, in^2/ft^2 of window	0.063	0.083	0.052
Double-hung			
Weather-stripped, in^2/ft^2 of window	0.043	0.063	0.023
Not weather-stripped, in^2/ft^2 of window	0.086	0.126	0.046
Single-slider			
Weather-stripped, in^2/ft^2 of window	0.026	0.039	0.013
Not weather-stripped, in^2/ft^2 of window	0.052	0.077	0.026
Double-slider			
Weather-stripped, in^2/ft^2 of window	0.037	0.054	0.02
Not weather-stripped, in^2/ft^2 of window	0.074	0.110	0.04
Doors			
Single door			
Weather-stripped, in^2/ft^2 of door	0.114	0.215	0.043
Not weather-stripped, in^2/ft^2 of door	0.157	0.243	0.086
Double door			
Weather-stripped, in^2/ft^2 of door	0.114	0.215	0.043
Not weather-stripped, in^2/ft^2 of door	0.16	0.32	0.1
Access to attic or crawl space			
Weather-stripped, in^2 per access	2.8	2.8	1.2
Not weather-stripped, in^2 per access	4.6	4.6	1.6
Wall-Window frame			
Wood frame wall			
Caulked, in^2/ft^2 of window	0.004	0.007	0.004
No caulking, in^2/ft^2 of window	0.024	0.038	0.022
Masonry wall			
Caulked, in^2/ft^2 of window	0.019	0.03	0.016
No caulking, in^2/ft^2 of window	0.093	0.15	0.082
Wall-Door frame			
Wood wall			
Caulked, in^2/ft^2 of door	0.004	0.004	0.001
No caulking, in^2/ft^2 of door	0.024	0.024	0.009
Masonry wall			
Caulked, in^2/ft^2 of door	0.0143	0.0143	0.004
No caulking, in^2/ft^2 of door	0.072	0.072	0.024
Domestic hot water systems			
Gas water heater (only if in conditioned space), in^2	3.1	3.9	2.325
Electric outlets and light fixtures			
Electric outlets and switches			
Gasketed, in^2 per outlet and switch	0	0	0
Not gasketed, in^2 per outlet and switch	0.076	0.16	0
Recessed light fixtures, in^2 per fixture	1.6	3.1	1.6
Pipe and duct penetrations through envelope			

TABLE 6.1.1 (continued) Data for Effective Leakage Areas of Building Components at 0.016 in WG (4 Pa), cm²

Component	Best Estimate	Maximum	Minimum
Pipes			
Caulked or sealed, in² per pipe	0.155	0.31	0
Not caulked or sealed, in² per pipe	9.3	1.55	0.31
Ducts			
Sealed or with continuous vapor barrier, in² per duct	0.25	0.25	0
Unsealed and without vapor barrier, in² per duct	3.7	3.7	2.2
Fireplace			
Without insert			
Damper closed, in² per fireplace	10.7	13	8.4
Damper open, in² per fireplace	54	59	50
With insert			
Damper closed, in² per fireplace	5.6	7.1	4.03
Damper open or absent, in² per fireplace	10	14	6.2
Exhaust fans			
Kitchen fan			
Damper closed, in² per fan	0.775	1.1	0.47
Damper open, in² per fan	6	6.5	5.6
Bathroom fan			
Damper closed, in² per fan	1.7	1.9	1.6
Damper open, in² per fan	3.1	3.4	2.8
Dryer vent			
Damper closed, in² per vent	0.47	0.9	0
Heating ducts and furnace-Forced-air systems			
Ductwork (only if in unconditioned space)			
Joints taped or caulked, in² per house	11	11	5
Joints not taped or caulked, in² per house	22	22	11
Furnace (only if in conditioned space)			
Sealed combustion furnace, in² per furnace	0	0	0
Retention head burner furnace, in² per furnace	5	6.2	3.1
Retention head plus stack damper, in² per furnace	3.7	4.6	2.8
Furnace with stack damper, in² per furnace	4.6	6.2	3.1
Air conditioner			
Wall or window unit, in² per unit	3.7	5.6	0

Note: For conversion to SI units: 1 in² = 6.45 cm², 1 ft² = 0.0929 m², and 1 in²/ft² = 69 cm²/m².
Source: From ASHRAE, 1989a.

Pressure Terms

The pressure difference $\Delta p = p_o - p_i$ is the sum of three terms:

$$\Delta p = \Delta p_{wind} + \Delta p_{stack} + \Delta p_{vent} \tag{6.1.3}$$

the first due to wind, the second due to the stack effect (like the flow induced in a heated smokestack), and the third due to forced ventilation, if any. We take the pressure differences to be positive when they cause air to flow toward the interior. The flow depends only on the total Δp, not on the individual terms. The relative contribution of the wind, stack, and ventilation terms varies across the envelope, and because of the nonlinearity, one cannot calculate separate airflows for each of these effects and add them at the end.

The wind pressure is given by Bernoulli's equation (in SI units)

$$p_{wind} = \frac{\rho}{2}(v^2 - v_f^2) \tag{6.1.4SI}$$

where v = wind speed (undisturbed by building), m/s
v_f = final speed of air at building boundary

ρ = air density, kg/m³

In USCS units, we have

$$p_{wind} = \frac{\rho}{2g_c}(v^2 - v_f^2) \qquad lb_f/ft^2 \tag{6.1.4US}$$

with $g_c = 32.17\ (lb_m \cdot ft)/(lb_f \cdot s^2)$, the wind speed being in feet per second, and the air density in pound-mass per cubic foot.

Under standard conditions of 14.7 psi (101.3 kPa) and 68°F (20°C), the density is

$$\rho = 0.075\ lb_m/ft^3 \qquad (\rho = 1.20\ kg/m^3)$$

but one should note that the density of outdoor air can deviate more than 20% above (winter at sea level) or below (summer in the mountains) these values. In USCS units, the ratio of

$$\frac{\rho}{g_c} = 0.00964\ inWG/(mi/h)^2$$

under standard conditions if pressure is in inches water gauge and wind speed in miles per hour.

The wind speed is strongly modified by terrain and obstacles, being significantly higher far above the ground (see ASHRAE, 2001). Since the final speed v_f is awkward to determine, a convenient shortcut is to use Equation 6.1.4 with $v_f = 0$, multiplying it instead by a pressure coefficient C_p:

$$p_{wind} = C_p \frac{\rho}{2} v^2 \tag{6.1.5}$$

The quantity $p_{wind}/C_p = (\rho/2)\ v^2$ is plotted versus wind speed v in Figure 6.1.4a. Numerical values for C_p can be gleaned from Figure 6.1.4b, where this coefficient is plotted as a function of the angle between the wind and the surface normal. Typical values are in the range from approximately –0.6 to 0.6, depending on the direction of the wind.

Actually we are interested in the pressure difference between the interior and exterior of a building. If the interior of an entire floor offers no significant flow resistance, one can find the indoor pressure due to wind by averaging the flow coefficient over all orientations of the surrounding wall. Since that average is approximately –0.2, the local pressure difference $p_o - p_i$ at a point of the wall is, in that case,

$$\Delta p_{wind} = \Delta C_p \frac{\rho}{2} v^2 \tag{6.1.6}$$

with $\Delta C_p = C_p - (-0.2)$ being the difference between the local pressure coefficient and the average.

The *stack effect* is the result of density differences between air inside and outside the building. In winter, the air inside the building is warmer, hence less dense than the air outside. Therefore, the indoor pressure difference (bottom versus top) is less than the outdoor pressure difference between the same heights. Consequently, there is an indoor-outdoor pressure difference. It varies linearly with height, and the level of neutral pressure is at the midheight of the building, as suggested by Figure 6.1.5, if the leaks are uniformly distributed. During the cooling season when indoor air is colder than the outside, the effect is reversed.

The pressure difference is given by

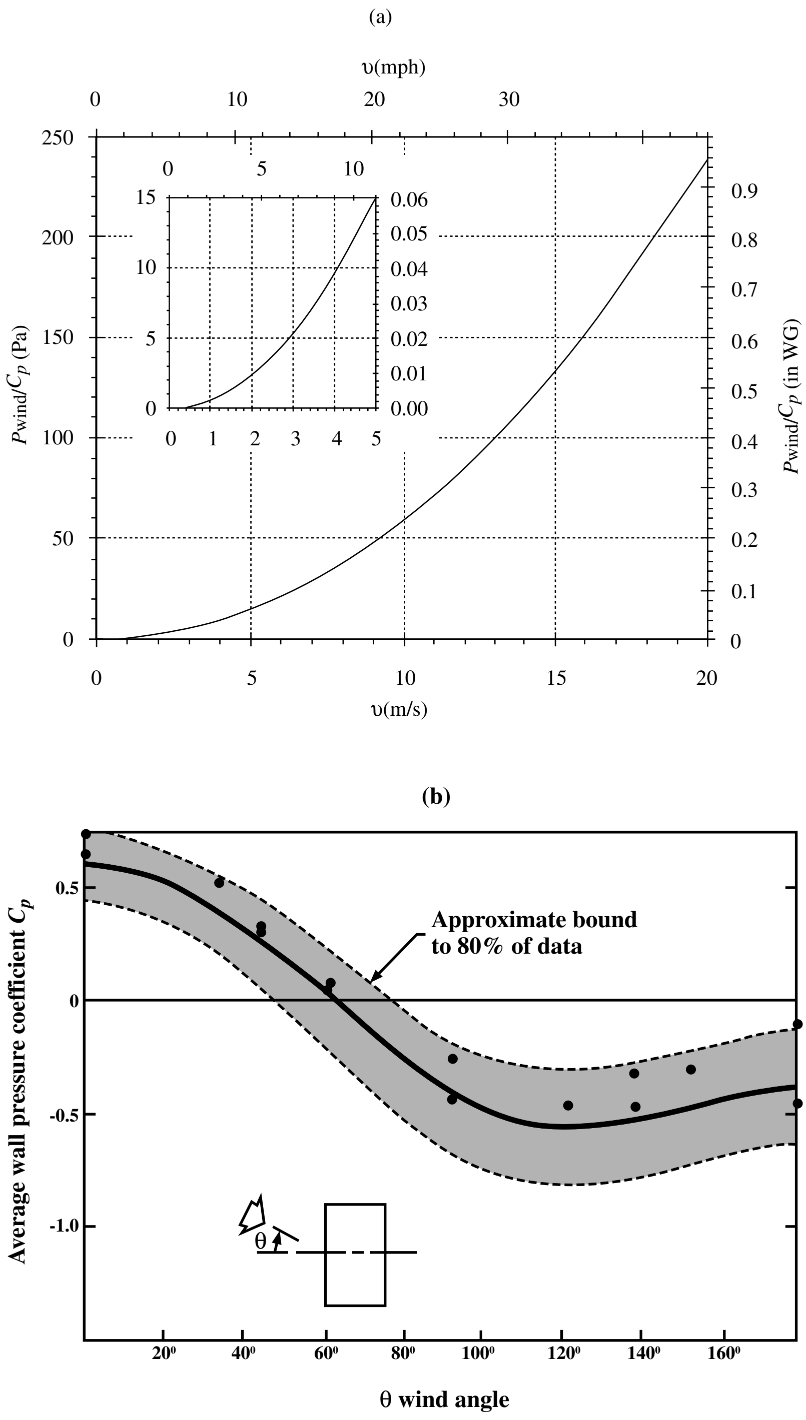


FIGURE 6.1.4 Correlations for wind pressure. (a) Wind pressure plotted as $p_{wind}/C_p = (\rho/2)v^2$ versus wind speed v. (b) Typical values of pressure coefficient C_p of Equation 6.1.5 for a rectangular building as a function of wind direction (from ASHRAE, 1989a; dots indicate the values from Figure 14.6 of that reference).

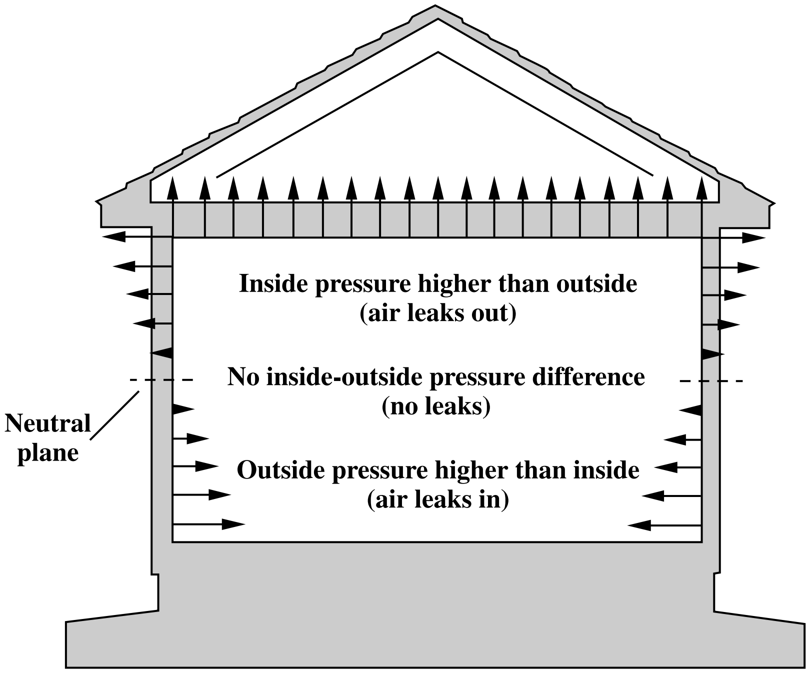


FIGURE 6.1.5 Air leakage due to stack effect during heating season (from Nisson and Vutt, 1985).

$$\Delta p_{stack} = -C_d \rho_i g \Delta h \frac{T_i - T_o}{T_o} \tag{6.1.7SI}$$

$$\Delta p_{stack} = -C_d \frac{\rho_i g}{g_c} \Delta h \frac{T_i - T_o}{T_o} \tag{6.1.7US}$$

where ρ_i = density of air in building = 0.075 lb_m/ft^3 (= 1.20 kg/m^3)
Δh = vertical distance from neutral pressure level, up being positive, ft (m)
g = 32.17 ft/s^2 (9.80 m/s^2) = acceleration due to gravity [g_c = 32.17 $(lb_m \cdot ft)/(lb_f \cdot s^2)$]
T_i and T_o = indoor and outdoor absolute temperatures, °R (K)
C_d = draft coefficient, a dimensionless number to account for the resistance to air flow between floors

The draft coefficient ranges from about 0.65 for typical modern office buildings to 1.0 if there is no resistance at all. Equation 6.1.7 is plotted in Figure 6.1.6 as a function of $\Delta T = T_i - T_o$ and Δh, assuming air at 75°F (24°C). Since the relation is linear in Δh, this figure can be read outside the range shown by simply changing the scales of the axes. For a brief summary, one can say that the stack pressure amounts to

$$\frac{\Delta p_{stack}}{C_d \Delta h \Delta T} = 0.04 \quad Pa/(m \cdot K) \tag{6.1.8SI}$$

$$\frac{\Delta p_{stack}}{C_d \Delta h \Delta T} = 0.00014 \quad lb_f/(ft^2 \cdot ft \cdot °R) \tag{6.1.8US}$$

The stack effect tends to be relatively small in low-rise buildings, up to about five floors, but in high-rise buildings it can dominate and should be given close attention.

Finally, in buildings with *mechanical ventilation*, there is the pressure difference Δp_{vent} if the intake and exhaust flows are not equal. The resulting pressure difference depends on the design and operation of

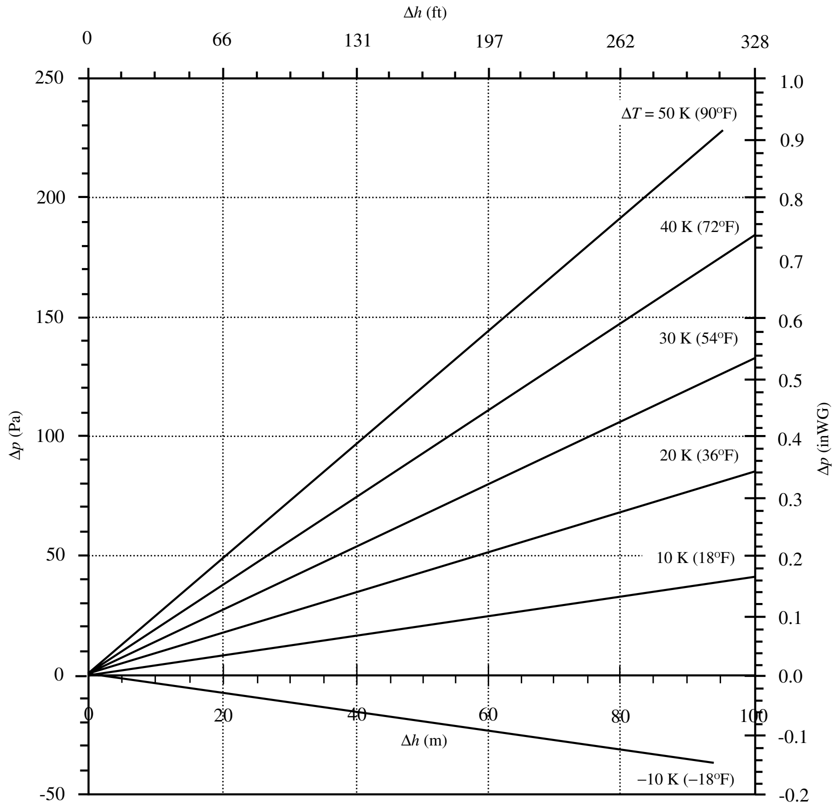


FIGURE 6.1.6 Pressure difference due to stack effect.

the ventilation system and on the tightness of the building. In addition, there is some coupling to the wind and stack terms. Thus, the determination of Δp_{vent} may be somewhat difficult. However, as we now show, the situation is simple when Δp_{vent} is larger in magnitude than the wind and stack terms. This is an important case since many designers aim for slight overpressurization of commercial buildings by making the outdoor air intake larger than the exhaust flow.

Consider how the pressures and flows are related in a fairly tight building where mechanical ventilation maintains overpressure or underpressure Δp_{vent} relative to the outside; for simplicity, we assume it uniform in the entire building. The law of conservation of mass implies that the net air flow provided by the ventilation system equals the net leakage $\dot{V}$ across the envelope, as calculated, according to Equation 6.1.2, by summing over all leakage sites k of the building envelope:

$$\dot{V} = \sum A_k c_k \Delta p_k^{n_k} \qquad \text{with} \qquad \Delta p_k = \Delta p_{wind,k} + \Delta p_{stack,k} + \Delta p_{vent} \tag{6.1.9}$$

For simplicity, let us assume at this point one single value n for the exponent. Then the pressure term on the right-hand side of Equation 6.1.9 can be rewritten in the form

$$\Delta p_k^n = \Delta p_{vent}^n (1 + x_k)^n \qquad \text{with} \qquad x_k = \frac{\Delta p_{wind,k} + \Delta p_{stack,k}}{\Delta p_{vent}} \tag{6.1.10}$$

TABLE 6.1.2 Stack Coefficient a_s

	Number of Stories		
	One	Two	Three
Stack coefficient a_s, $(\text{ft}^3/\text{min})^2/(\text{in}^4 \cdot °\text{F})$	0.0156	0.0313	0.0471
Stack coefficient a_s, $(\text{L/s})^2/(\text{cm}^4 \cdot \text{K})$	0.000145	0.000290	0.000435

Source: From ASHRAE, 1989a.

As long as $|x_k| < 1$, the binomial expansion can be used, with the result*

$$\dot{V}_{vent} = \Delta p_{vent}^n \sum A_k c_k \left[1 + n x_k + \frac{n(n-1)}{2} x_k^2 + \ldots\right]$$

The quantity x_k is positive in some parts of the building, negative in others. In fact, if the distribution of cracks is approximately symmetric (top-bottom and windward-leeward), then for each term with positive x_k there will also be one with approximately the same coefficient but negative x_k. Thus the linear terms in the expansion tend to cancel. The higher-order terms are small, beginning with x_k^2 which is multiplied by $n(n-1)/2$, a factor that is always less than 0.125 in absolute value since $0 < n < 1$. Thus the contributions of the x_k-dependent terms are much smaller than that of the leading term. Therefore, *if a building is pressurized to Δp_{vent} by mechanical ventilation and if wind and stack pressures are smaller than Δp_{vent} then it is indeed a fair approximation to neglect them altogether and write*

$$\dot{V}_{vent} \approx \Delta p^n \sum A_k c_k \qquad \text{with } \Delta p = \Delta p_{vent} \tag{6.1.11}$$

the sum covering the entire envelope of the building. Had we allowed for different exponents n_k in Equation 6.1.9, Δp with its exponent would remain inside the sum, but the conclusion about the negligibility of stack and wind terms continues to hold.

LBL Model for Air Leakage

To apply Equation 6.1.2, one needs data for leakage areas and flow coefficients of all the components of a building. Much research has been done to obtain such data, both for components and for complete buildings, e.g., by pressurizing a building with a blower door. Data were presented in Table 6.1.1.

The total leakage area is obtained by adding all the leakage areas of the components as illustrated in the following example. Once the total leakage area has been found, either by such a calculation or by a pressurization test, the airflow $\dot{V}$ can be estimated by the following model, developed at Lawrence Berkeley Laboratory (LBL) as reported by ASHRAE (2001):

$$\dot{V} = A_{leak} \sqrt{a_s \Delta T + a_w v^2} \quad \text{L/s} \tag{6.1.12}$$

where A_{leak} = total effective leakage area of building, cm^2
a_s = stack coefficient of Table 6.1.2, $(\text{L/s})^2/(\text{cm}^4 \cdot \text{K})$
ΔT = $T_i - T_o$, K
a_w = wind coefficient of Table 6.1.3, $(\text{L/s})^2/[\text{cm}^4 \cdot (\text{m/s})^2]$
v = average wind speed, m/s

This model is applicable to single-zone buildings *without* mechanical ventilation.

* The ith power of x_k in this series is multiplied by the binomial coefficient

$$\binom{n}{i} = \frac{n!}{i!(n-i)!}$$

TABLE 6.1.3 Wind Coefficient a_w

Shielding class	Description	Wind Coefficient a_w, $(L/s)^2/[cm^4 \cdot (m/s)^2]$ Number of Stories: One	Two	Three	Wind Coefficient a_w, $(ft^3/min)^2/[in^4 \cdot (mi/h)^2]$ Number of Stories: One	Two	Three
1	No obstructions or local shielding	0.000319	0.000420	0.000494	0.0119	0.0157	0.0184
2	Light local shielding; few obstructions, a few trees or small shed	0.000246	0.000325	0.000382	0.0092	0.0121	0.0143
3	Moderate local shielding; some obstructions within two house heights, thick hedge, solid fence, or one neighboring house	0.000174	0.000231	0.000271	0.0065	0.0086	0.0101
4	Heavy shielding; obstructions around most of perimeter, buildings or trees within 10 m in most directions; typical suburban shielding	0.000104	0.000137	0.000161	0.0039	0.0051	0.0060
5	Very heavy shielding; large obstructions; typical downtown shielding	0.000032	0.000042	0.000049	0.0012	0.0016	0.0018

Source: From ASHRAE, 1989a.

Further Correlations for Building Components

Most commercial buildings have features that are not included in the model of the previous section:

- Mechanical ventilation
- Revolving or swinging doors
- Curtain walls (i.e., the non load-bearing wall construction commonly employed in commercial buildings)

These features can be analyzed by using the method presented in the *Cooling and Heating Load Calculation Manual* (1979, 1992), published by ASHRAE. Here we give a brief summary. The air flows are determined from the following correlations, where Δp is the total pressure difference at each point of the building, calculated as described above.

For residential-type doors and windows, the flow per length l_p of perimeter is given by an equation of the form

$$\frac{\dot{V}}{l_p} = k(\Delta p)^n \qquad \dot{V},\ ft^3/min;\ l_p,\ ft;\ \Delta p,\ in\ WG \tag{6.1.13US}$$

Numerical values can be found in Figure 6.1.7 for windows and residential-type doors, and in Figure 6.1.8 for swinging doors when they are closed, as functions of the pressure difference Δp, for several values of k corresponding to different types of construction. The exponent n is 0.5 for residential-type doors and windows, and 0.65 for swinging doors. The larger values for n and for k for the latter account for the larger cracks of swinging doors. Since the equations are dimensional, all quantities must be used with the specified units. We have added dual scales to the graphs, so Figures 6.1.7–6.1.10 can be read directly in both systems of units.

Obviously the air flow increases markedly when doors are opened. Figure 6.1.9 permits an estimate of the air flow through swinging doors, both single-bank and vestibule-type, as a function of traffic rate. The coefficient C $[(ft^3/min)/(in\ WG)^{-0.5}]$ for Figure 6.1.9a is found from Figure 6.1.9b for the number of people passing the door per hour. The equation for the flow in part a is

$$\dot{V} = C(\Delta p)^{0.5} \qquad \dot{V},\ ft^3/min;\ \Delta p,\ in\ WG \tag{6.1.14US}$$

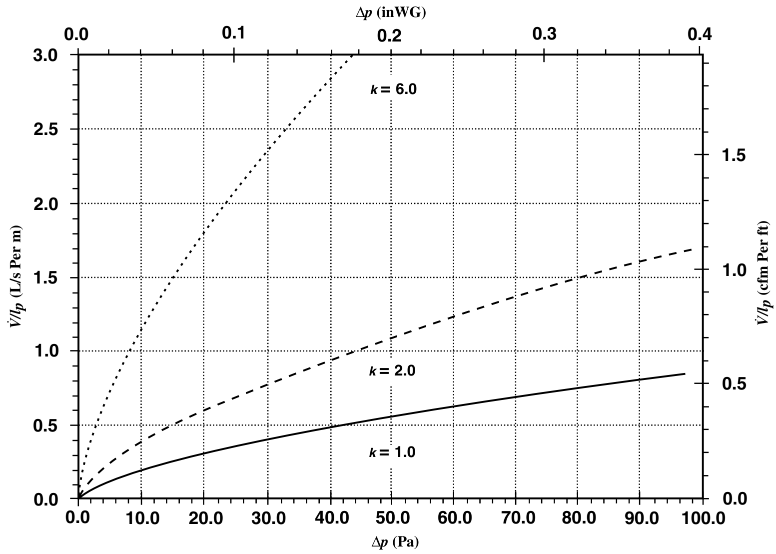


FIGURE 6.1.7 Window and residential-type door air infiltration $\dot{V}$ per perimeter length l_p. The curves correspond to Equation 6.1.13, with n = 0.65 and coefficient k [(ft³/min)/(inWG)$^{0.65}$] according to construction type, as shown in the following table:

Coefficient	Windows: Wood Double-Hung (locked)	Windows: Other Types	Doors (Residential Type)
k = 1.0 "tight"	Weather-stripped, small gap width 0.4 mm (1/64 in)	Weather-stripped: wood casement and awning windows, metal casement windows	Very small perimeter gap and perfect-fit weather-stripping — often characteristic of new doors
k = 2.0 "average"	Non weather-stripped, small gap width 0.4 mm (1/64 in); or weather-stripped, large gap width 2.4 mm (3/32 in)	All types of sliding windows, weather-stripped (if gap width is 0.4 mm, this could be "tight"; or non weather-stripped metal casement windows (if gap width is 2.4 mm, this could be "loose")	Small perimeter gap with stop trim, good fit around door, and weather-stripping
k = 6.0 "loose"	Non weather-stripped, large gap width 2.4 mm (3/32 in)	Non weather-stripped vertical and horizontal sliding windows	Large perimeter gap with poor-fitting stop trim and weather-stripping, or small perimeter gap without weather-stripping

Analogous information on flow per unit area of curtain wall can be determined by the equation

$$\frac{\dot{V}}{A} = K\left(\Delta p\right)^{0.65} \qquad \dot{V},\ \text{ft}^3/\text{min};\ \text{A, ft}^2;\ \Delta p,\ \text{in WG} \tag{6.1.15US}$$

It is presented in Fig. 6.1.10 for three construction types, corresponding to the indicated values of the coefficient K (ft³/min)/(ft² · inWG$^{0.65}$).

6.1.2 Principles of Load Calculations

Design Conditions

Loads depend on the indoor conditions that one wants to maintain and on the weather, the latter of which is not known in advance. If the HVAC equipment is to guarantee comfort at all times, it must be designed for peak conditions. What are the extremes? For most buildings it would not be practical to aim for total protection by choosing the most extreme weather on record and adding a safety margin.

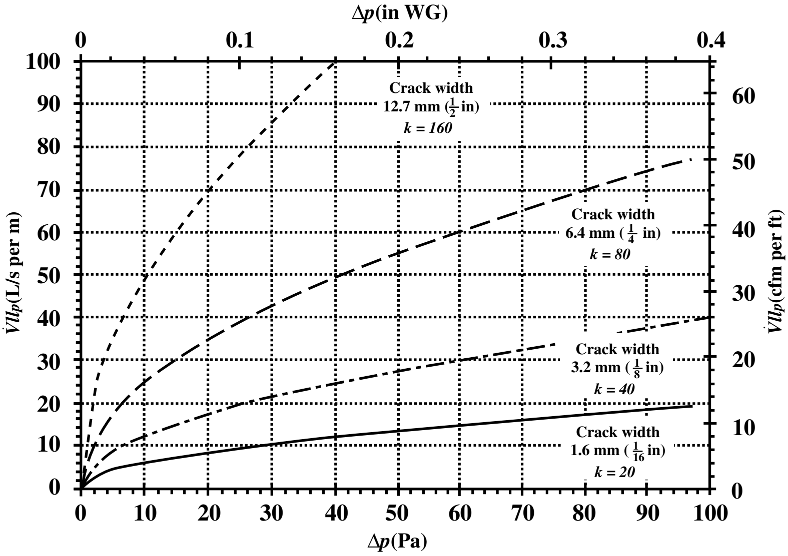


FIGURE 6.1.8 Infiltration through closed swinging door cracks, $\dot{V}$ per perimeter length l_p. The curves correspond to Equation 6.1.13 with n = 0.5 and k [(ft³/min)/(inWG)$^{0.5}$].

(a)

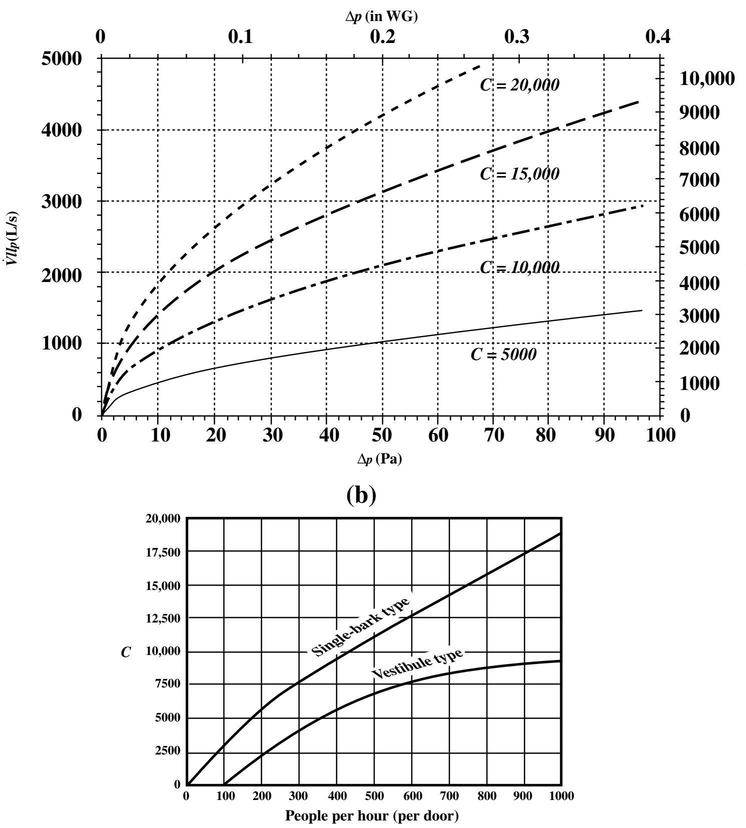


FIGURE 6.1.9 Infiltration due to door openings as a function of traffic rate. (a) Infiltration (with n = 0.5). (b) Coefficient C [(ft³/min)/(inWG)$^{0.5}$].

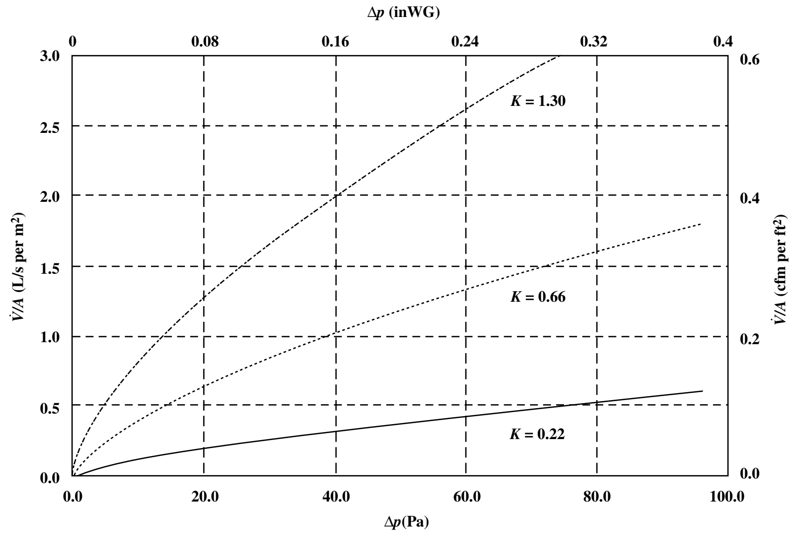


FIGURE 6.1.10 Infiltration per area of curtain wall for one room or one floor. The curves correspond to Equation 6.1.15, with coefficient k $[(ft^3/min)/(ft^2 \cdot inWG)^{0.65}]$ according to construction type.

Coefficient	Construction
K = 0.22 "tight"	Close supervision of workmanship; joints are redone when they appear inadequate
K = 0.66 "average"	Conventional
K = 1.30 "loose"	Poor quality control, or older building where joints have not been redone

Such oversizing of the HVAC equipment would be excessive, not just in first cost but also in operating cost; most of the time, the equipment would run with poor part-load efficiency. Therefore compromise is called for, reducing the cost of the HVAC equipment significantly while accepting the risk of slight discomfort under rare extremes of weather. The greater the extreme, the rarer the occurrence.

To help with the choice of design conditions, ASHRAE has published weather statistics corresponding to several levels of probability. They are the conditions that are exceeded at the site in question during a specified percentage of time of an average season. For warm conditions, the *ASHRAE Handbook of Fundamentals* lists design conditions for the 0.4%, 1.0%, and 2% levels. For cooling, these percentage probabilities refer to 12 months (8760 hours). To see what these statistics imply, consider Washington, D.C., where the 1% level for the dry-bulb temperature is 92°F (33°C). Here the temperature is above 92°F during 0.010×8760 h = 87.6 h of an average summer. Since the hottest hours are concentrated during afternoons rather than spread over the entire day, the corresponding number of days can be considerably higher than 1% of the 122 days of the summer season (June – September).

The cold weather design conditions are listed as 99.0% and 99.6% conditions because that is the percentage of the typical year when the temperature is *above* these levels.

A certain amount of judgment is needed in the choice of design conditions. For ordinary buildings, it is customary to base the design on the level of 1.0% in summer and 99.0% in winter. For critical applications such as hospitals or sensitive industrial processes, or for lightweight buildings, one may prefer the more stringent level of 0.4% in summer (99.6% in winter). Thermal inertia can help in reducing the risk of discomfort; it delays and attenuates the peak loads, as will be explained in the following sections. Therefore one may move to a less stringent level for a given application if the building is very massive.*

* As a guide for the assessment of the relation between persistence of cold weather and thermal inertia, we note that according to studies at several stations, temperatures below the design conditions can persist for up to a week (ASHRAE, 2001).

For peak heating loads, one need not bother with solar radiation because the extremes occur during winter nights. For cooling loads, solar radiation is crucial, but its peak values are essentially a function of latitude alone. For opaque surfaces, the effect of solar radiation is treated by means of the sol-air temperature, for glazing, by means of the solar heat gain factor. Design values of the solar heat gain factor for a set of surface orientations and latitudes can be found in (ASHRAE 2001).

As for humidity and latent loads, the ASHRAE tables include design wet-bulb temperatures, also at the 0.4%, 1.0%, and 2% levels along with the coincident dry-bulb temperature. Alternatively, the Tables also show the mean coincident wet-bulb temperatures, defined as the average wet-bulb temperature at the corresponding dry-bulb values (also at the 0.4%, 1.0%, and 2% levels). For winter no wet-bulb temperature data are given. Usually this poses no serious problem because latent loads during the heating season are zero if one does not humidify. If one does humidify, uncertainties in the value of the outdoor humidity have little effect on the latent load because the absolute humidity of outdoor air in winter is very low.

Wind speed is another weather-dependent variable that has a bearing on loads. Traditionally the ASHRAE (2001) value

$$v_{win} = 15 \text{ mi/h } (6.7 \text{ m/s}) \tag{6.1.16a}$$

has been recommended for heating loads, if there is nothing to imply extreme conditions (such as an exposed hilltop location). For cooling loads, a value half as large is recommended

$$V_{sum} = 7.5 \text{ mi/h } (3.4 \text{ m/s}) \tag{6.1.16b}$$

because wind tends to be less strong in summer than in winter. Of particular interest is the surface heat transfer coefficient (radiation plus convection) h_o for which ASHRAE (2001) recommends the design values.

$$h_{o,win} = 6.0 \text{ Btu/(h} \cdot \text{ft}^2 \cdot \text{°F)} \qquad [34.0 \text{ W/(m}^2 \cdot \text{K)}] \tag{6.1.17a}$$

$$h_{o,sum} = 4.0 \text{ Btu/(h} \cdot \text{ft}^2 \cdot \text{°F)} \qquad [22.7 \text{ W/(m}^2 \cdot \text{K)}] \tag{6.1.17b}$$

The better a building is insulated and tightened, the less its heat transmission coefficient depends on wind. With current practice for new construction in the U.S., typical wind speed variations may change the heat transmission coefficient by about 10% relative to the value at design conditions. Temperature and humidity for normal indoor activities should be within the comfort region delineated in Chapter 2.2. The comfort chart indicates higher indoor temperatures in summer than in winter because of the difference in clothing.

Building Heat Transmission Coefficient

One of the most important terms in the heat balance of a building is the heat flow across the envelope. As discussed in Chapter 2.1, heat flow can be assumed to be linear in the temperature difference when the range of temperatures is sufficiently small; this is usually a good approximation for heat flow across the envelope. Thus one can calculate the heat flow through each component of the building envelope as the product of its area A, its conductance U, and the difference $T_i - T_o$ between the interior and outdoor temperatures. The calculation of U (or its inverse, the R_{th} value) is described in Chapter 2.1. Here we combine the results for the components to obtain the total heat flow.

The total conductive heat flow from interior to exterior is

$$\dot{Q}_{cond} = \sum_k U_k A_k \left(T_i - T_o\right), \tag{6.1.18}$$

with the sum running over all parts of the envelope that have a different composition. It is convenient to define a total *conductive heat transmission coefficient* K_{cond}, or *UA* value, as

$$K_{cond} = \sum_k U_k A_k \tag{6.1.19}$$

so that the conductive heat flow for the typical case of a single interior temperature T_i can be written as

$$\dot{Q}_{cond} = K_{cond}\left(T_i - T_o\right) \tag{6.1.20}$$

In most buildings, the envelope consists of a large number of different parts; the greater the desired accuracy, the greater the amount of detail to be taken into account.

As a simplification, one can consider a few major groups and use effective values for each. The three main groups are glazing, opaque walls, and roof. The reason for distinguishing the wall and the roof lies in the thickness of the insulation; roofs tend to be better insulated because it is easier and less costly to add extra insulation there than in the walls. With these three groups one can write

$$K_{cond} = U_{glass} \cdot A_{glass} + U_{wall} \cdot A_{wall} + U_{roof} \cdot A_{roof} \tag{6.1.21}$$

if one takes for each the appropriate effective value. For instance, the value for glazing must be the average over glass and framing.

In the energy balance of a building, there is one other term that is proportional to $T_i - T_o$. It is the flow of sensible heat [in watts (Btu/h)] due to air exchange:

$$\dot{Q}_{air} = \rho c_p \dot{V}\left(T_i - T_o\right) \tag{6.1.22}$$

where ρ = density of air
c_p = specific heat of air
$\dot{V}$ = air exchange rate ft^3/h (m^3/s)

At standard conditions, 14.7 psia (101.3 kPa) and 68°F (20°C), the factor ρc_p has the value

$$\rho c_p = 0.018 \text{ Btu/(ft}^3 \cdot \text{°F)} \qquad [1.2 \text{ kJ/(m}^3 \cdot \text{K)}] \tag{6.1.23}$$

In USCS units, if $\dot{V}$ is in cubic feet per minute, it must be converted to ft^3/h by multiplying by 60 (ft^3/h)/(ft^3/min). It is convenient to combine the terms proportional to $T_i - T_o$ by defining the total heat transmission coefficient K_{tot} of the building as the sum of conductive and air change terms:

$$K_{tot} = K_{cond} + \rho c_p \dot{V} \tag{6.1.24}$$

A more refined calculation would take surface heat transfer coefficients into account, as well as details of the construction. In practice, such details can take up most of the effort.

Heat Gains

Heat gains affect both heating and cooling loads. In addition to familiar solar gains, there are heat gains from occupants, lights, and equipment such as appliances, motors, computers, and copiers. Power densities for lights in office buildings are around 20–30 W/m^2. For lights and for resistive heaters, the nominal power rating (i.e., the rating on the label) is usually close to the power drawn in actual use. But for office equipment, that would be quite misleading; the actual power has been measured to be much lower, often by a factor of 2 to 4 (Norford et al., 1989). Some typical values are indicated in Table 6.1.4. In recent years, the computer revolution has brought a rapid increase in electronic office equipment, and the impact on loads has become quite important, comparable to lighting. The energy consumption for office equipment is uncertain — will the occupants turn off the computers between uses or keep them running nights and weekends?

TABLE 6.1.4 Typical Heat Gain Rates for Several Kinds of Equipment

Equipment	Heat Gain Btu/h	Heat Gain W	Comments
Television set	170–340	50–100	
Refrigerator	340–680	100–200	Recent models more efficient
Personal computer (desktop)	170–680	50–200	Almost independent of use while turned on
Impact printer	34–100	10–30 standby	Increases about twofold during printing
Laser printer	510	150 standby	Increases about twofold during printing
Copier	500–1000	150–300 standby	Increases about twofold during printing

Note: Measured values are often less than half of the nameplate rating.
Source: Based on ASHRAE, 1989a, Norford et al., 1989, and updates.

TABLE 6.1.5 Nominal Heat Gain Values from Occupants

Activity	Total Btu/h	Total W	Sensible Btu/h	Sensible W	Latent Btu/h	Latent W
Seated at rest	340	100	240	70	100	30
Seated, light office work	410	120	255	75	150	45
Standing or walking slowly	495	145	255	75	240	70
Light physical work	850	250	310	90	545	160
Heavy physical work	1600	470	630	185	970	285

Source: Based on ASHRAE, 1989a.

For special equipment such as laboratories or kitchens, it is advisable to estimate the heat gains by taking a close look at the inventory of the equipment to be installed, paying attention to the possibility that much of the heat may be drawn directly to the outside by exhaust fans.

Heat gain from occupants depends on the level of physical activity. Nominal values are listed in Table 6.1.5. It is instructive to reflect on the origin of this heat gain. The total heat gain must be close to the caloric food intake, since most of the energy is dissipated from the body as heat. An average of 100 W corresponds to

$$100\text{ W} = 0.1\text{ kJ/s} \times \left(\frac{L\,kcal}{4.186\,kJ}\right) \times (24 \times 3600\text{ s/day}) = 2064\text{ kcal/day} \tag{6.1.25}$$

indeed a reasonable value compared to the typical food intake (note that the dieticians' calorie is really a kilocalorie). The latent heat gain must be equal to the heat of vaporization of the water that is exhaled or transpired. Dividing 30 W by the heat of vaporization of water, we find a water quantity of 30 W/(2450 kJ/kg) = 12.2×10^{-6} kg/s, or about 1.1 kg/24 h. That also appears quite reasonable.

The latent heat gain due to the air exchange is

$$\dot{Q}_{air,lat} = \dot{V}\rho h_{fg}\left(W_o - W_i\right) \tag{6.1.26}$$

where $\dot{V}$ = volumetric air exchange rate, ft^3/min (m^3/s or L/s)
ρ = density, lb_m/ft^3 (kg/m^3)
$\rho\, h_{fg}$ = 4840 Btu/(h · ft^3/min) [3010 W/(L/s)] at standard conditions
W_i, W_o = humidity ratios of indoor and outdoor air

Heat Balance

Loads are the heat that must be supplied or removed by the HVAC equipment to maintain a space at the desired conditions. The calculations are like accounting. One considers all the heat that is generated in the space or that flows across the envelope; the total energy, including the thermal energy stored in

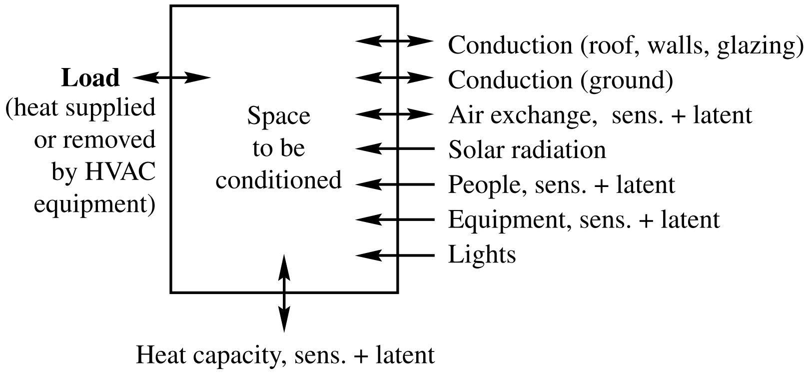


FIGURE 6.1.11 The terms in a load calculation.

the space, must be conserved according to the first law of thermodynamics. The principal terms are indicated in Figure 6.1.11. Outdoor air, occupants, and possibly certain kinds of equipment contribute both sensible and latent heat terms.

Load calculations are straightforward in the static limit, i.e., if all input is constant. As discussed in the following section, that is usually an acceptable approximation for the calculation of peak heating loads. But for cooling loads, dynamic effects (i.e., heat storage) must be taken into account because some of the heat gains are absorbed by the mass of the building and do not contribute to the loads until several hours later. Dynamic effects are also important whenever the indoor temperature is allowed to float.

Sometimes it is appropriate to distinguish several aspects of the load. If the indoor temperature is not constant, the instantaneous load of the space may differ from the rate at which heat is being supplied or removed by the HVAC equipment. The load for the heating or cooling plant is different from the space load if there are significant losses from the distribution system, or if part of the air is exhausted to the outside rather than being returned to the heating or cooling coil.

It is convenient to classify the terms of the static energy balance according to the following groups. The sensible energy terms are

1. Conduction through the building envelope other than ground,

$$\dot{Q}_{cond} = K_{cond}\left(T_i - T_o\right) \tag{6.1.27}$$

2. Conduction through the floor, $\dot{Q}_{floor}$
3. Heat due to air exchange (infiltration and/or ventilation), at rate $\dot{V}$,

$$\dot{Q}_{air} = \dot{V}\rho c_p\left(T_i - T_o\right) \tag{6.1.28}$$

4. Heat gains from solar radiation, lights, equipment (appliances, computers, fans, etc.), and occupants,

$$\dot{Q}_{gain} = \dot{Q}_{sol} + \dot{Q}_{lit} + \dot{Q}_{equ} + \dot{Q}_{occ} \tag{6.1.29}$$

Combining the heat loss terms and subtracting the heat gains, one obtains the total *sensible load*

$$\dot{Q} = \dot{Q}_{cond} + \dot{Q}_{air} + \dot{Q}_{floor} - \dot{Q}_{gain} + \dot{Q}_{stor} \tag{6.1.30}$$

where we have added a term $\dot{Q}_{stor}$ on the right to account for storage of heat in the heat capacity of the building (the terms *thermal mass* and *thermal inertia* are also used to designate this effect). A dynamic analysis includes this term; a static analysis neglects it.

We have kept $\dot{Q}_{floor}$ as a separate item because it should not be taken proportional to $T_i - T_o$ except in cases such as a crawl space or uninsulated slab on grade, where the floor is in fairly direct contact with outside air. More typical is conduction through massive soil (see Chuangchid and Krarti, 2000; Kreider, Rabl, and Curtiss, 2001) are appropriate. In traditional construction, the floor term has usually been small, and often it has been neglected altogether. But in superinsulated buildings it can be relatively important.

Using the total heat transmission coefficient K_{tot},

$$K_{tot} = K_{cond} + \dot{V}\rho c_p \tag{6.1.31}$$

one can write the sensible load in the form

$$\dot{Q} = K_{tot}\left(T_i - T_o\right) + \dot{Q}_{floor} - \dot{Q}_{gain} \pm \dot{Q}_{stor} \tag{6.1.32}$$

For signs, we take the convention that $\dot{Q}$ is positive when there is a heating load and negative when there is a cooling load. Sometimes, however, we prefer a positive sign for cooling loads. In that case, we will add subscripts *c* and *h* with the understanding that

$$\dot{Q}_c = -\dot{Q} \qquad \text{and} \qquad \dot{Q}_h = \dot{Q} \tag{6.1.33}$$

The latent heat gains are mainly due to air exchange, equipment (such as in the kitchen and bathroom), and occupants. Their sum is

$$\dot{Q}_{lat} = \dot{Q}_{lat,air} + \dot{Q}_{lat,occ} + \dot{Q}_{lat,equ} \tag{6.1.34}$$

The total load is the sum of the sensible and the latent loads.

During the heating season, the latent gain from air exchange is usually negative (with the signs of Equation 6.1.26) because the outdoor air is relatively dry. A negative Q_{lat} implies that the total heating load is greater than the sensible heating load alone — but this is relevant only if there is humidification to maintain the specified humidity ratio W_i. For buildings without humidification, one has no control over W_i, and there is not much point in calculating the latent contribution to the heating load at a fictitious value of W_i.

6.1.3 Storage Effects and Limits of Static Analysis

The storage term $\dot{Q}_{stor}$ in Equation 6.1.32 is the rate of heat flow into or out of the mass of the building, including its furnishings and even the air itself. The details of the heat transfer depend on the nature of the building, and they can be quite complex.

One of the difficulties can be illustrated by considering an extreme example: a building that contains in its interior a large block of solid concrete several meters thick. The conductivity of concrete is relatively low, and diurnal temperature variations do not penetrate deeply into the block; only in the outer layer, to a depth of roughly 0.20 m, are they appreciable. Thus the bulk of the block does not contribute any storage effects on a diurnal time scale. The static heat capacity, defined as the product of the mass and the specific heat, would overestimate the storage potential because it does not take into account the temperature distribution under varying conditions.

To deal with this effect, some people (e.g., Sonderegger, 1978) have used the concept of *effective heat capacity* C_{eff}, defined as the periodic heat flow into and out of a body divided by the temperature swing at the surface. It depends on the rate of heat transfer and on the frequency. The effective heat capacity is smaller than the static heat capacity, approaching it in the limit of infinite conductivity or infinitely long charging and discharging periods. As a rule of thumb, for diurnal temperature variations, the effective heat capacity of walls, floors, and ceilings is roughly 40 to 80% of the static heat capacity, assuming typical construction of buildings in the U.S. (wood, plaster, or concrete, 3–10 cm thick). For items, such as furniture, that are thin relative to the depth of temperature variations, the effective heat capacity approaches the full static value.

Further complications arise from the fact that the temperatures of different parts of the building are almost never perfectly uniform. For instance, sunlight entering a building is absorbed by the floor, walls, and furniture and raises their temperature. The air itself does not absorb any appreciable solar radiation and is warmed only indirectly. Thus the absorbed radiation can cause heat to flow from the building mass to the air, even if the air is maintained thermostatically at uniform and constant temperature.

Heat capacity tends to be more important for cooling than for heating loads, for a number of reasons. Summer heat flows are more peaked than those in winter. Peak heating loads correspond to times without sun and the diurnal variation of $T_i - T_o$ is small compared to its maximum in most climates. By contrast, for peak cooling loads, the diurnal variation of $T_i - T_o$ is comparable to its maximum, and solar gains are crucial. Also, in climates with cold winters, heating loads are larger than cooling loads, and the storage terms, for typical temperature excursions, are relatively less important in winter than in summer.

Consequently, the traditional steady-state calculation of peak heating loads was well justified for buildings with a constant thermostat setpoint. However, thermostat setback can have a sizable impact on peak heating loads because setback recovery occurs during the early morning hours on top of the peak heat loss; section 6.1.5 discusses this point in more detail. Peak cooling loads, by contrast, are usually not affected by thermostat setup because recovery is not coincident with the peak gains.

Storage effects for latent loads are difficult to analyze (see e.g., Fairey and Kerestecioglu, 1985; and Kerestecioglu and Gu, 1990), and most of the current computer programs for building simulation, such as DOE2.1 and BLAST (see Chapter 6.2), do not account for moisture exchange with the building mass. In practice, this neglect of moisture storage is usually not a serious problem. Precise humidity control is not very important in most buildings. Where it is important, e.g., in hospitals, temperature and humidity are maintained constant around the clock. When the air is at constant conditions, the moisture in the materials does not change much and storage effects can be neglected; but in buildings with intermittent operation, these effects can be large, as shown by Fairey and Kerestecioglu (1985) and by Wong and Wang (1990).

From this discussion emerge the following recommendations for the importance of dynamic effects:

- They can significantly reduce the peak cooling loads, with or without thermostat setup.
- They can be neglected for peak heating loads, except if thermostat setback recovery is to be applied even during the coldest periods of the year.
- For the calculation of annual consumption, they can have an appreciable effect if the indoor temperature is not kept constant.

Storage of *latent* heat is neglected for most applications.

Thus a simple static analysis is sufficient for some of the problems the designer is faced with, but not for the peak cooling load. To preserve much of the simplicity of the static approach in a method for peak cooling loads, ASHRAE has developed the CLF-CLTD method which modifies the terms of a static calculation to account for thermal inertia. This method is presented in section 6.1.6; it can be used for standard construction if the thermostat setpoint is constant.

6.1.4 Zones

So far we have considered the interior as a single zone at uniform temperature — a fair approximation for simple houses, for certain buildings without windows (such as warehouses), or for buildings that are dominated by ventilation. But in large or complex buildings, one usually has to calculate the loads separately for a number of different zones. There may be several reasons. An obvious case is a building where different rooms are maintained at different temperatures, e.g., a house with an attached sunspace.

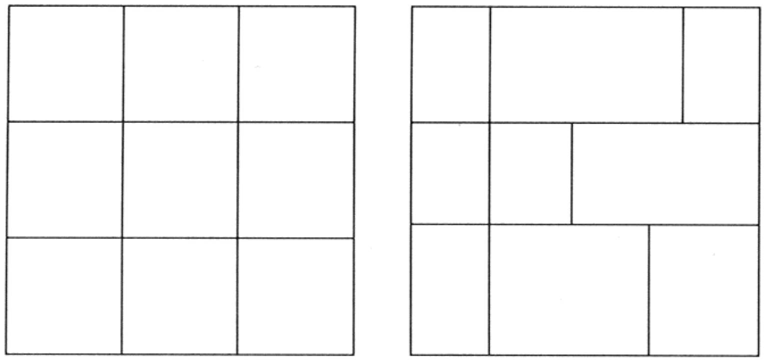


FIGURE 6.1.12 Variation of schematic floor plan to show that surface area of interior walls is independent of arrangement.

Here the heat balance equation is written for each zone, in the form of Equation 6.1.32 but with an additional term

$$\dot{Q}_{j-k} = U_{j-k} A_{j-k} \left(T_j - T_k \right) \tag{6.1.35}$$

for the heat flow between zones j and k.

However, even when the entire building is kept at the same temperature, multizone analysis becomes necessary if the spatial distribution of heat gains is too nonuniform. Consider, for example, a building with large windows on the north and south sides, during a sunny winter day when the gains just balance the total heat loss. Then neither heating nor cooling would be required, according to a one-zone analysis. But how can the heat from the south get to the north?

Heat flow is the product of the heat transfer coefficient and the temperature difference, as in Equation 6.1.35. Temperature differences between occupied zones are small, usually not more than a few Kelvins; otherwise there would be complaints about comfort. The heat transfer coefficients between zones are often not sufficiently large for effective redistribution of heat, especially if there are walls or partitions.

The basic criterion for zoning is the ability to control the comfort conditions; the control is limited by the number of zones one is willing to consider. To guarantee comfort, the HVAC plant and distribution system must be designed with sufficient capacity to meet the load of each zone. In choosing the zones for a multizone analysis, the designer should try to match the distribution of heat gains and losses. A common and important division is between interior and perimeter zones, because the interior is not exposed to the changing environment. Different facades of the perimeter should be considered separately for cooling load calculations, as suggested in Figure 6.1.12. Corner rooms should be assigned to the facade with which they have the most in common; usually this will be the facade where a comer room has the largest windows. Corner rooms are often the critical rooms in a zone, requiring more heating or cooling (per unit floor area) than single-facade rooms of the same zone while being most distant from AHUs.

Actually there are different levels to a zoning analysis, corresponding to different levels of the HVAC system. In an air system, there are major zones corresponding to each air handler. Within each air handler zone, the air ducts, air outlets, and heating or cooling coils must have sufficient capacity and sufficient controllability to satisfy the loads of each sub zone; the design flow rates for each room are scaled according to the design loads of the room. For best comfort (and if cost were no constraint), each zone should have its own air handler and each room its own thermostat. There is a tradeoff between equipment cost and achievable comfort, and the best choice depends on the circumstances. If temperature control is critical, one installs separate air handlers for each of the five zones in Figure 6.1.12 and separate thermostats for each room. To save equipment cost, one often assigns several zones to one air handler and

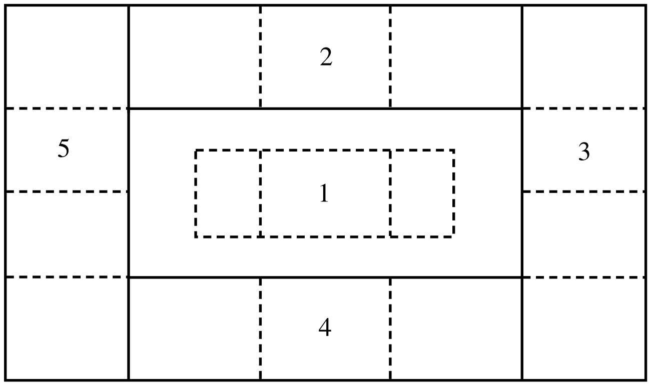


FIGURE 6.1.13 Example of recommended zoning. Thick lines represent zones, labeled 1 through 5. Dashed lines represent subzones.

several rooms to one thermostat, but the more divergent the loads, the more problematic the control. For the building of Figure 6.1.12, a single air handler and five thermostats may be adequate if the distribution of heat gains is fairly uniform and if the envelope is well insulated with good control of solar gains.

Another example is a house whose air distribution system has a single fan (typical of all but the largest houses). Even though there is only one major zone, the detailed design of the distribution system demands some attention to subzones. Within each room, the peak heating capacity should match the peak heat loss. Also, it is advisable to place heat sources close to points with large heat loss, i.e., under windows (unless they are highly insulating).

The choice of zones is not always clear-cut, and the design process may be iterative. Depending on the distribution of gains and losses, one may want to assign several rooms to a zone, one room to a zone, or even several zones to a room (if it is very large). With finer zonal detail one improves the control of comfort, but at the price of greater calculational effort and higher HVAC system cost. In an open office space, there is no obvious boundary between interior and perimeter; here a good rule is to make the perimeter zone as deep as the penetration depth of direct solar radiation, typically a few meters. Spaces connected by open doors, e.g., offices and adjacent hallways, can sometimes be treated as a single zone. Separate zones are advisable for rooms with large computers or energy-intensive equipment. In multistory buildings, one may want to treat the top floor apart from the rest.

The calculation of peak heating loads and capacities can often be done without considering separate perimeter zones, because peak heating loads occur when there is no sun; with uniform internal gains, the corresponding thermal balance is uniform around the perimeter. But while the calculation can be carried out for a single zone, the operation requires multiple zones: The heating system must allow separate control of different facades to compensate for the variability of solar gains during the day. For cooling loads, a multizone analysis is essential, because the peak loads occur when the sun is shining.

As discussed in the previous section, peak cooling loads require a dynamic analysis whereas peak heating loads can be estimated quite well by static models (at least in the absence of thermostat setback). Compared to heating loads, the calculation of cooling loads of large buildings is thus doubly complicated: It requires multiple zones and dynamic analysis if one wants reasonable accuracy.

A related issue is the coincidence between peak loads of different zones. To determine the capacity of the central plant, one needs to know the peak load of the totality of zones served by the plant. This is usually less than the simple sum of the individual peak loads because of noncoincidence. The term diversity is used to designate the ratio of the actual system peak to the sum of the individual peak loads. In practice, one often finds a diversity around 0.6 to 0.8 for large buildings or groups of buildings (e.g., university campuses); for better estimates at the design stage, computer simulations are recommended (see Chapter 6.2).

6.1.5 Heating Loads

Since the coldest weather may occur during periods without solar radiation, it is advisable not to rely on the benefit of solar heat gains when calculating peak heating loads (unless the building contains long-term storage). If the indoor temperature T_i is constant, a static analysis is sufficient and the calculation of the peak heating load $\dot{Q}_{h,max}$ is very simple. Find the design heat loss coefficient K_{tot}, multiply by the design temperature difference $T_i - T_o$, and subtract the internal heat gains on which one can count during the coldest weather

$$\dot{Q}_{h.max} = K_{tot}\left(T_i - T_o\right) - \dot{Q}_{gain} \tag{6.1.36}$$

to find the design heat load. However, it is also necessary to warm a space that has had night setback. In a given situation, the required extra capacity, called the *pickup load*, depends on the amount of setback $T_i - T_o$, the acceptable recovery time, and building construction. For reasonable accuracy, a dynamic analysis is recommended. Optimizing the capacity of the heating system involves a tradeoff between energy savings and capacity savings, with due attention to part load efficiency. As a general rule for residences, ASHRAE (1989a) recommends oversizing by about 40% for a night setback of 10°F (5.6 K), to be increased to 60% oversizing if there is additional setback during the day. In any case, some flexibility can be provided by adapting the operation of the building. If the heating capacity turns out insufficient, one can reduce the depth and duration of the setback during the very coldest periods.

In commercial buildings with mechanical ventilation, the demand for extra capacity during setback recovery is reduced if the outdoor air intake is closed during unoccupied periods. In winter that should always be done for energy conservation (unless air quality problems demand high air exchange at night).

6.1.6 CLTD/CLF Method For Cooling Loads*

Because of thermal inertia, it is advisable to distinguish several heat flow rates. The heat gain is the rate at which heat is transferred to or generated in a space. The cooling load is the rate at which the cooling equipment would have to remove thermal energy from the air in the space in order to maintain constant temperature and humidity. Finally, the heat extraction rate is the rate at which the cooling equipment actually does remove thermal energy from the space.**

Conductive heat gains and radiative heat gains do not enter the indoor air directly; rather they pass through the mass of the building, increasing its temperature relative to the air. Only gradually are they transferred to the air. Thus their contribution to the cooling load is delayed, and there is a difference between heat gain and cooling load. Averaged over time, these rates are, of course, equal, by virtue of the first law of thermodynamics.

The heat extraction rate is equal to the cooling load only if the temperature of the indoor air is constant (as assumed in this section). Otherwise, the heat flow to and from the building mass causes the heat extraction rate to differ from the cooling load.

ASHRAE, which sets standard load calculation procedures, is in a transition period regarding its load estimation as this book goes to press. Therefore, what follows is the long-standing CLTD/CLF method used for at least two decades by HVAC engineers. The final section of this chapter summarizes the most recent developments in load calculation procedures even though not all are finalized.

To account for transient effects without having to resort to a full-fledged dynamic analysis, a special shorthand method has been developed that uses the cooling load temperature difference (CLTD) and

* An updated version of the CLTD/CLF method, the CLTD/SCL/CLF method, is described in Section 6.1.8.

** In Chapter 4.3 on HVAC systems, we encountered yet another rate, the coil load; it is the rate at which the cooling coil removes heat from the air, and it can be different from the heat extraction rate due to losses in the distribution system.

cooling load factor (CLF). To explain the principles, note that the cooling load due to conduction across an envelope element of area A and conductance U would be simply

$$\dot{Q}_{cond} = UA(T_o - T_i) \tag{6.1.37}$$

under static conditions, i.e., if indoor temperature T_i and outdoor temperature T_o were both constant. When the temperatures vary, this is no longer the case because of thermal inertia. But if the temperatures follow a periodic pattern, day after day, $\dot{Q}_{c,cond}$ will also follow a periodic pattern. Once $\dot{Q}_{c,cond}$ has been calculated, one can define a CLTD as the temperature difference that gives the same cooling load when multiplied by UA. If such temperature differences are tabulated for typical construction and typical temperature patterns, they can be looked up for quick determination of the load. Thus the conductive cooling load is

$$\dot{Q}_{cond} = UA \cdot CLTD_t \tag{6.1.38}$$

where the subscript t indicates the hour t of the day.

Likewise, if there is a constant radiative heat gain in a zone, the corresponding cooling load is simply equal to that heat gain. If the heat gain follows a periodic pattern, the cooling load also follows a periodic pattern. The cooling load factor (CLF) is defined such that it yields the cooling load at hour t when multiplied by the daily maximum $\dot{Q}_{max}$ of the heat gain:

$$\dot{Q}_{c,rad,t} = \dot{Q}_{\max} \cdot CLF_t \tag{6.1.39}$$

The CLFs account for the fact that radiative gains (solar, lights, etc.) are first absorbed by the mass of the building, becoming a cooling load only as they are being transferred to the air. Only convective gains can be counted as cooling load without delay. Some heat gains, e.g., from occupants, are partly convective and partly radiative; the corresponding CLFs take care of that.

The CLTDs and CLFs of ASHRAE have been calculated by means of the transfer functions discussed in the next section. To keep the bulk of numerical data within reasonable limits, only a limited set of standard construction types and operating conditions has been considered. Some correction factors are provided to extend the applicability, however, without escaping the constraint that the indoor temperature T_i be constant.

If one has to do a CLTD/CLF calculation by hand, it is advisable to use a worksheet such as the one reproduced in Figure 6.1.14 to make sure that nothing is overlooked*. The calculation needs to be done for the hour when the peak occurs. That hour can be guessed if a single load dominates because in that case it is the hour with the largest value of CLTD or CLF. If several loads with noncoincident peaks are of comparable importance, the hour of the combined peak may not be entirely obvious, and the calculation may have to be repeated several times. In most buildings, peak cooling loads occur in the afternoon or early evening. Figures 6.1.15 to 6.1.18 give an indication when the components of the cooling load are likely to reach their peak.

The steps of the calculation are summarized in the worksheet of Figure 6.1.14. We now proceed to discuss these steps, illustrating them by filling out the worksheet for a zone of an office building. The procedure has to be carried out for each zone of the building.

For *walls* and *roofs*, the conductive cooling load at time t is calculated by inserting the appropriate CLTD into Equation 6.1.38. We have plotted CLTD versus time for three roof types in Figure 6.1.15. The heavier the construction, the smaller the amplitude and the later the peak. Figure 6.1.16 shows analogous results for sunlit walls having the four cardinal orientations.

* The tables of CLTD and CLF values are too voluminous to include in this book. They are included in the "HCB Software" available from Kreider & Associates (jfk@well.com) in electronic form or from ASHRAE (1989a) in tabular form.

Job ID	Date		Initials	
Site	Latitude		Longitude	
Design conditions	Indoor temp.	Rel. humid.	Outdoor temp.	Rel. humid.
Room	Identification		Dimensions	

Latent loads					Instantaneous
	$\dot{V}$	W_o	W_i	$\Delta W = W_o - W_i$	$\dot{Q}_{lat} = p \times h_{fg} \times \dot{V} \times \Delta W$
Air exchange					
	N = number			$\dot{Q}_{lat/unit}$	$\dot{Q}_{lat} = N \times \dot{Q}_{lat/unit}$
Appliances					
People					
TOTAL LATENT					

Sensible loads					hour t			hour t		
Component and orientation	**Construction type**		U	A	$CLTD_t$			$\dot{Q}_t = U \times A \times CLTD_t$		
Walls										
Roof										
Glazing conduction										
Glazing solar		A	SC	$SHGF_{max}$	CLF_t			$\dot{Q}_t = A \times SC \times SHGF_{max} \times CLF_t$		
Air exchange		V	$\dot{V}$	T_i	T_o			$\dot{Q} = p \times c_p \times \dot{V} \times (T_o - T_i)$ (instantaneous)		
Internal partitions			U	A	ΔT across partition			$\dot{Q} = U \times A \times \Delta T$ (instantaneous)		
Ceiling										
Floor										
Sides										
Ducts										
Internal gains		number	gain /unit	$\dot{Q}$	CLF_t			$\dot{Q}_t = \dot{Q} \times CLF_t$		
Appliances										
Fans										
Lights										
Motors										
People										
TOTAL SENSIBLE										

FIGURE 6.1.14 Worksheet for CLTD/CLF method for a specific zone. At sea level $\rho c_p = 1.08$ Btu/(h · °F)]/(ft³/min) [1.2 (W/K)/(L/s)] and $\rho h_{fg} = 4840$ (Btu/h)/(ft³/min) [3010 W/(L/s)].

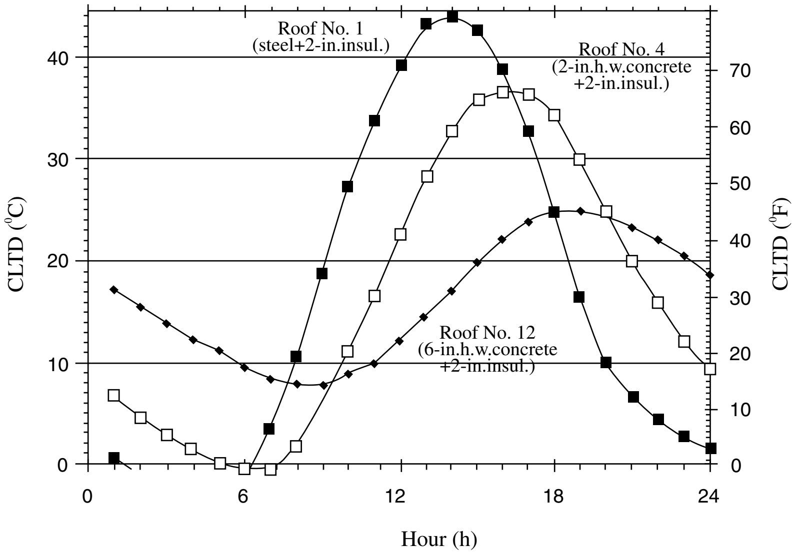


FIGURE 6.1.15 CLTDs for three roof types.

For these CLTDs, the following conditions have been assumed:

- High absorptivity for solar radiation ("dark").
- Solar radiation for 40°N on July 21.
- T_i = 25.5°C (78°F).
- T_o has a mean of $T_{o,av} = (T_{o,max} + T_{o,min})/2$ = 29.4°C (85.0°F) and a daily range = $T_{o,max} - T_{o,min}$ = 11.7°C (21.0°F), with $T_{o,max}$ = 35.0°C (95.0°F) being the design temperature.
- Outdoor convective heat transfer coefficient ho = 17 W/(m² · K) [3.0 Btu/(h · ft² · °F)].
- Indoor convective heat transfer coefficient hi = 8.3 W/(m² · K) [1.46 Btu/(h · ft² · °F)].
- No forced ventilation or air ducts in the ceiling space.

When conditions are different, one should correct the CLTDs according to the formula

$$\text{CLTD}_{\text{cor}} = (\text{CLTD} + \text{LM})K + (25.5°\text{C} - T_i) + (T_{o,av} - 29.4°\text{C}) \qquad (6.1.40\text{SI})$$

$$\text{CLTD}_{\text{cor}} = (\text{CLTD} + \text{LM})K + (78°\text{C} - T_i) + (T_{o,av} - 85°\text{C}) \qquad (6.1.40\text{US})$$

where LM = correction factor for latitude and month
K = color adjustment factor
T_i, $T_{o,av}$ = actual values for application

And $T_{o,av}$ is obtained by subtracting 0.50 × daily range from $T_{o,max}$, the design temperature of the site. The color correction K is 1.0 for dark and 0.5 for light surfaces; values less than 1.0 should be used only when one is confident that the surface will permanently maintain low absorptivity.

How about other construction types? Two factors are affected: the U value and the CLTD. One should always use the correct U value for the actual construction in Equation 6.1.38. As for the CLTD, one should select the construction type that is closest in terms of mass and heat capacity.

For *windows*, one treats conductive and solar heat gains separately, according to the decomposition:

Heat gain through glass = conduction due to $T_i - T_o$

+ heat gain due to solar radiation transmitted through or absorbed by glass (6.1.41)

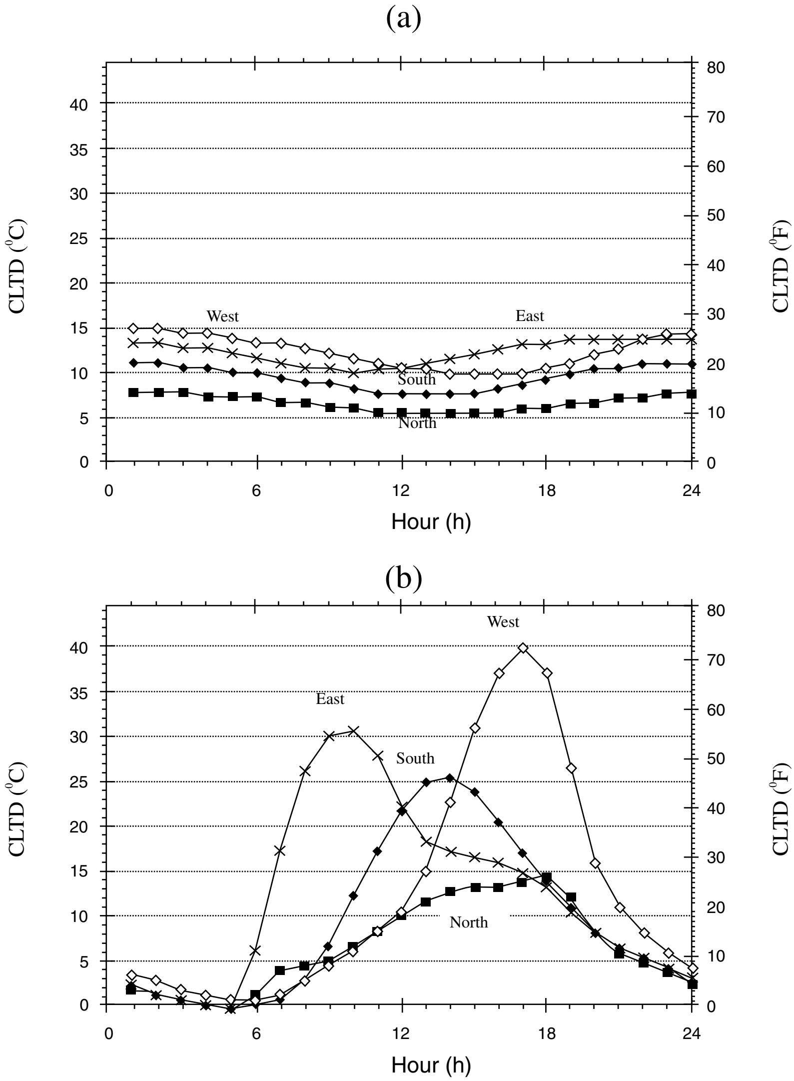


FIGURE 6.1.16 CLTDs for sunlit walls. Four orientations are shown for two construction types: (a) Group A walls [heavy, for example, 8-in (200 mm) concrete with insulation]; (b) Group G walls (light, for example, frame or curtain wall).

The conductive part is calculated as in Equation 6.1.38:

$$\dot{Q}_{c,cond,glaz,t} = UA \cdot CLTD_{glaz,t} \tag{6.1.42}$$

Solar gains through windows are treated by means of the solar heat gain factor SHGF. It is defined as the instantaneous heat gain [Btu/(h · ft^2)(W/m^2)] due to solar radiation through reference glazing. There are two components in this solar gain: the radiation absorbed in the glass and the radiation transmitted through the glass. The latter is assumed to be totally absorbed in the interior of the building, a reasonable assumption in view of the cavity effect. The radiation absorbed in the glass raises its temperature, thereby changing the conductive heat flow. The SHGF combines this latter contribution with the radiation transmitted to the interior. For glazing types other than the reference glazing, one multiplies the SHGF by the shading coefficient SC.

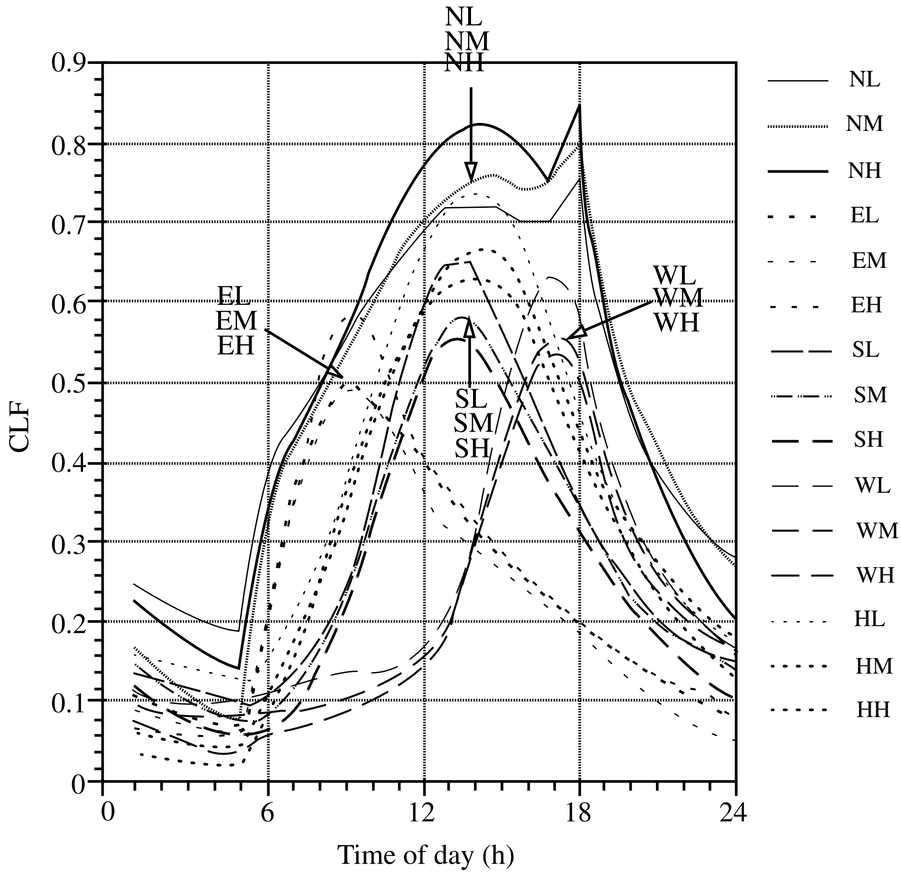


FIGURE 6.1.17 Cooling load factors for glass without interior shading for 5 orientations (E = east, S = south, W = west, N = north, H = horizontal) and 3 construction types (L = light, M = medium, H = heavy).

To calculate the contribution to the cooling load, the daily maximum of the solar heat gain is multiplied by the cooling load factor. Thus the actual cooling load at time t due to solar radiation is given by the formula

$$\dot{Q}_{c,sol,t} = A \cdot SC \cdot SHGF_{max} \cdot CLF_t \qquad (6.1.43)$$

where A = area, ft^2 (m^2)
SC = shading coefficient
$SHGF_{max}$ = maximum solar heat gain factor, Btu/(h · ft^2) (W/m^2)
CLF_t = cooling load factor for time t

SHGFmax is the value of SHGF at the hour when the radiation attains its maximum for a particular month, orientation, and latitude. The CLF takes into account the variation of the solar radiation during the day, as well as the dynamics of its absorption in the mass of the building and the gradual release of this heat. A separate set of CLFs is available (ASHRAE, 1989a) for each orientation and for each of three construction types, characterized in terms of the mass of building material per floor area: light = 30 lb/ft^2 (146 kg/m^2), medium = 70 lb/ft^2 (341 kg/m^2), and heavy = 130 lb/ft^2 (635 kg/m^2). Each set comprises all hours from 1 to 24. A subset is plotted in Figure 6.1.17.

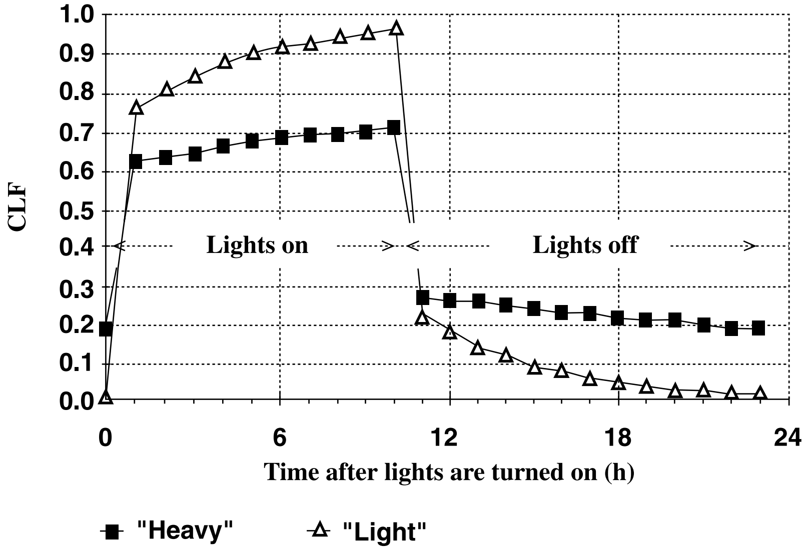


FIGURE 6.1.18 Cooling load factors for lights that are on 10 h/day, for two extreme construction types: light and heavy (a coefficient and b classification, as per Table 6.1.14A, are 0.45 D for heavy and 0.75 A for light).

In analogous fashion, CLFs have been computed for heat gains from *internal heat sources*. There are different factors for each of the three major categories:

Occupants

$$\dot{Q}_{occ,t} = \dot{Q}_{occ}\mathrm{CLF}_{\mathrm{occ,t}} \tag{6.1.44}$$

Lights

$$\dot{Q}_{lit,t} = \dot{Q}_{lit}\mathrm{CLF}_{\mathrm{lit,t}} \tag{6.1.45}$$

Equipment such as appliances

$$\dot{Q}_{app,t} = \dot{Q}_{app}\mathrm{CLF}_{\mathrm{app,t}} \tag{6.1.46}$$

In these equations, the $\dot{Q}$ Btu/h (W) on the right side is the rate of heat production, assumed constant for a certain number of hours and zero the rest of the time. The $\dot{Q}_t$ on the left side is the resulting cooling load at hour t, for t from 1 to 24. For each load profile there is a different set of CLFs.

Figure 6.1.18 plots a set of CLFs for lights. The lights are on for 10 h/day, and the time axis shows the number of hours after the lights have been turned on. Two construction types are shown, representing the highest and the lowest thermal inertia in the tables. Once again, the CLF curves show how the actual loads are attenuated and delayed by the thermal inertia.

Equations 6.1.38 to 6.1.46, together with the corresponding tables, as summarized in Figure 6.1.13, are what is known as the *ASHRAE CLTD/CLF method for cooling load calculations*. Note the assumptions that have been made:

- *The indoor temperature T_i is assumed to be constant*
- *Periodic conditions*, corresponding to a series of identical design days

Such limitations are the price of simplicity. If one wants to analyze features like variable occupancy (weekday or weekend) or thermostat setup, one must resort to a dynamic analysis.

Since thermostat setup and reduced weekend heat gains are frequently encountered in commercial buildings, one may wonder about the applicability of the CLF-CLTD method for such cases. If the building is kept at constant T_i, the method can indeed be used (for identical weather there is a relatively small increase in cooling load from Monday to Friday, and, since it is preceded by four days with identical conditions, the prediction of the peak is reliable). Thermostat setup, on the other hand, necessitates a dynamic analysis, as presented in the next section.

This traditional CLTD/CLF method has been changed by ASHRAE researchers recently to include a larger selection of wall types and other features. This new method is described in Section 6.1.8 along with tables of values needed for its use. We have not included tables for the traditional CLTD/CLF method in this handbook in the interest of space. The coefficients are available for this original method as indicated in an earlier footnote.

6.1.7 Transfer Functions for Dynamic Load Calculations

Basis of the Method

The instantaneous load $\dot{Q}$ can be considered the response of the building or room to the driving terms {T_i, T_o, $\dot{Q}_{sol}$, etc.) that act on it. The transfer function method calculates the response of a system by making the following basic assumptions:

- Discrete time steps (all functions of time are represented as series of values at regular time steps, hourly in the present case)
- Linearity (the response of a system is a linear function of the driving terms and of the state of the system)
- Causality (the response at time t can depend only on the past, not on the future)

As an example, suppose there is a single driving term $u(t)$ and the response is $y(t)$. To make the expressions more readable, let us indicate the time dependence as a subscript, in the form $y(t) = y_t$, $u(t) = u_t$, and so on. Then according to the transfer function model, the relation between the response and the driving term is of the form

$$y_t = -(a_1 y_{t-1\Delta t} + a_2 y_{t-2\Delta t} + \cdots + a_{\mathrm{n}} y_{t-\mathrm{n}\Delta t}) + (b_0 u_t + b_1 u_{t-1\Delta t} + b_2 u_{t-2\Delta t} + \cdots + b_{\mathrm{m}} u_{t-\mathrm{m}\Delta t}) \quad (6.1.47)$$

with time step

$$\Delta t = 1\mathrm{h} \quad (6.1.48)$$

where a_1 to a_{n} and b_0 to b_{m} are coefficients that characterize the system; they are independent of the driving term or response. Equation 6.1.47 is obviously linear. It satisfies causality because y_t depends only on the past values of the response ($y_{t-1\Delta t}$ to $y_{t-\mathrm{n}\Delta t}$) and on present and past values of the driving terms* (u_t to $u_{t-m\Delta t}$).

The past state of the system enters because of the coefficients a_1 to a_n and b_1 to b_m; this is how thermal inertia is taken into account. The response is instantaneous only if these coefficients are zero. The greater their number and magnitude, the greater the weight of the past.

The accuracy of the model increases as the number of coefficients is enlarged and as the time step is reduced. For load calculations, hourly time resolution and a handful of coefficients per driving term will suffice. The coefficients are called *transfer function coefficients*.

Incidentally, the relation between u and y could be written in symmetric form

$$a_0 y_t + a_1 y_{t-1\Delta t} + a_2 y_{t-2\Delta t} + \cdots + a_{\mathrm{n}} y_{t-\mathrm{n}\Delta t} = b_0 u_t + b_1 u_{t-1\Delta t} + b_2 u_{t-2\Delta t} + \cdots + b_{\mathrm{m}} u_{t-\mathrm{m}\Delta t} \quad (6.1.49)$$

* A series such as Equation 6.1.47 is also known as a time series.

which is equivalent because one can divide both sides of the equation by a_0. Since the roles of u and y are symmetric, one can use the same model to find, e.g., the load (i.e., the heat $\dot{Q}$ to be supplied or removed) as a function of T_i, or T_i as a function of $\dot{Q}$.

Equation 6.1.49 can be readily generalized to the case where there are several driving terms. For instance, if the response T_i is determined by two driving terms, heat input $\dot{Q}$ and outdoor temperature T_o, then one can write the transfer function model in the form

$$a_{i,0}T_{i,t} + a_{i,1}T_{i,t-1\Delta t} + \ldots + a_{i,\mathrm{n}}T_{i,t-\mathrm{n}\Delta t} = a_{o,0}T_{o,t} + a_{o,1}T_{o,t-1\Delta t} + \ldots + a_{o,m}T_{o,t-\mathrm{m}\Delta t}$$

$$+ a_{Q,0}\dot{Q}_t + a_{Q,1}\dot{Q}_{t-1\Delta t} + a_{Q,2}\dot{Q}_{t-2\Delta t} + \ldots + a_{Q,r}\dot{Q}_{t-\mathrm{r}\Delta t} \tag{6.1.50}$$

with three sets of transfer function coefficients: $a_{i,0}$ to $a_{i,n}$, $a_{o,0}$ to $a_{o,m}$, and $a_{Q,0}$ to $a_{Q,r}$. This equation can be considered an algorithm for calculating $T_{i,t}$, hour by hour, given the previous values of T_i and the driving terms T_o and $\dot{Q}$. Likewise, if T_i and T_o were given as driving terms, one could calculate $\dot{Q}$ as response.

Any set of response and driving terms can be handled in this manner. Thus loads can be calculated hour by hour, for any driving terms (meteorological data, building occupancy, heat gain schedules, etc.), and it is, in fact, the method used by the computer simulation program DOE2.1 (Birdsall et al., 1990; see also Chapter 6.2 of this handbook).

Once the necessary numerical values of the transfer function coefficients have been obtained, the calculation of peak loads is simple enough for a spreadsheet. One specifies the driving terms for the peak day and iterates an equation like Equation 6.1.50 until the result converges to a steady daily pattern. Transfer function coefficients have been calculated and listed for a wide variety of standard construction types (ASHRAE, 1989a), and some excerpts will be presented here. PREP (1990) can be used to calculate transfer function coefficients for walls and roofs not in the standard ASHRAE database.

The remainder of this section discusses the transfer function method in detail; it is also included in the software. The method involves three steps:

1. Calculation of the conductive heat gain (or loss) for each distinct component of the envelope, by Equation 6.1.51.
2. Calculation of the load of the room at constant temperature, based on this conductive heat gain (or loss) as well as any other heat source in the room, by Equation 6.1.56.
3. Calculation of the heat extraction (or addition) rate for the cooling (or heating) device and thermostat setpoints of the room, by Equation 6.1.61.

Conductive Heat Gain

The conductive heat gain (or loss) $\dot{Q}_{\mathrm{cond},t}$ at time t through the roof and walls is calculated according to the formula

$$\dot{Q}_{cond,t} = -\sum_{n\geq t} d_n \dot{Q}_{cond,t-n\Delta t} + A\left(\sum_{n\geq 0} b_n T_{os,t-n\Delta t} - T_i \sum_{n\geq 0} c_n\right) \tag{6.1.51}$$

where A = area of roof or wall, m² (ft²)
Δt = time step = 1 h
$T_{o,st}$ = sol-air temperature of outside surface at time $_t$
b_n, c_n, d_n = coefficients of conduction transfer function

The indoor temperature T_i is multiplied by the sum of the c_n values, so the individual c_n coefficients are not needed (this is because T_i is assumed constant at this point; the extension to arbitrary T_i comes shortly). In general, the initial value $\dot{Q}_{\mathrm{cond},t} = \mathrm{O}$ is not known; its value does not matter if the calculation is repeated over a sufficient number of time steps until the resulting pattern becomes periodic within the desired accuracy. Usually 4–7 days' worth will be sufficient.

Numerical values of the coefficients of the conduction transfer function are listed in Table 6.1.6: roofs in Table 6.1.6a and walls in Table 6.1.6b. If the room in question is adjacent to rooms at a different temperature, the heat gain across the partitions is also calculated according to Equation 6.1.51.

It is instructive to establish the connection of the transfer function coefficients with the U value. In the steady-state limit, i.e., when $\dot{Q}_{cond}$, T_{os}, and T_i are all constant, Equation 6.1.51 becomes

$$\dot{Q}_{cond} \sum_{n \geq 1} d_n = A\left(T_{os} \sum_{n \geq 0} b_n - T_i \sum_{n \geq 0} c_n\right) \qquad \text{where } d_0 = 1 \tag{6.1.52}$$

Since in that limit we also have

$$\dot{Q}_{cond} = AU(T_{os} - T_i) \tag{6.1.53}$$

the coefficients of T_{os} and T_i must be equal,

$$\sum_{n \geq 0} b_n = \sum_{n \geq 0} c_n \tag{6.1.54}$$

and the U value is given by

$$U = \frac{\sum_{n \geq 0} c_n}{\sum_{n \geq 0} d_n} \tag{6.1.55}$$

The Load at Constant Temperature

The above calculation of the conductive heat gain (or loss) is to be repeated for each portion of the room envelope that has a distinct composition. The relation between these conductive gains and the total load depends on the construction of the entire room. For example, a concrete floor can store a significant fraction of the heat radiated by lights or by a warm ceiling, thus postponing its contribution to the cooling load of the room.

For each heat gain component $\dot{Q}_{gain}$, the corresponding cooling load $\dot{Q}_c$ (or reduction of the heating load) at constant T_i is calculated by using another set of coefficients, the coefficients v_n and w_n, of the *room transfer function*,

$$\dot{Q}_{c,t} = v_0 \dot{Q}_{gain,t} + v_1 \dot{Q}_{gain,t-1\Delta t} + v_2 \dot{Q}_{gain,t-2\Delta t} + \ldots$$

$$- w_1 \dot{Q}_{c,t-1\Delta t} - w_2 \dot{Q}_{c,t-2\Delta t} - \ldots \tag{6.1.56}$$

with the subscript t indicating time, as before. The coefficient w_0 of $\dot{Q}_{c,t}$ is not shown because it is set equal to unity. The coefficients for a variety of room construction types are listed in Tables 6.1.7 and 6.1.8. In these tables, all coefficients with index 2 or higher are zero. Since w_0 is unity, Table 6.1.7 shows only a single coefficient w_1. Again, it is instructive to take the steady-state limit and check the consistency with the first law of thermodynamics. It requires that the sum of the v_n values equal the sum of the w_n values:

$$\sum_{n \geq 0} v_n = \sum_{n \geq 0} w_n \tag{6.1.57}$$

The entries of Tables 6.1.7 and 6.1.8 do indeed satisfy this condition.

TABLE 6.1.6 Coefficients of Conduction Transfer Function[a]

(a) Roofs												
(Layer sequence left to right = inside to outside)		n = 0	n = 1	n = 2	n = 3	n = 4	n = 5	n = 6	Σc_n	U	δ	λ
Layers E0 A3 B25 E3 E2 A0	b_n	0.00487	0.03474	0.01365	0.00036	0.00000	0.00000	0.00000	0.05362	0.080	1.63	0.97
Steel deck with 3.33-in insulation	d_n	1.00000	–0.35451	0.02267	–0.00005	0.00000	0.00000	0.00000				
Layers E0 A3 B14 E3 E2 A0	b_n	0.00056	0.01202	0.01282	0.00143	0.00001	0.00000	0.00000	0.02684	0.055	2.43	0.94
Steel deck with 5-in insulation	d_n	1.00000	–0.60064	0.08602	–0.00135	0.00000	0.00000	0.00000				
Layers E0 E1 B15 E4 B7 A0	b_n	0.00000	0.00065	0.00339	0.00240	0.00029	0.00000	0.00000	0.00673	0.043	4.85	0.82
Attic roof with 6-in insulation	d_n	1.00000	–1.34658	0.59384	–0.09295	0.00296	–0.00001	0.00000				
Layers E0 B22 C12 E3 E2 C12 A0	b_n	0.00059	0.00867	0.00688	0.00037	0.00000	0.00000	0.00000	0.01652	0.138	5.00	0.56
1.67-in insulation with 2-in h.w. concrete RTS	d_n	1.00000	–1.11766	0.23731	–0.00008	0.00000	0.00000	0.00000				
Layers E0 E5 E4 B12 C14 E3 E2 A0	b_n	0.00000	0.00024	0.00217	0.00251	0.00055	0.00002	0.00000	0.00550	0.057	6.32	0.60
3-in insulation w/4-in I.w. conc. deck and susp. clg.	d_n	1.00000	–1.40605	0.58814	–0.09034	0.00444	–0.00006	0.00000				
Layers E0 E5 E4 C5 B6 E3 E2 A0	b_n	0.00001	0.00066	0.00163	0.00049	0.00002	0.00000	0.00000	0.01477	0.090	7.16	0.16
1-in insul. w/4-in h.w. conc. deck and susp. clg.	d_n	1.00000	–1.24348	0.28742	–0.01274	0.00009	0.00000	0.00000				
Layers E0 E5 E4 C13 B20 E3 E2 A0	b_n	0.00001	0.00060	0.00197	0.00086	0.00005	0.00000	0.00000	0.00349	0.140	7.54	0.15
6-in h.w. deck w/0.76-in insul. and susp. clg.	d_n	1.00000	–1.39181	0.46337	–0.04714	0.00058	0.00000	0.00000				
Layers E0 E5 E4 B15 C15 E3 E2 A0	b_n	0.00000	0.00000	0.00002	0.00014	0.00024	0.00011	0.00002	0.00053	0.034	10.44	0.30
6-in insul. w/6-in I.w. conc. deck and susp. clg.	d_n	1.00000	–2.29459	1.93694	–0.75741	0.14252	–0.01251	0.00046				
Layers E0 C13 B15 E3 E2 C12 A0	b_n	0.00000	0.00000	0.00007	0.00024	0.00016	0.00003	0.00000	0.00050	0.045	10.48	0.24
6-in h.w. deck w/6-in ins. and 2-in h.w. RTS	d_n	1.00000	–2.27813	1.82162	–0.60696	0.07696	–0.00246	0.00001				

TABLE 6.1.6 (continued) Coefficients of Conduction Transfer Function[a]

(b) Walls

(Layer sequence left to right = inside to outside)		n = 0	n = 1	n = 2	n = 3	n = 4	n = 5	n = 6	Σc_n	U	δ	λ
Layers E0 A3 B1 B13 A3 A0	b_n	0.00768	0.03498	0.00719	0.00006	0.00000	0.00000	0.00000	0.04990	0.066	1.30	0.98
Steel siding with 4-in insulation	d_n	1.00000	–0.24072	0.00168	0.00000	0.00000	0.00000	0.00000				
Layers E0 E1 B14 A1 A0 A0	b_n	0.00016	0.00545	0.00961	0.00215	0.00005	0.00000	0.00000	0.01743	0.055	3.21	0.91
Frame wall with 5-in insulation	d_n	1.00000	–0.93389	0.27396	–0.02561	0.00014	0.00000	0.00000				
Layers E0 C3 B5 A6 A0 A0	b_n	0.00411	0.03230	0.01474	0.00047	0.00000	0.00000	0.00000	0.05162	0.191	3.33	0.78
4-in h.w. concrete block with 1-in insulation	d_n	1.00000	–0.76963	0.04014	–0.00042	0.00000	0.00000	0.00000				
Layers E0 A6 C5 B3 A3 A0	b_n	0.00099	0.00836	0.00361	0.00007	0.00000	0.00000	0.00000	0.01303	0.122	5.14	0.41
4-in h.w. concrete with 2-in insulation	d_n	1.00000	–0.93970	0.04664	0.00000	0.00000	0.00000	0.00000				
Layers E0 E1 C8 B6 A1 A0	b_n	0.00000	0.00061	0.00289	0.00183	0.00018	0.00000	0.00000	0.00552	0.109	7.11	0.37
8-in h.w. concrete block with 2-in insulation	d_n	1.00000	–1.52480	0.67146	–0.09844	0.00239	0.00000	0.00000				
Layers E0 A2 C2 B15 A0 A0	b_n	0.00000	0.00000	0.00013	0.00044	0.00030	0.00005	0.00000	0.00093	0.043	9.36	0.30
Face brick and 4-in I.w. conc. block with 6-in insulation	d_n	1.00000	–2.00875	1.37120	–0.37897	0.03962	–0.00165	0.00002				
Layers E0 C9 B6 A6 A0 A0	b_n	0.00000	0.00005	0.00064	0.00099	0.00030	0.00002	0.00000	0.00200	0.106	8.97	0.20
8-in common brick with 2-in insulation	d_n	1.00000	–1.78165	0.96017	–0.16904	0.00958	–0.00016	0.00000				
Layers E0 C11 B6 A1 A0 A0	b_n	0.00000	0.00001	0.00019	0.00045	0.00022	0.00002	0.00000	0.00089	0.112	10.20	0.13
12-in h.w. concrete with 2-in insulation	d_n	1.00000	–2.12812	1.53974	–0.45512	0.05298	–0.00158	0.00002				

[a] U, b_n, and, c_n are in Btu/(h · ft² · °F); d_n and A are dimensionless; and δ is in hours [1 Btu/(h · ft² · °F) = 5.678 W/(m² · K)]. For definition of layer codes and thermal properties, see Table 6.1.1A.

Source: From ASHRAE, 1989a, with permission.

TABLE 6.1.7 The w_1 Coefficient of the Room Transfer Function (w_0 = 1.0 and higher terms are zero)

	Room Envelope Construction[b]				
	2-in (51-mm) Wood floor	3-in (76-mn) Concrete floor	6-in (152-mm) Concrete floor	8-in (203-mm) Concrete floor	12-in (305-mm) Concrete floor
Room air[a] circulation and S/R type	Specific mass per unit floor area, lb/ft^2				
	10	40	75	120	160
Low	–0.88	–0.92	–0.95	–0.97	–0.98
Medium	–0.84	–0.90	–0.94	–0.96	–0.97
High	–0.81	–0.88	–0.93	–0.95	–0.97
Very high	–0.77	–0.85	–0.92	–0.95	–0.97
	–0.73	–0.83	–0.91	–0.94	–0.96

[a] Circulation rate:

Low: Minimum required to cope with cooling load from lights and occupants in interior zone. Supply through floor, wall, or ceiling diffuser. Ceiling space not used for return air, and h = 0.4 Btu/(h · ft^2 · °F) [2.27 W/(m^2 · K)], where h = inside surface convection coefficient used in calculation of w_1 value.

Medium: Supplied through floor, wall, or ceiling diffuser. Ceiling space not used for return air, and h = 0.6 Btu/(h · ft^2 · °F) [3.41 W/(m^2 · K)].

High: Room air circulation induced by primary air of induction unit, or by room fan and coil unit. Ceiling space used for return air, and h = 0.8 Btu/(h · ft^2 · °F) [4.54 W/(m^2 · K)].

Very high: Used to minimize temperature gradients in a room. Ceiling space used for return air, and h = 1.2 Btu/(h · ft^2 · °F) [6.81 W/(m^2 · K)].

[b] Floor covered with carpet and rubber pad; for a bare floor or if covered with floor tile, take next w_1 value down the column.

Source: From ASHRAE, 1989a, with permission.

Therefore, Equation 6.1.56 has to be applied separately to each of the heat gain types in Table 6.1.8, and the resulting cooling load components $\dot{Q}_{c,t}$ are added to obtain the total cooling load of the room at time t. The heat gain types are as follows:

- Solar gain (through glass without interior shade) and the radiative component of heat from occupants and equipment
- Conduction through envelope and solar radiation absorbed by interior shade
- Lights
- Convective gains (from air exchange, occupants, equipment)

For lights, the coefficients depend on the arrangement of the lighting fixture and the ventilation system.

While specific numbers vary a great deal with the circumstances, the general pattern is common to all peak cooling loads: *thermal inertia attenuates and delays the peak contributions of individual load components*. The total peak is usually less than the result of a steady state calculation, although it could be more if the time delays act in the sense of making the loads coincide. Daily average loads, in contrast to peak loads, can be determined by a static calculation, if the average indoor temperature is known; that follows from the first law of thermodynamics. But if the thermostat allows floating temperatures, the indoor temperature is, in general, not known without a dynamic analysis. With the transfer functions described so far, one can calculate peak loads when the indoor temperature T_i is constant. That is how the CLFs and CLTDs of Section 6.1.6 were determined. We now address the generalization to variable T_i.

Variable Indoor Temperature and Heat Extraction Rate

The indoor temperature T_i may vary, not only because of variable thermostat setpoints but also because of limitations of the HVAC equipment (capacity, throttling range, imperfect control). The extension to variable T_i requires one additional transfer function. Recall that the behavior of a room can be described

TABLE 6.1.8 The v Coefficients of the Room Transfer Function[a] (Only v_0 and v_1 Are Nonzero)

Heat Gain Component	Room Envelope Construction[b]	v_0 (Dimensionless)	v_1 (Dimensionless)
Solar heat gain through glass[c] with no interior shade; radiant heat from equipment and people	Light	0.224	$1 + w_1 - v_0$
	Medium	0.197	$1 + w_1 - v_0$
	Heavy	0.187	$1 + w_1 - v_0$
Conduction heat gain through exterior walls, roofs, partitions, doors, windows with blinds, or drapes	Light	0.703	$1 + w_1 - v_0$
	Medium	0.681	$1 + w_1 - v_0$
	Heavy	0.676	$1 + w_1 - v_0$
Convective heat generated by equipment and people, and from ventilation and infiltration air	Light	1.000	0.0
	Medium	1.000	0.0
	Heavy	1.000	0.0

Heat Gain from Lights[d]

Furnishings	Air Supply and Return	Type of Light Fixture	v_0	v_1
Heavyweight simple furnishings, no carpet	Low rate; supply and return below ceiling ($V \leq 0.5$)[e]	Recessed, not vented	0.450	$1 + w_1 - v_0$
Ordinary furnishings, no carpet	Medium to high rate, supply and return below or ceiling ($V \geq 0.5$)	Recessed, not vented	0.550	$1 + w_1 - v_0$
Ordinary furnishings, with or without carpet on floor	Medium to high rate, or induction unit or fan and coil, supply and return below, or through ceiling, return air plenum ($V \geq 0.5$)	Vented	0.650	$1 + w_1 - v_0$
Any type furniture, with or without carpet	Ducted returns through light fixtures	Vented or freehanging in air stream with ducted returns	0.750	$1 + w_1 - v_0$

[a] The transfer functions in this table were calculated by procedures outlined in Mitalas and Stephenson (1967) and are acceptable for cases where all heat gain energy eventually appears as cooling load. The computer program used was developed at the National Research Council of Canada, Division of Building Research.

[b] The construction designations denote the following:

Light construction: such as frame exterior wall, 2-in (51-mm) concrete floor slab, approximately 30 lb of material/ft^2 (146 kg/m^2) of floor area.

Medium construction: such as 4-in (102-mm) concrete exterior wall, 4-in (102-mm) concrete floor slab, approximately 70 lb building material/ft^2 (341 kg/m^2) of floor area.

Heavy construction: such as 6-in (152-mm) concrete exterior wall, 6-in (152-mm) concrete floor slab, approximately 130 1b of building material/ft^2 (635 kg/m^2) of floor area.

[c] The coefficients of the transfer function that relate room cooling load to solar heat gain through glass depend on where the solar energy is absorbed. If the window is shaded by an inside blind or curtain, most of the solar energy is absorbed by the shade and is transferred to the room by convection and long-wave radiation in about the same proportion as the heat gain through walls and roofs; thus the same transfer coefficients apply.

[d] If room supply air is exhausted through the space above the ceiling, and lights are recessed, such air removes some heat from the lights that would otherwise have entered the room. This removed light heat is still a load on the cooling plant if the air is recirculated, even though it is not a part of the room heat gain as such. The percent of heat gain appearing in the room depends on the type of lighting fixture, its mounting, and the exhaust airflow.

[e] V is room air supply rate in (ft^3/min)/ft^2 of floor area.

Source: From ASHRAE, 1989a, with permission.

by a relation like Equation 6.1.50 which links the output (room temperature T_i) to all the relevant input variables (outdoor temperature T_o, heat input or extraction by the HVAC system $\dot{Q}$, solar heat gains, etc.)

$$a_{i,0}T_{i,k} + a_{i,1}T_{i,k-1} + \ldots + a_{i,l}T_{i,k-l} = a_{o,0}T_{o,k} + a_{o,1}T_{o,k-1} + \ldots + a_{o,m}T_{o,k-m}$$

$$+ a_{Q,0}\dot{Q}_k + a_{Q,1}\dot{Q}_{k-1} + \ldots + a_{Q,n}\dot{Q}_{k-n} \tag{6.1.58}$$

TABLE 6.1.9 Normalized Coefficients of Space Air Transfer Function

Room envelope construction	p_0	p_1	g_0^*	g_1^*	g_2^*	g_0^*	g_1^*	g_2^*
	Dimensionless		Btu/(h · ft² · °F)			W/(m² · K)		
Light	1.00	–0.82	1.68	–1.73	0.05	9.54	–9.82	0.28
Medium	1.00	–0.87	1.81	–1.89	0.08	10.28	–10.73	0.45
Heavy	1.00	–0.93	1.85	–1.95	0.10	10.50	–11.07	0.57

Source: From ASHRAE, 1989a, with permission.

A separate set of transfer function coefficients is needed for each input variable with different time-delay characteristics; here we have indicated only T_o and $\dot{Q}$ explicitly. Now consider two different control modes, mode 1 with the constant value $T_{i,ref}$ assumed and mode 2 with arbitrary T_i, all input being the same except for $\dot{Q}$. Let

$$\delta T_i = T_{i,\text{ref}} - T_i \tag{6.1.59}$$

and

$$\delta\dot{Q} = \dot{Q}_{\text{ref}} - \dot{Q} \tag{6.1.60}$$

Designate the differences in T_i and $\dot{Q}$ between these two control modes. Taking the difference between Equation 6.1.50 for mode 1 and for mode 2, we see that all variables other than δT_i and $\delta\dot{Q}$ drop out. The transfer function between δT_i and $\delta\dot{Q}$ is called *space air transfer function*, and, following ASHRAE practice, its coefficients are designated by p_n $(= a_{Q,n})$ and g_n $(= a_{i,n})$

$$\sum_{n\geq 0} p_n \delta\dot{Q}_{t-n\Delta t} = \sum_{n\geq 0} g_{n,t}\delta T_{i,t-n\Delta t} \tag{6.1.61}$$

A subscript t has been added to g_n to allow the transfer function to vary with time if the air exchange rate varies. Numerical values can be obtained from Table 6.1.9. While p_n is listed directly, g_n is given in terms of g_n^* from which g_n is calculated according to

$$g_{0,t} = g_0^* A + P_0 K_{\text{tot},t}$$

$$g_{1,t} = g_1^* A + P_1 K_{\text{tot},t\text{-}\Delta t}$$

$$g_{2,t} = g_2^* A \tag{6.1.62}$$

where A = floor area and $K_{\text{tot},t}$ W/K [Btu/(h · °F)] is the total heat transmission coefficient of the room. The latter is the sum of conductive and air change terms according to Equation 6.1.24:

$$K_{\text{tot},t} = K_{cond} + \rho c_p \dot{V} \tag{6.1.24}$$

and a subscript t for time dependence has been added to allow for the possibility of variable air change. Of course, K_{cond} is the sum of the conductance-area products for the envelope of the room.

To verify the consistency of these coefficients with the first law of thermodynamics, let us take the steady state limit where $\delta\dot{Q}$, δT_i, and $K_{tot,t}$ are constant and can be pulled outside the sum. Replacing the g_n by Equation 6.1.62, we find

$$\delta\dot{Q}\,\Sigma p_n = \delta T_i\,[A\Sigma g_n^* + K_{\text{tot}}\,\Sigma p_n] = \text{steady state limit} \tag{6.1.63}$$

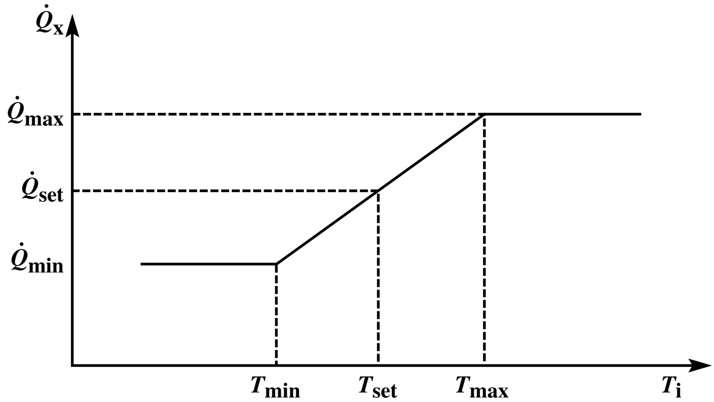


FIGURE 6.1.19 Control law of Equation 6.1.66 for heat extraction rate $\dot{Q}_x$ (solid line) as function of room temperature T_i.

A look at the numerical values of g_n^* in Table 6.1.9 shows that their sum vanishes. Thus the equation reduces to

$$\delta\dot{Q} = \delta T_i K_{tot} \tag{6.1.64}$$

as it should. Since K_{tot} is positive, $\delta\dot{Q}$ and δT_i have the same sign; this means that $\delta\dot{Q}$ is positive for positive heat input to the room. If we want to state cooling loads $\dot{Q}_c$ as positive quantities, we should therefore take $\dot{Q}_c = -\dot{Q}$ and $\delta\dot{Q}_c = -\delta\dot{Q}$. In particular, if we call the cooling load at temperature T_i the heat extraction rate $\dot{Q}_x$ (because that is the rate at which the HVAC equipment must extract heat to obtain the temperature T_i), we can write Equation 6.1.61 in the form

$$\sum_{n\geq 0} p_n\left(\dot{Q}_{x,t-n\Delta t} - \dot{Q}_{c,ref}\right) = \sum_{n\geq 0} g_{n,t}\left(T_{i,ref} - T_{i,t-n\Delta t}\right) \tag{6.1.65}$$

where $\dot{Q}_{c,ref}$ is the cooling load at the constant temperature $T_{i,ref}$.

Using Equation 6.1.61, one can calculate $\delta\dot{Q}$ for any δT_i, or δT_i for any $\delta\dot{Q}$. It can also be used for a mixed regime where δT_i is specified for certain hours and $\delta\dot{Q}$ for others. The calculation proceeds from one hour to the next, solving for δT_i or $\delta\dot{Q}$ as appropriate. The daily cycle is iterated until the result converges to a stable pattern.

Capacity limitations of the HVAC equipment can also be included. One checks, at each hour with thermostatic control, whether the actual load (at T_i = thermostat setpoint) exceeds the capacity. If it does, one solves for T_i instead, setting $\dot{Q}_x$ equal to the capacity for this hour.

Likewise, one can account for the throttling range of a control system which modulates the heat extraction rate according to the control law shown in Figure 6.1.19. Stated as an equation, this means that the heat extraction rate $\dot{Q}_x$ is determined by the room temperature T_i according to

$$\dot{Q}_{x,t} = \begin{cases} \dot{Q}_{max} & \text{for } T_{i,t} > T_{max} \\ \dot{Q}_{set} + \dot{Q}'\left(T_{i,t} - T_{set}\right) & \text{for } T_{min} < T_{i,t} < T_{max} \\ \dot{Q}_{min} & \text{for } T_{i,t} < T_{min} \end{cases} \tag{6.1.66}$$

where $\dot{Q}' = (\dot{Q}_{max} - \dot{Q}_{min})/(T_{max} - T_{min})$ and T_{set} is the thermostat setpoint; we have added the subscript t to indicate that this equation applies instantaneously at each hour t. At each new hour t, Equations 6.1.65 and 6.1.66 can be considered as a system of two equations for two unknowns: $\dot{Q}_{x,t}$ and $T_{i,t}$. After finding the solution, one repeats the process for the next hour.

TABLE 6.1.10 Summary of Load Calculations

Item	Method and Comments
Zones	Define zones Zone = part of building that can be assumed to have uniform loads. For each zone carry out the steps below
Design conditions	Determine appropriate values of temperatures (T_i and T_o) and humidities (W_i and W_o) for peak conditions at site in question
Conduction	$K_{cond} = \sum_k U_k A_k$
Air change	$\dot{V} \rho c_p$ For relatively simple buildings, use LBL model, Equation 6.1.12; otherwise use correlations
Heat gains	Solar, lights, equipment, occupants
Heating load, sensible	$\dot{Q}_{h,max} = K_{tot}(T_i - T_o) - \dot{Q}_{gain}$, with $K_{tot} = K_{cond} + \dot{V} \rho c_p$
Cooling load, "static," sensible	$\dot{Q}_{c,cond,t} = UA\ CLTD_t$ $\dot{Q}_{c,rad,t} = \dot{Q}_{max} CLF_t$
Cooling load, dynamic, sensible	Transfer function method Equations 6.1.51 to 6.1.66
Latent loads	Latent gain from air change $\dot{Q}_{air,lat} = \dot{V} h_{fg}(W_o - W_i)$, also latent gains from occupants and from equipment

A general load calculation procedure is summarized in Table 6.1.10 to summarize the chapter to this point.

6.1.8 New Methods for Load Calculations

In the ever-present quest for more accurate and versatile load prediction methods, new procedures are being developed all the time. In the past few years, two new calculation procedures have been developed that are relatively similar to the existing methods but implement enough differences to warrant mention. The CLTD/CLF method has been updated to include a new term, the solar cooling load (SCL), and is now termed the CLTD/SCL/CLF method. The radiant transfer series (RTS) method is a noniterative modification of the transfer function method. An overview of both of these new methods is presented in this section.

CLTD/SCL/CLF Method for Calculating Cooling Loads

The CLTD/CLF method presented in section 6.1.6 has been modified in a number of important ways. The selection of roof and wall CLTD values requires a number of look-up tables but allows the use of essentially any arbitrary wall construction. In addition, the solar heat gain factors have been replaced with a term called the solar cooling load. While the overall methodology of the CLTD/CLF method has been preserved, a full description of the necessary computations of the new method is presented here to avoid confusion with the original method in Section 6.1.6.

Roof CLTD Value Selection

The CLTD/SCL/CLF method uses 10 types of roofs. The roof types are numbered 1, 2, 3, 4, 5, 8, 9, 10, 13, and 14. The roof type chosen depends on the principal roof material, the location of the mass in the roof, the overall R-value of the roof, and whether or not there is a suspended ceiling. Table 6.1.11 below shows the cross reference chart used to select a roof type.

The tables of new roof CLTD values are calculated based on an indoor temperature of 78°F, maximum and mean outdoor temperatures of 95°F and 85°F, respectively, and a daily range of 21°F. Once the 24 CLTD values are selected, they are each adjusted by

$$Corrected\ CLTD = CLTD + (78 - T_i) + (T_{om} - 85) \qquad (6.1.67)$$

Where T_i is the actual inside design dry-bulb temperature and T_{om} is the mean outside design dry-bulb temperature,

TABLE 6.1.11 Cross Reference Table Used to Determine Roof Type

Mass Location	Principal Roof Material: Description	Principal Roof Material: ASHRAE code	Susp. Ceiling	R Value (ft²·h·°F/Btu): 0–5	5–10	10–15	15–20	20–25	25–30
Inside insulation	2 in HW Concrete	C12	No	2	2	4	4	5	—
			Yes	5	8	13	13	14	—
Evenly spaced	1 in Wood	B7	No	1	2	2	4	4	—
			Yes	—	4	5	9	10	10
	2 in HW Concrete	C12	No	2	—	—	—	—	—
			Yes	3	—	—	—	—	—
	Steel deck	A3	No	1	1	1	2	2	—
			Yes	1	1	2	2	4	—
	Attic-Ceiling comb.	n/a	No	1	2	2	2	4	—
Outside insulation	2 in HW Concrete	C12	No	2	3	4	5	5	—
			Yes	3	3	4	5	—	—

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

$$T_{om} = \text{Outside design dry-bulb temperature} - \frac{\text{Daily range}}{2} \qquad (6.1.68)$$

No adjustments to the CLTD are recommended for color or ventilation. The CLTD charts are usually published for several different latitudes; interpolation between the latitudes for an exact site is acceptable.

Wall CLTD Value Selection

The CLTD/SCL/CLF uses 15 wall types numbered sequentially 1 through 16 with no wall 8. The wall type is chosen based on the principal wall material, the secondary wall material, the location of the mass in the wall, and the overall wall R-value. Table 6.1.12 below shows an example cross-reference chart used to select a wall type. The tables of wall CLTD values are divided by latitude. The wall CLTDs were calculated using the same conditions as the roof CLTD values and may require adjustments based on the actual inside and ambient conditions. Interpolation between the tables may be necessary to obtain the correct values for a given site.

Once the roof and wall CLTD values have been selected and adjusted as necessary, the conductive heat flow through the roof and walls is calculated for each hour as in the original CLTD/CLF method,

$$q(hr) = U \cdot A \cdot CLTD(hr) \qquad (6.1.69)$$

where

U = overall heat transfer coefficient for the surface (Btu/hr·ft²·°F)
A = area of the surface, and
$CLTD$ = the cooling load temperature difference.

Glass CLTD Value Selection

The glass CLTD values remain the same as they were in the original method. As with the roof and wall CLTDs, the fenestration CLTD values may need to be corrected based on Equations 6.1.67 and 6.1.68. The conductive load calculation from the glass uses the same method as for the roof and walls. The CLTD values for the glass are given in Table 6.1.13.

Solar Cooling Load

The new method replaces the maximum solar heat gain factor with the solar cooling load (SCL). This new value is used to calculate the radiative (solar) heat gain through any glass surface in the building. The radiative solar gains are then given by

$$q(hr) = A \cdot SC \cdot SCL \qquad (6.1.70)$$

where A is the area of the glass surface, SC is the shading coefficient, and SCL is the solar cooling load factor. The shading coefficient is the ratio of the actual solar heat gain to that from the reference window used to calculate the SCL.

TABLE 6.1.12 Example Wall Type Selection Table. Values Are Shown for Mass Located Inside Insulation.

R Value ft2·h·°F/Btu	Principal Wall Material (ASHRAE Material Code)										
	A2	C1	C2	C3	C4	C5	C6	C7	C8	C17	C18
	Stucco and/or plaster										
2.0 to 2.5	5	—	—	—	—	5	—	—	—	—	—
2.5 to 3.0	5	3	—	2	5	6	—	—	5	—	—
3.0 to 3.5	5	4	2	2	5	6	—	—	6	—	—
3.5 to 4.0	5	4	2	3	6	6	10	4	6	—	5
4.0 to 4.75	6	5	2	4	6	6	11	5	10	—	10
4.75 to 5.5	6	5	2	4	6	6	11	5	10	—	10
5.5 to 6.5	6	5	2	5	10	7	12	5	11	—	10
6.5 to 7.75	6	5	4	5	11	7	16	10	11	—	11
7.75 to 9.0	6	5	4	5	11	7	—	10	11	—	11
9.0 to 10.75	6	5	4	5	11	7	—	10	11	4	11
10.75 to 12.75	6	5	4	5	11	11	—	10	11	4	11
12.75 to 15.0	10	10	4	5	11	11	—	10	11	9	12
15.0 to 17.5	10	10	5	5	11	11	—	11	12	10	16
17.5 to 20.0	11	10	5	9	11	11	—	15	16	10	16
20.0 to 23.0	11	10	9	9	16	11	—	15	16	10	16
23.0 to 27.0	—	—	—	—	—	—	—	16	—	15	—
	Steel or other light-weight siding										
2.0 to 2.5	3	—	—	2	3	5	—	—	—	—	—
2.5 to 3.0	5	2	—	2	5	3	—	—	5	—	—
3.0 to 3.5	5	3	1	2	5	5	—	—	5	—	—
3.5 to 4.0	5	3	2	2	5	5	6	3	5	—	5
4.0 to 4.75	6	4	2	2	5	5	10	4	6	—	5
4.75 to 5.5	6	5	2	2	6	6	11	5	6	—	6
5.5 to 6.5	6	5	2	3	6	6	11	5	6	—	6
6.5 to 7.75	6	5	2	3	6	6	11	5	6	—	10
7.75 to 9.0	6	5	2	3	6	6	12	5	6	—	11
9.0 to 10.75	6	5	2	3	6	6	12	5	6	4	11
10.75 to 12.75	6	5	2	3	6	7	12	6	11	4	11
12.75 to 15.0	6	5	2	4	6	7	12	10	11	5	11
15.0 to 17.5	10	6	4	4	10	7	—	10	11	9	11
17.5 to 20.0	10	10	4	4	10	11	—	10	11	10	11
20.0 to 23.0	11	10	4	5	11	11	—	10	11	10	16
23.0 to 27.0	—	—	—	—	—	—	—	10	—	11	16

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

TABLE 6.1.13 CLTD Values for Fenestration

Hour	CLTD	Hour	CLTD	Hour	CLTD	Hour	CLTD
1	1	7	–2	13	12	19	10
2	0	8	0	14	13	20	8
3	–1	9	2	15	14	21	6
4	–2	10	4	16	14	22	4
5	–2	11	7	17	13	23	3
6	–2	12	9	18	12	24	2

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

Using the SCL value tables requires that you know the number of walls, floor covering, inside shading, and a number of other variables for the zone. The tables are also broken down by building type, with different tables for zones in

- Single story buildings
- Top floor of multistory buildings
- Middle floors of multistory buildings
- First floor of multistory buildings

Table 6.1.14 gives the zone types for the SCL for the first story of multistory buildings. The zone type listed here is for the SCL *and is not necessarily the same zone type used for the CLF Tables*. Once the zone type has been determined, the SCL can be found from tables such as shown in Table 6.1.15.

Accounting for Adjacent Zones

The CLTD/SCL/CLF method treats the conductive heating load from any adjacent spaces through internal partitions, ceilings, and floors as a simple steady state energy flow

$$q(hr) = U \cdot A \cdot (T_a - T_r) \tag{6.1.71}$$

where T_a is the temperature in the adjacent space and T_r is the temperature of the room in question.

Occupant Loads

People within a space add both sensible and latent loads to the space. The heating load at any given hour due to the occupants is given as

$$q(hr) = N \cdot F_d \cdot [q_s \cdot CLF(hr) + q_l] \tag{6.1.72}$$

where N is the number of people in the space and F_d is the diversity factor. As implied by the preceding equation, the latent load is assumed to immediately translate into a cooling load on the system, while the sensible load is subject to some time delay as dictated by the mass of the room, i.e., its capability to absorb heat and release it at a later time. The diversity factor, F_d, takes into account the variability of the actual number of occupants in the space and has typical values as given in Table 6.1.16.

The CLF values are read from tables. To find the *CLF* it is first necessary to determine the zone type. This is done in a similar fashion as for the solar cooling loads. That is, the building type, room location, and floor coverings must be known before the zone type can be found. Table 6.1.17 gives the zone types for people, equipment, and lights for interior (nonperimeter) zones. Note that the zone type for occupants and equipment is not the same as for the lighting. The same holds true for the solar cooling load: the zone types for occupants is not the same as the zone type for the SCL.

Once the zone type has been determined, the occupant CLF is found from the lookup tables such as shown in Table 6.1.18. This table shows values for Type A zones only; the zones get progressively more massive for types B, C, and D. Figure 6.1.20 shows the cooling load factors for type A and D zones that are occupied for twelve hours.

Note that the occupant CLF will be 1.0 for all hours in building with high occupant density (greater than 1 person per 10 ft^2), such as auditoriums and theaters. The CLF will also be 1.0 in buildings where there is 24 hour per day occupancy.

Lighting Loads

At any given hour the load due to the lighting is approximated as

$$q(hr) = Watts \cdot F_d \cdot F_{sa} \cdot CLF(hr) \tag{6.1.73}$$

where *Watts* is the total lamp wattage in the space, F_d is the diversity factor, and F_{sa} is a ballast special allowance factor. The diversity factor i takes into account the variability of the actual wattage of lights on at any given time and has typical values as given in Table 6.1.19.

The lighting CLF values come from tables and are found in a fashion similar to that for the occupants. It should be remembered that the zone types for lighting are not necessarily the same zone types for the solar cooling load or the occupants. Note that the lighting *CLF* will be 1.0 for buildings in which the lights are on 24 hours per day or where the cooling system is shut off at night or on the weekends.

If the calculations are done in IP units, then the result from Equation 6.1.73 is multiplied by 3.41 to convert watts to Btu/hr.

TABLE 6.1.14 Zone Type for Solar Cooling Load for First Story of Multistory Buildings

Mid-Floor Type	Ceiling Type	Floor Covering	Partition Type	Inside Shade	Zone Type
		1 or 2 Walls			
2.5 in Concrete	With	Carpet	Gypsum	Full	A
				Half to None	B
			Concrete block	Full	B
				Half to None	C
		Vinyl	Gypsum	Full	C
				Half to None	C
			Concrete block	Full	D
				Half to None	D
	Without	Carpet	Gypsum	—	B
			Concrete block	Full	C
				Half to None	C
		Vinyl	Gypsum	Full	C
				Half to None	D
			Concrete block	Full	C
				Half to None	D
1 in Wood	—	Carpet	Gypsum	Full	A
				Half to None	B
			Concrete block	Full	B
				Half to None	C
		Vinyl	Gypsum	Full	B
				Half to None	C
			Concrete block	Full	C
				Half to None	D
		3 Walls			
2.5 in Concrete	With	Carpet	Gypsum	Full	A
		Carpet	Gypsum	Half to None	B
		Carpet	Concrete block	—	B
		Vinyl	Gypsum	Full	C
		Vinyl	—	Half to None	C
		Vinyl	Concrete block	Full	C
	Without	Carpet	Gypsum	—	B
		Carpet	Concrete block	Full	B
		Carpet	Concrete block	Half to None	C
		Vinyl	Gypsum	Full	C
		Vinyl		Half to None	C
		Vinyl	Concrete block	Full	C
1 in Wood	—	Carpet	Gypsum	Full	A
				Half to None	B
			Concrete block	—	B
		Vinyl	Gypsum	Full	B
				Half to None	C
			Concrete block	Full	C
				Half to None	C
		4 Walls			
2.5 in Concrete	With	Carpet	Gypsum	Full	A
				Half to None	B
		Vinyl	Gypsum	—	C
	Without	Carpet	Gypsum		B
		Vinyl	Gypsum		B
1 in Wood	—	Carpet	Gypsum	Full	A
				Half to None	A
		Vinyl	Gypsum	Full	B
				Half to None	C

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

TABLE 6.1.15 Solar Cooling Load (SCL) for Sunlit Glass at 36° North Latitude for July

Zone Type/	Orientation	Solar Time (Hour of Day) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A	N	0	0	0	0	0	25	29	28	32	36	39	40	41	39	36	32	33	36	12	6	3	1	1	0
	NE	0	0	0	0	0	79	129	139	120	84	58	50	45	41	37	32	26	17	7	3	2	1	0	0
	E	0	0	0	0	0	86	153	184	182	155	107	67	54	45	39	33	26	17	7	3	2	1	0	0
	SE	0	0	0	0	0	42	90	125	142	140	119	86	58	48	40	34	27	17	7	3	2	1	0	0
	S	0	0	0	0	0	8	17	24	36	53	70	80	79	68	52	38	29	18	7	3	2	1	0	0
	SW	0	0	0	0	0	8	17	24	30	35	38	57	90	122	141	144	127	85	32	15	8	4	2	1
	W	1	0	0	0	0	8	17	24	30	35	38	40	66	115	159	188	191	149	53	25	12	6	3	2
	NW	1	0	0	0	0	8	17	24	30	35	38	40	40	56	93	129	148	127	43	21	10	5	2	1
	HOR	0	0	0	0	0	20	66	120	171	215	246	263	265	251	221	178	124	66	28	13	7	3	2	1
B	N	2	2	1	1	1	21	25	25	29	33	36	38	38	38	35	32	33	35	15	10	7	5	4	3
	NE	2	1	1	1	1	68	109	120	108	81	61	54	50	46	42	37	30	22	12	9	6	5	3	3
	E	2	2	1	1	1	73	130	158	161	143	106	75	63	55	48	41	34	25	14	10	7	5	4	3
	SE	2	2	1	1	1	36	77	107	124	125	111	85	64	55	48	41	33	24	14	10	7	5	4	3
	S	2	2	1	1	1	7	14	21	31	47	61	71	72	65	52	41	33	24	13	9	7	5	4	3
	SW	6	4	3	3	2	8	15	21	27	31	35	51	80	108	126	131	119	86	43	29	20	14	11	8
	W	8	6	5	4	3	9	16	22	27	32	35	37	60	101	140	166	172	141	63	42	29	20	15	11
	NW	6	5	4	3	2	8	15	21	27	31	35	37	38	52	84	115	132	117	49	32	22	16	11	8
	HOR	8	6	5	4	3	19	57	103	148	188	218	237	244	237	215	182	137	88	53	37	26	19	14	11
C	N	5	5	4	4	3	24	25	24	27	31	33	35	35	34	32	29	31	34	14	10	8	7	6	6
	NE	7	6	6	5	5	71	106	111	95	68	51	48	46	44	41	37	32	24	16	13	11	10	9	8
	E	9	8	8	7	6	77	128	148	145	124	89	62	56	52	47	43	37	29	20	17	15	13	12	11
	SE	8	8	7	6	5	40	77	102	114	112	97	73	55	49	45	40	35	27	18	15	13	12	11	9
	S	6	6	5	4	4	10	17	22	31	45	58	65	65	57	45	35	30	22	14	11	10	9	8	7
	SW	13	12	10	9	8	14	20	25	29	32	35	50	77	102	116	118	105	74	34	26	21	18	16	14
	W	16	15	13	12	11	16	22	27	31	34	36	37	59	98	132	154	155	122	48	34	28	24	21	18
	NW	12	11	10	9	8	14	20	25	29	32	35	36	36	50	80	108	122	104	37	26	21	18	15	14
	HOR	24	22	19	17	16	31	66	107	145	178	203	217	220	212	192	161	122	81	53	44	38	34	30	27
D	N	8	7	6	6	5	21	22	21	25	27	30	31	32	32	31	29	30	32	17	14	12	11	10	9
	NE	11	10	9	8	7	59	87	93	82	63	51	49	47	46	43	40	35	29	22	19	17	15	14	12
	E	15	13	12	11	10	65	105	123	124	110	84	65	60	57	53	48	43	36	28	25	22	20	18	16
	SE	13	12	11	10	9	36	65	85	96	97	87	70	56	52	49	45	40	33	25	22	20	18	16	15
	S	9	9	8	7	6	11	16	20	27	39	49	56	57	52	43	36	31	26	19	16	15	13	12	11
	SW	20	18	16	14	13	17	21	25	28	31	33	45	67	87	100	103	95	72	41	35	30	27	24	22
	W	25	22	20	18	16	20	24	27	30	33	34	36	53	84	112	131	134	111	55	45	39	34	31	28
	NW	18	17	15	14	12	16	20	24	27	30	32	34	34	45	69	92	104	92	42	34	29	26	23	21
	HOR	37	33	30	27	24	35	62	94	125	153	174	189	195	191	179	157	128	95	72	63	56	51	46	41

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

TABLE 6.1.16 Typical Diversity Factors for Occupants in Large Buildings

Building Type	F_d
Apartment	0.40 to 0.60
Industrial	0.85 to 0.95
Hotel	0.40 to 0.60
Office	0.75 to 0.90
Retail	0.80 to 0.90

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

TABLE 6.1.17 Zone Types for Use in Determining the CLF — Interior (i.e., Nonperimeter) Zones Only

Zone Parameters			Zone Type	
Middle Floor	Ceiling Type	Floor Covering	People and Equipment	Lights
		Single Story		
N/A	N/A	Carpet	C	B
N/A	N/A	Vinyl	D	C
		Top Floor		
2.5 in Concrete	With	Carpet	D	C
2.5 in Concrete	With	Vinyl	D	D
2.5 in Concrete	Without	*	D	B
1 in Wood	*	*	D	B
		Bottom Floor		
2.5 in Concrete	With	Carpet	D	C
2.5 in Concrete	*	Vinyl	D	D
2.5 in Concrete	Without	Carpet	D	D
1 in Wood	*	Carpet	D	C
1 in Wood	*	Vinyl	D	D
		Mid-Floor		
2.5 in Concrete	N/A	Carpet	D	C
2.5 in Concrete	N/A	Vinyl	D	D
1 in Wood	N/A	*	C	B

* The effect of this parameter is negligible in this case.
Source: Adapted from McQuiston, F. and Spitler, J., (1992).

Appliance and Equipment Loads

Equipment can add heat either through resistive heating or from electrical motors operating in the equipment. The CLTD/SCL/CLF method accounts for both types of equipment heat separately. In addition, the equipment loads are further broken down into sensible or latent components. The latent components are assumed to become immediate loads on the cooling system. The latent loads are found in tables devoted to hospital equipment, restaurant equipment, and office equipment; latent loads are cited only for the hospital and restaurant equipment. An example of these kinds of loads is given in Table 6.1.20.

The sensible component of the loads is adjusted by

$$q(hr) = q_{sa} \cdot CLF(hr) \qquad (6.1.74)$$

where q_{sa} is the sensible heat gain per appliance as found from the tables. The cooling load factor is found by first determining the zone type and then by looking up the CLF in a table appropriate for that zone type as was done for the occupants and lighting. While the zone type is similar for occupants and equipment, it may not be the same as for lighting.

TABLE 6.1.18 Occupant Cooling Load Factors for Type A Zones

Hour After Occupants Enter Space	Total Hours That Space Is Occupied								
	2	4	6	8	10	12	14	16	18
1	0.75	0.75	0.75	0.75	0.75	0.75	0.76	0.76	0.77
2	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.89	0.89
3	0.18	0.93	0.93	0.93	0.93	0.93	0.93	0.94	0.94
4	0.08	0.95	0.95	0.95	0.95	0.96	0.96	0.96	0.96
5	0.04	0.22	0.97	0.97	0.97	0.97	0.97	0.97	0.97
6	0.02	0.10	0.97	0.97	0.97	0.98	0.98	0.98	0.98
7	0.01	0.05	0.33	0.98	0.98	0.98	0.98	0.98	0.98
8	0.01	0.03	0.11	0.98	0.98	0.98	0.99	0.99	0.99
9	0.01	0.02	0.06	0.24	0.99	0.99	0.99	0.99	0.99
10	0.01	0.02	0.04	0.11	0.99	0.99	0.99	0.99	0.99
11	0.00	0.01	0.03	0.06	0.24	0.99	0.99	0.99	0.99
12	0.00	0.01	0.02	0.04	0.12	0.99	0.99	0.99	1.00
13	0.00	0.01	0.02	0.03	0.07	0.25	1.00	1.00	1.00
14	0.00	0.01	0.01	0.02	0.04	0.12	1.00	1.00	1.00
15	0.00	0.00	0.01	0.02	0.03	0.07	0.25	1.00	1.00
16	0.00	0.00	0.01	0.01	0.02	0.04	0.12	1.00	1.00
17	0.00	0.00	0.01	0.01	0.02	0.03	0.07	0.25	1.00
18	0.00	0.00	0.00	0.01	0.01	0.02	0.05	0.12	1.00
19	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.07	0.25
20	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.05	0.12
21	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.07
22	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03	0.05
23	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03
24	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.02	0.03

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

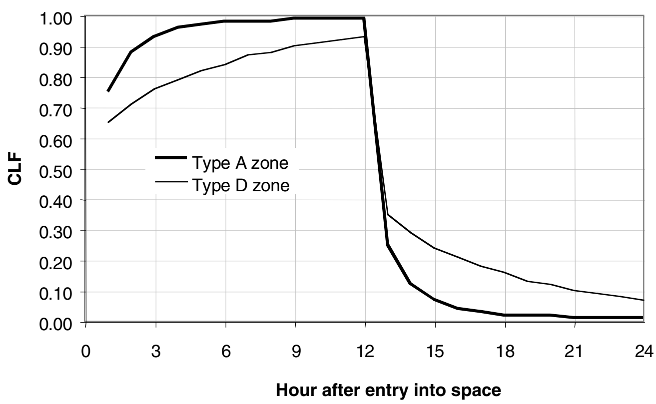


FIGURE 6.1.20 Occupant cooling load factors for Type A and Type D zones for a space that is occupied for 12 hours.

TABLE 6.1.19 Typical Diversity Factors for Lighting in Large Buildings

Building Type	F_d
Apartment	0.30 to 0.50
Industrial	0.80 to 0.90
Hotel	0.30 to 0.50
Office	0.70 to 0.85
Retail	0.90 to 1.00

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

TABLE 6.1.20 Partial List of Recommended Heat Gain for Restaurant Equipment

Appliance Type	Size	Maximum Input Rating		Heat Gain Rate (Btu/hr)		
				Unhooded		Hooded
		Watts	Btu/hr	Sensible	Latent	Sensible
Barbeque (pit), per 5 lbs of food capacity	80–300 lbs	200	680	440	240	210
Barbeque (pressurized), per 5 lbs of food capacity	45 lbs	470	1600	550	270	260
Blender, per gal of capacity	0.25–1.0 gals	1800	6140	4060	2080	1980
Braising pan, per gal of capacity	27–35 gals	400	1360	720	380	510
Cabinet (large hot holding)	16.3–17.3 ft^3	2080	7100	610	340	290
Cabinet (large hot serving)	37.6–40.5 ft^3	2000	6820	610	310	280
Cabinet (large proofing)	16.0–17.0 ft^3	2030	6930	610	310	280
Cabinet (small hot holding)	3.3–6.5 ft^3	900	3070	270	140	130
Cabinet (very hot holding)	17.3 ft^3	6150	20,980	1880	960	850
Can opener		170	580	580		0
Coffee brewer	12 cups/2 burners	1660	5660	3750	1910	1810
Coffee heater, per boiling burner	1–2 burners	670	2290	1500	790	720
Coffee heater, per warming burner	1–2 burners	100	340	230	110	110
Coffee/hot water holding urn, per gal of capacity	3.0 gal	460	1570	580	200	260
Coffee urn (large), per gal of capacity	6.0–10.0 gal	2500	8530	2830	1430	1.36
Coffee urn (small), per gal of capacity	3.0 gal	1580	5390	1770	920	850
Cutter (large)	18 in bowl	750	2560	2560		820
Cutter (small)	14 in bowl	370	1260	1260		410
Cutter and mixer (large)	7.5–11.3 gal	3730	12,730	12,730		4060

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

The total cooling load in the space is then found from the sum of the sensible and latent loads. If there is a cooling load due to equipment with electrical motors that run equipment in the space then the space cooling load is incremented by

$$q(hr) = 2545 \cdot \frac{HP}{\eta} \cdot F_l \cdot F_u \cdot CLF(hr) \tag{6.1.75a}$$

where HP is the rated horsepower of the motor, η is the efficiency, F_l is the load factor (power used divided by rated horsepower, typically around 12), and F_u is the motor use factor (accounting for intermittent use). The term 2545 converts from HP to Btu per hour. Equation 6.1.75a assumes that both the equipment and the motor are located within the space. If the equipment is in the space but the motor is located outside the space, then this equation is de-rated by the motor efficiency:

$$q(hr) = 2545 \cdot HP \cdot F_l \cdot F_u \cdot CLF(hr) \tag{6.1.75b}$$

Conversely, if the motor is inside the space but it acts on equipment outside the space, the cooling load is incremented by

$$q(hr) = 2545 \cdot HP \cdot \frac{1-\eta}{\eta} \cdot F_l \cdot F_u \cdot CLF(hr) \tag{6.1.75c}$$

As with the lighting, the CLF is always 1.0 when the cooling system does not operate 24 hours per day.

Air Infiltration

The sensible and latent cooling loads introduced by infiltration are treated the same way in the CLTD/SCL/CLF method as they were in the original CLTD/CLF method. Specifically, the infiltrating air is assumed to immediately become a load on the cooling system.

TABLE 6.1.21 Period Response Factors for Representative Roof Types 1 Through 8, Btu/h·ft²·°F

	Roof Type							
	1	2	3	4	5	6	7	8
Y_{P0}	0.004870	0.000556	0.006192	0.000004	0.000105	0.003675	0.001003	0.003468
Y_{P1}	0.036463	0.012356	0.044510	0.000658	0.002655	0.034908	0.009678	0.022622
Y_{P2}	0.026468	0.020191	0.047321	0.004270	0.007678	0.054823	0.017455	0.045052
Y_{P3}	0.008915	0.012498	0.035390	0.007757	0.008783	0.050193	0.017588	0.047168
Y_{P4}	0.002562	0.005800	0.026082	0.008259	0.007720	0.041867	0.015516	0.042727
Y_{P5}	0.000708	0.002436	0.019215	0.006915	0.006261	0.034391	0.013169	0.037442
Y_{P6}	0.000193	0.000981	0.014156	0.005116	0.004933	0.028178	0.011038	0.032544
Y_{P7}	0.000053	0.000388	0.010429	0.003527	0.003844	0.023078	0.009213	0.028228
Y_{P8}	0.000014	0.000152	0.007684	0.002330	0.002982	0.018900	0.007678	0.024472
Y_{P9}	0.000004	0.000059	0.005661	0.001498	0.002309	0.015478	0.006397	0.021212
Y_{P10}	0.000001	0.000023	0.004170	0.000946	0.001787	0.012675	0.005328	0.018386
Y_{P11}	0.000000	0.000009	0.003072	0.000591	0.001383	0.010380	0.004437	0.015937
Y_{P12}	0.000000	0.000003	0.002264	0.000366	0.001070	0.008501	0.003696	0.013814
Y_{P13}	0.000000	0.000001	0.001668	0.000225	0.000827	0.006962	0.003078	0.011973
Y_{P14}	0.000000	0.000001	0.001229	0.000138	0.000640	0.005701	0.002563	0.010378
Y_{P15}	0.000000	0.000000	0.000905	0.000085	0.000495	0.004669	0.002135	0.008995
Y_{P16}	0.000000	0.000000	0.000667	0.000052	0.000383	0.003824	0.001778	0.007797
Y_{P17}	0.000000	0.000000	0.000491	0.000032	0.000296	0.003131	0.001481	0.006758
Y_{P18}	0.000000	0.000000	0.000362	0.000019	0.000229	0.002564	0.001233	0.005858
Y_{P19}	0.000000	0.000000	0.000267	0.000012	0.000177	0.002100	0.001027	0.005077
Y_{P20}	0.000000	0.000000	0.000196	0.000007	0.000137	0.001720	0.000855	0.004401
Y_{P21}	0.000000	0.000000	0.000145	0.000004	0.000106	0.001408	0.000712	0.003815
Y_{P22}	0.000000	0.000000	0.000107	0.000003	0.000082	0.001153	0.000593	0.003306
Y_{P23}	0.000000	0.000000	0.000079	0.000002	0.000063	0.000945	0.000494	0.002866

Source: Adapted from Spitler, J.D. and Fisher, D.E., (1999).

The Radiant Time Series Method for Hourly Cooling Load Calculations

The radiant time series method is a new method currently under development by ASHRAE. This method is similar to the transfer function method except that the several-day-long iterative computations for the conductive heat flows and room radiative transfer functions have been replaced by a set of 24 response factors that are used directly for the calculations at each hour. The principal differences between the transfer function method and the RTS method are outlined in this section.

Surface Conduction Heat Transfer

The transfer function method uses an iterative process to calculate the conductive heat flow across the roof and wall surfaces of a building. Depending on the driving forces and the wall material, this may require several repetitions of each day's values before the iteration converges. The RTS method replaces this iteration with a simple summation,

$$q_{cond}(hr) = A \cdot \sum_{j=0}^{23} Y_{Pj} \cdot \left(T_{e,\theta-j\delta} - T_r\right) \tag{6.1.76}$$

where A is the surface area, Y_{Pj} is the jth response factor, $T_{e,\theta-j\delta}$ is the sol-air temperature from j hours ago, and T_r is the space temperature, assumed to be constant. The response factors for the walls and roof can be found from lookup tables (such as Table 6.1.21) similar to those created for the transfer function coefficients.

Once the conductive loads have been calculated, the transmitted solar heat and window conductive heat gains through each window, the absorbed solar gain, and the internal gains are calculated the same as with the transfer function method.

TABLE 6.1.22 Typical Radiative Fraction of Building Heat Gains

Heat Gain Type	Typical Radiative Fraction
Occupants	0.7
Suspended fluorescent lighting, unvented	0.67
Recessed fluorescent lighting, vented to return air	0.59
Recessed fluorescent lighting, vented to supply & return air	0.19
Incandescent lighting	0.71
Equipment	0.2–0.8
Conductive heat gain through walls	0.63
Conductive heat gain through roofs	0.84
Transmitted solar radiation	1.0
Solar radiation absorbed by window glass	0.63

Source: Adapted from McQuiston, F. and Spitler, J., (1992).

Radiative and Convective Fractions

When all the heat flows into the building have been calculated, the loads must be further broken down into the radiative and convective components. Table 6.1.22 shows recommended values for the radiative fraction; the convective fraction is simple

$$\textit{Load convective fraction} = 1 - \textit{Load radiative fraction} \tag{6.1.77}$$

The convective fraction immediately becomes a cooling load on the building HVAC system. The radiative portion is absorbed by the building materials, furniture, etc. and is convected into the space as a time-lagged and attenuated cooling load as described in the next section.

Conversion of Radiant Loads

The radiant loads are converted to hourly cooling loads through the use of radiant time factors. Similar to the response factors, the time factors estimate the cooling load based on past and present heat gains.

$$q_{cool}(hr) = \sum_{j=0}^{23} r_j \cdot q_{\theta - j\delta} \tag{6.1.78}$$

where r_0 is the fraction of the load convected to the space at the current time, r_1 is the fraction at the previous hour, and so forth. This step replaces the zone transfer function of the transfer function method.

Two sets of radiative time factors must be determined for each zone: one for the transmitted solar heat gain and one for all other types of heat gain. The difference between the two is that the former is assumed to be absorbed by the floor only while the latter is assumed to be evenly distributed throughout the space. The radiant time factors are determined through a zone heat balance model as described by Spitler et al (1997).

6.1.9 Summary

We have described the tools for calculating heating and cooling loads. The focus has been on peak loads (annual loads and energy consumption are addressed in Chapter 6.2). The procedure begins with the definition of the zones and the choice of the design conditions, followed by a careful accounting of all thermal energy terms, including conduction, air change, and heat gains. The formulas for the load calculation depend on whether the thermostat setpoint is constant or variable. The first case is much simpler, allowing a static calculation (for heating loads) or a quasistatic calculation (for cooling loads). Correct analysis of loads for variable setpoints requires a dynamic method; in such a case, the transfer function method can be used both for heating and for cooling. For latent loads, a static calculation is usually considered sufficient. Further detail on load calculations is contained in ASHRAE (1998).

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6.2 Simulation and Modeling — Building Energy Consumption

Joe Huang, Jeffrey S. Haberl, and Jan F. Kreider

The advent of the oil embargo in 1973 and the subsequent oil shocks led to an increased awareness of the cost of energy consumed to heat and cool buildings. Whereas previous advances in building heating and cooling had been focused mostly on increased comfort and convenience, attention also went to the amount of energy wasted and the need to develop ways to make energy use more efficient.

The first step to understanding building energy utilization is to know how much energy is being used in the building and how that is divided among space conditioning and other uses. Unfortunately, this is not as easy to do as it sounds. Even if that information were readily available, such as how much natural gas and electricity are consumed by a boiler and air conditioner, it would still be difficult to evaluate in terms of energy efficiency, which would require accounting for differences in building size, usage patterns, internal conditions, and climate. As interest has grown in improving building energy efficiency, engineers, energy experts, and analysts have gone more and more to computer-based methods that simulate in detail the energy flows in a building over long extended periods, typically of a year or more.

6.2.1 Steady State Energy Calculation Methods

Degree-Day Method

The earliest method used to estimate the heating energy consumption of a building is the degree-day method first developed in the 1930s by the gas utilities to predict gas consumption. A degree-day is the sum of the number of degrees that the average daily temperature (technically the average of the daily maximum and minimum) is above (for cooling) or below (for heating) a base temperature times the duration in days. Thus, a day where the average daily temperature is 12 degrees lower than the base temperature would accumulate 12 degree-days, as would three days, each of which was 4 degrees below the base temperature. Summed over an entire year, the number of heating or cooling degree-days remains a convenient single number for indicating climate severity.

Historically, gas companies found 65°F to be the most appropriate base temperature for estimating fuel deliveries in the 1930s. The concept behind the degree-day method is that the base temperature represents the "balance point" of a building at which the building's internal heat gains are just sufficient to counterbalance the heat losses to the outside, so that the building requires neither heating nor cooling. Below that balance temperature the building requires heating, while above that temperature the building requires cooling, in proportion to the difference from the base temperature.

Since its invention in the 1930s, base 65°F heating degree-days, and to less of an extent, base 65°F cooling degree-days, have become widely accepted as the most convenient, simple indicators of climate severity. In the U.S., heating degree-days vary from less than 500 in Miami, 1000–3000 in the south, 3000–7000 in the north, to extremes of over 8000 in Bismarck, ND and 10,000 in Anchorage, AK. Correspondingly, cooling degree-days vary from 0 in Anchorage, less than 100 in Seattle, 500–1200 in the north, 1200–3000 in the south, and over 3000 in Phoenix and Miami. Figures 6.2.1 and 6.2.2 show the heating and cooling degree-days for the U.S. averaged over 30 years from 1950 to 1980.

In the degree-day method, the building heat load, i.e., the amount of heating energy input or cooling energy extraction, is estimated as the number of degree-days times 24 (to convert to degree hours), times the overall building heat loss coefficient (Btu/hr °F). The overall heat loss coefficient is the sum of the (U-value x area) for all external surfaces, such as walls, windows, doors, and roof, plus the heat losses or gains due to infiltration. The heating load equation is

$$HL = HDD_{65} * 24\left[\sum \mathrm{U_i A_i} + (\text{Infiltration Air Changes per Hour} \times \text{Volume}) \times 0.018^{*}\right]$$

[*] The constant 0.018 is the product of density and specific heat for air at sea level. For other altitudes this constant must be adjusted by the density ratios. For example, at the altitude of Denver the density is 0.06 lb/ft^3 and the constant has a value of 0.0144.

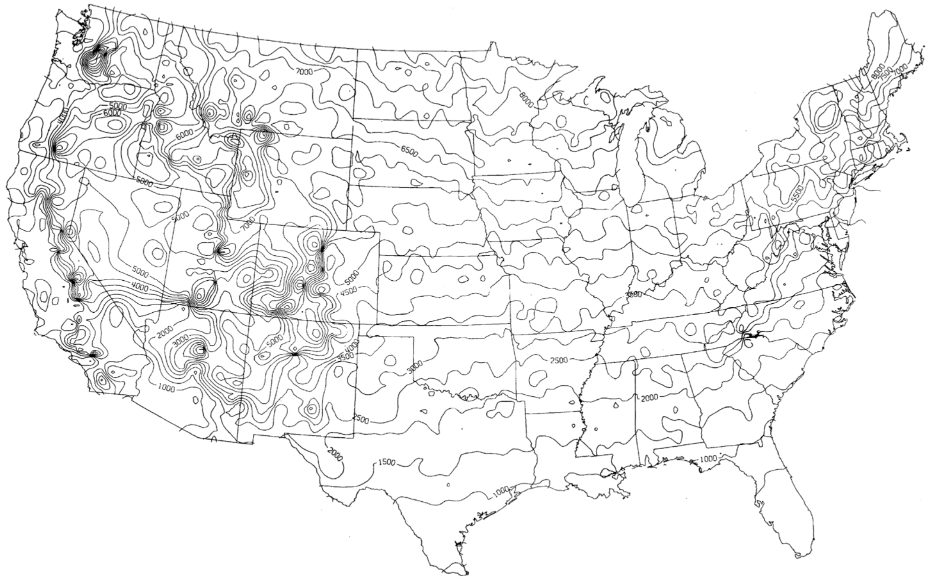

FIGURE 6.2.1 U.S. heating degree-days base 65°F (1950–1980, 30-year averages).

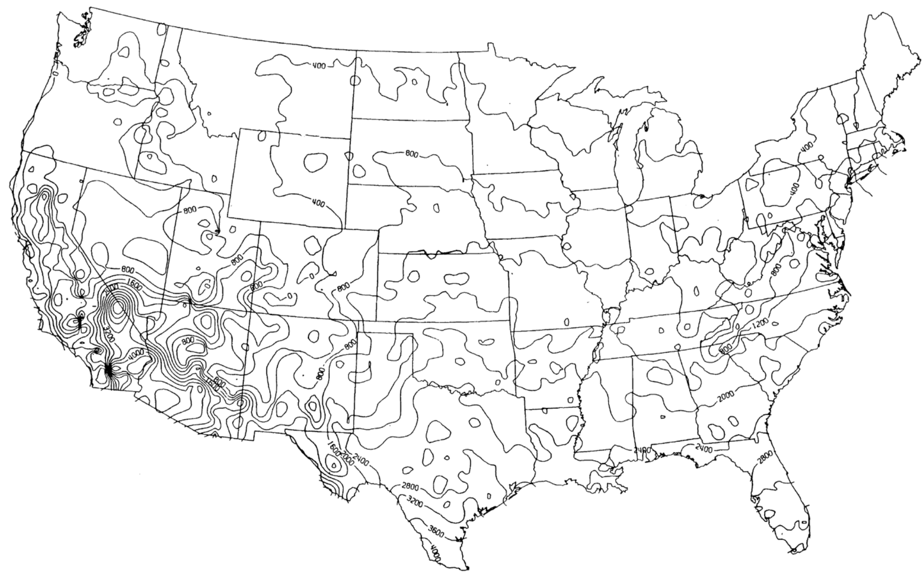

FIGURE 6.2.2 U.S. cooling degree-days base 65°F (1950–1980, 30-year averages).

The cooling load equation is similar except that cooling degree-days are used in place of heating degree-days.

To derive the heating or cooling energy consumption, the heating or cooling loads need to be multiplied by the efficiency of the HVAC system. For example, for a 1800 ft^2 house in Denver (HDD=5940) with an overall heat loss coefficient of 400 Btu/hr-°F, 0.7 air change rate per hour, 14,400 ft^3 volume, heated by a furnace with an AFUE of 0.78, and having an average duct loss factor of 0.10, the total energy use would be

$$HE = [5940 * 24 * (400 + 0.7 * 14000 * 0.0144)]/(0.78 * 0.90 * 1000000) = 110 \ MMBtu$$

Similarly, for the same house in Denver (CDD = 630) cooled by an air conditioner with a SEER of 9.0, the cooling energy use in kWh would be

$$CE = [630 * 24 *(400 + 0.7 * 14000 * 0.0144)]/(9.0 * 0.90 * 1000) = 1010 \text{ kWh}$$

The above example shows the degree-day method in its simplest form. Its limitations are easy to list. The method does not consider the effects of solar heat gain or building thermal mass, nor can it account for variations in infiltration rates, thermostat settings (such as night setback), or occupant actions such as window venting on cool summer nights or during the spring and fall seasons.

When building energy calculations started to attract more attention in the late 1970s and early 1980s, efforts were made to improve the degree-day method by using variable base temperatures, calculating degree-hours instead of days, etc. These are described in the following section. Although these modified degree-day methods have gained in accuracy, this has come at the expense of computational ease, and in most cases calculations can be done conveniently only using a computer program. As the capability of personal computers has grown, degree-day methods have fallen increasingly out of favor because they remain fundamentally steady state calculations that are unable to capture fully the transient heat flows that dominate building thermal processes.

Despite its limitations, there are situations where the simple degree-day method can still be of use. By virtue of its simplicity, it provides a quick answer that can be used as a starting point or check for more detailed calculations. For estimating heating energy use in light construction residential buildings with low solar gain in cold climates, the simple degree-day method may be adequate when gathering the additional data on climate and building conditions may be unwarranted or impractical. The simple and clear-cut formulation of the degree-day method is also valuable as a way to distill the results from more detailed calculations that are often hard to interpret. For example, in the correlation methods described later, detailed hourly simulation results can be presented as the imputed heating degree-days that a building "sees" when the variations in building operations and conditions are considered. This not only helps in visualizing the detailed results, but permits interpolation using the degree-day method for small changes in the building shell.

Variable Base Degree-Day Method

The variable base degree-day method was developed to account for the fact that balance point temperatures vary between buildings and even within a building depending on the time of day. The original 65°F base temperature developed in the 1930s implied that if a building were maintained at 70°F, the heat gains from the sun and internal processes would contribute on average 5°F of "free heat," so that heating was required only when the outside temperature dropped below 65°F. As buildings are now better insulated and more air-tight, their balance point temperatures should be lower. For residential buildings, several studies have found that the average balance point temperature is now 55–57°F, instead of 65°F. For commercial buildings, the combination of low surface-to-volume ratios, high window-to-wall ratios, and high internal gains have caused their balance point temperatures to drop even further to 50°F or lower.

The balance point temperature for a building differs markedly between daytime and nighttime. During the day, the building receives heat gain from the sun as well as from human activity, including equipment and lights. At night, there is, of course, no solar heat gain and human activity is reduced. In a typical residential building, the balance point temperature depression may be around 15°F, while at night it is only 3°F. In a commercial building, the difference can be even greater because of higher internal heat gains during the day and very low heat gains at night.

The variable base degree-day method attempts to account for these different building conditions by calculating first the balance point temperature of a building and then the heating and cooling degree hours at that base temperature. Since the method subdivides the day into daytime and nighttime periods, degree-hours have to be used in place of degree-days. Whereas degree-days are calculated from the average between the daily maximum and minimum temperatures, degree-hours are calculated from the temperature for each hour. In general, the number of (degree-hours)/24 can be from slightly to significantly larger than the number of degree-days at the same base temperature. The differences are particularly significant for cooling. This can be explained by considering what happens on a spring day when the average daily temperature may be below the base temperature, but several afternoon hours are above it. Such a day would have no cooling degree-days but a number of cooling degree-hours. In Washington, the (heating degree-hours)/24 and (cooling degree-hours)/24 are 4% and 5% greater than their respective degree-day values. However, in Sacramento, the differences are 24% and 26%, respectively.

In this method, the degree-day calculations are repeated for daytime and nighttime conditions for each month of the year. The balance point temperature depression (BPD) for any building is calculated as the total heat gains divided by the overall building conductance, i.e.,

$$\mathrm{BPD} = \frac{(\text{solar heat gain} + \text{internal heat gain})_{\text{average per hour}}}{\text{overall building conductance}}$$

For example, a building in Denver with 50ft^2 of double-pane windows (solar heat gain coefficient of 0.79) in each orientation receives average total daily solar heat gains of 9219 Btu on the northside, 24,526 Btu on the eastside, 60,388 Btu on the southside, and 24,846 Btu on the westside. The average hourly solar heat gain (assuming 12 hours as daytime hours) is 9915 Btu/hour. If the building has other internal heat gains of 3200 Btu/hour and an overall building conductance of 576.4 Btu/hr-°F, its BPD would be 13,115/576.4 = 23°F. During the nighttime hours, the building has internal gains of only 1400 Btu/hour, and BPD of 1400/576.4 = 2°F. If the thermostat were maintained at 70°F during the day and 65°F at night, base 47°F (70 – 23°F) heating degree-hours should be used for the daytime hours, while base 63°F (65 – 2°F) heating degree-hours should be used for the nighttime hours.

On the cooling side of the equation, the variable base degree day (VBDD) method follows a similar logic to identify the number of cooling degree-hours that a building actually "sees." The cooling balance point changes dramatically depending on whether the building is being vented. If the windows are open, the heat gains are flushed out of the building and have no effect on its cooling load. However, if the windows are closed, then the solar and internal gains create a balance temperature significantly lower than the thermostat setpoint for cooling. The way these two conditions are handled in a VBDD method is that the cooling degree-hours are calculated using the balance temperature with the windows closed, but they are not accumulated for the hours when the temperatures are below the thermostat setpoint, when the windows are assumed to be open. This is illustrated in Figure 6.2.3, which shows the one-to-one relationship between cooling degree-hours and the temperature difference between the balance and outdoor air temperature. However, those degree-hours occurring in the shaded triangle when the outdoor temperatures are below the thermostat setpoint are considered "vented" and not added to the running total of cooling degree-hours.

Although the simple example shown earlier for the variable degree-day method may not seem very onerous, one must keep in mind that the balance point calculations have to be repeated for each month, and that it requires calculating the solar heat gain through windows (and skylights), which in turns requires calculating sun angles and the distribution of solar gain by orientation. After the balance point temperatures have been derived, the procedure then requires the calculation of heating and cooling degree-hours at different base temperatures.

The net result of this extra detail is to make the method too tedious for either hand calculations or implementation on a spreadsheet program. In the early 1980s, several PC programs were written using the variable base degree-day method. Researchers at LBL developed the CIRA (Computerized Instrumented Residential Audit) program, that was licensed to Burt Hill Kosan Rittelman (www.burthill.com) in 1984, who marketed it under the name EEDO (Energy Efficient Design Options). The CIRA/EEDO program is a DOS program written in BASIC for quick analysis of retrofit potentials and options in residential buildings. After the inspector or analyst has entered basic information about the location, building geometry and thermal conditions, and already installed retrofit measures, the program uses the variable base degree-day method to calculate the base case energy use of the house and the energy savings for 100 or more potential energy retrofits. The program then compares these energy savings to the costs

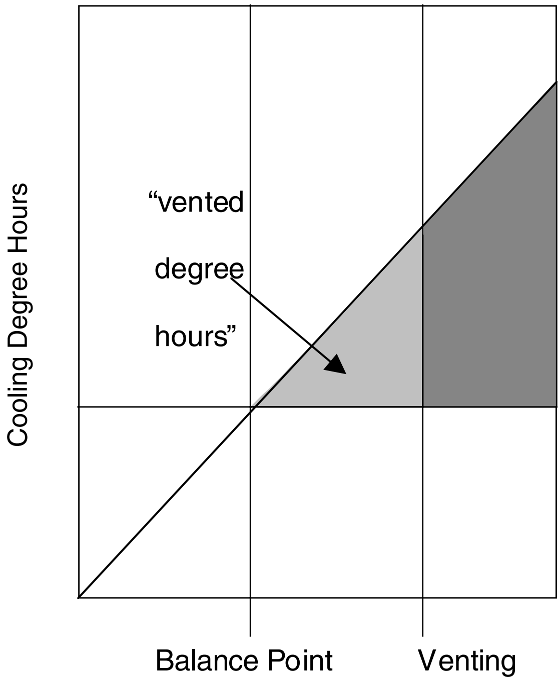

FIGURE 6.2.3 Schematic representation of "vented" cooling degree-hours.

of the measures, and produces a report listing the recommended retrofit measures in order of their cost effectiveness.

The CIRA/EEDO program contains weather data for 200 U.S. locations, including monthly solar heat gain by orientation, and a regression-based technique to interpolate monthly heating and cooling degree-hours at any base temperature. In calculating the effects of night setback on heating loads, the program uses correlations to hourly simulations done with the BLAST program (see section on Simulations) to account for the thermal lag due to the building thermal mass.

Variable base degree-day programs like CIRA represent the best that can be expected of this steady state method. The CIRA/EEDO program was very appropriate at the time it was developed given the limited capabilities of personal computers at the time, and its intended use for analysis of retrofit measures for residential buildings. Comparisons of CIRA results to those using the DOE-2 hourly simulation program done by one author (Huang) in 1984 showed good agreement for heating energy use, but some discrepancies in cooling energy use. The comparisons are particularly divergent in places such as Miami, since CIRA does not calculate latent cooling loads or the energy used for dehumidification. Further refinement of the degree-day method does not seem warranted because (1) it remains a steady state method that does not recognize a building's thermal history, and (2) additional refinement of degree-day terminology would require detailed processing of hourly weather data at a complexity approaching their use in hourly simulations.

Bin and Modified Bin Methods

The next evolution in building energy calculations from the various degree-day methods are the bin methods, which have also developed into several variations. The underlying assumption of the bin method is that for a given temperature at the same general time of day (morning, afternoon, evening, etc.), the heating and cooling loads of a building should be roughly the same. Therefore, one can derive a building's annual heating and cooling loads by calculating its loads for a set of "snapshots" defined by temperature "bins," multiplying the calculated loads by the number of hours represented by each bin, and then totaling the sums to derive the building's annual heating and cooling loads. In the original formulation of the bin method, there was no accounting of the effects of solar gain or wind on the calculated loads, which were done simply as the difference between the outdoor and indoor balance temperatures times the building conductance, divided by the efficiency of the heating or cooling system.

Later versions of the bin method accounted for these effects by using more detailed binned data that gave the average wind speeds and solar gains by month, and the number of hours within bins separated by month as well as time of day. When doing the calculation, the solar and wind effects are taken into account for each month and time of day period. The bin method is described in Kreider, Rabl, and Curtiss (1994).

6.2.2 Dynamic Hourly Simulation Methods

The previous methods described are all steady state calculations, the differences being the number of snapshots used to characterize the energy use of the building over the entire year. Even the most complex of these methods still misses the dynamic response of the building to changes in the weather or the building controls. As public interest in building energy use increased in the late 1970s, a number of general purpose computer programs have been developed to simulate the energy flows of a building, including its system and plant, on an hourly or even subhourly basis for an entire year. These efforts have been largely funded by branches of the federal government, notably the Department of Energy and Department of Defense, and some state government offices, such as the California Energy Commission.

The simplest simulation programs use networks that are the thermal equivalents to electrical RC circuits. Temperatures are represented by voltages, heat flows by currents, and thermal masses by capacitances. Network programs are generally limited to smaller, one-zone buildings such as residences or small office buildings that have shell-dominant loads and simple heating and cooling systems. Network programs that are still widely used today include the *CalRes* program, mandated by the California Energy Commission as the official program for showing compliance to California's Title-24 Building Energy Standard in residential buildings, *SeriRes* and *ENERGY-10*, both developed by the National Renewable Energy Laboratory (NREL, formerly known as the Solar Energy Research Institute, or SERI).

Energy-10

ENERGY-10 is a recent software product completed in 1996 through a partnership of the Passive Solar Industries Council (e-mail address: psicdc@aol.com), NREL, LBNL, and the Berkeley Solar Group with funding from DOE. The aim of the program is to provide a user-friendly simulation tool for the design of passive solar strategies in small and medium-sized buildings under 10,000 ft^2. The CNE simulation engine of *ENERGY-10* is a two-zone network model that runs on an hourly time-step. Substantial effort was made to add capabilities to CNE to model passive solar and energy-efficient strategies as daylighting, solar orientation, thermal mass, ventilation, and ground-coupled cooling.

Because the objective of *ENERGY-10* is to encourage architects and engineers to incorporate passive solar design strategies in the early design phase of a project, the user interface requires a minimum number of inputs and has an Auto-Build feature that automatically generates two building files at once — one for the proposed design and the other for a generic reference design of the same size and usage pattern. The Auto-Build feature assists users in quickly evaluating the merits of a proposed design or design strategies. Figure 6.2.4 is a sample input screen showing the Windows-based input procedure of *ENERGY-10* which, at a minimum, requires only five inputs — location, building use category, size, HVAC, and utility rates — to make an initial simulation. Figure 6.2.5 shows a second level, more detailed input screen, once the user has more specific data on the proposed building. In keeping with the philosophy for a quick and simple-to-use design tool, *ENERGY-10* also presents the program output in a highly graphical manner. Figures 6.2.6 and 6.2.7 show sample output for the total heating and cooling energy costs and heat flows for a proposed design compared to the reference case.

DOE-2 and BLAST

For larger and more complex buildings, the two most widely used public-domain whole-building simulation programs are DOE-2 and BLAST. In contrast to *ENERGY-10*, these two are much more like standard engineering programs rather than design tools; the primary work has gone into algorithm

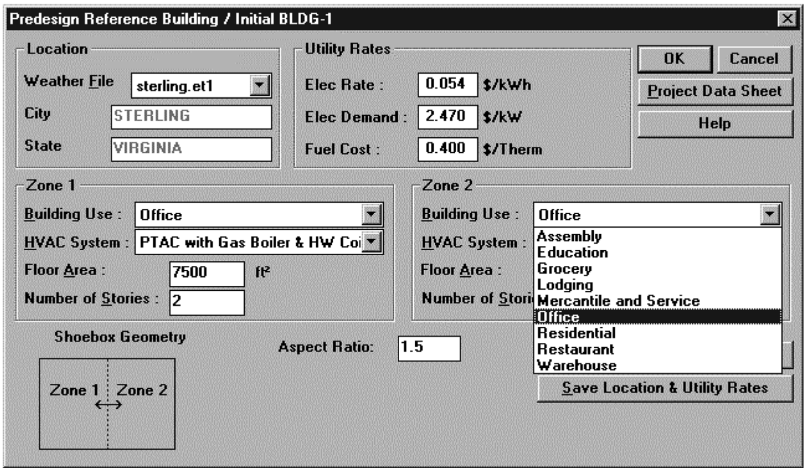

FIGURE 6.2.4 *ENERGY-10* input screen (1).

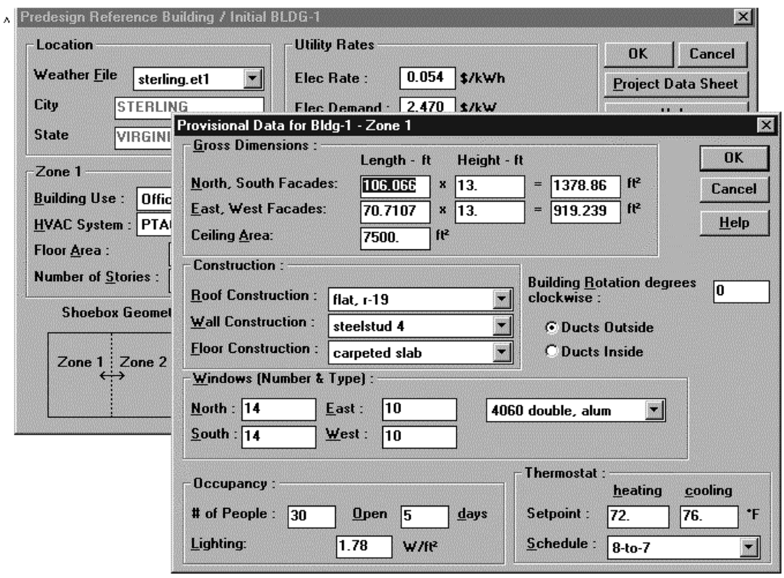

FIGURE 6.2.5 *ENERGY-10* input screen (2).

development and numerical analysis, rather than the user interface (although private vendors have since developed several graphical interfaces). In addition to DOE-2 and BLAST, there are also a number of private sector programs, developed primarily for practicing engineers to design HVAC systems, that can also do annual simulations, including TRACE (developed by the Trane Company) and HAP (developed by Carrier Corporation). This review will not cover these proprietary programs since their calculational routines are not publicly available. The general sense of these proprietary programs is that they are less detailed than the two primary public-domain programs in their loads calculation but are comparable in their system simulations.

DOE-2 is a public domain program originally started by the Lawrence Berkeley National Laboratory (LBNL) in 1979 in collaboration with Los Alamos Scientific Laboratory and Argonne National Laboratory, with support from the U.S. Department of Energy (DOE). For the past 20 years, LBNL has continued to develop and maintain the program, the current (and probably last) public version of the program

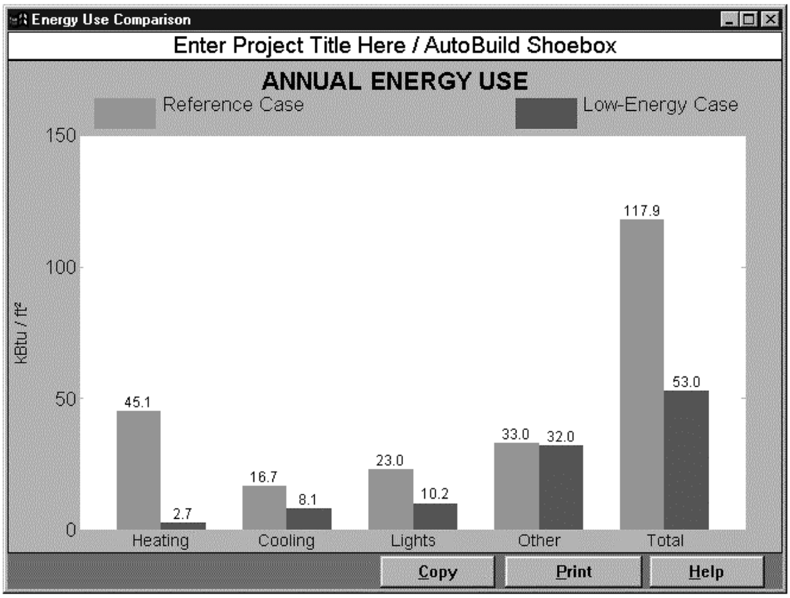

FIGURE 6.2.6 *ENERGY-10* output screen (1).

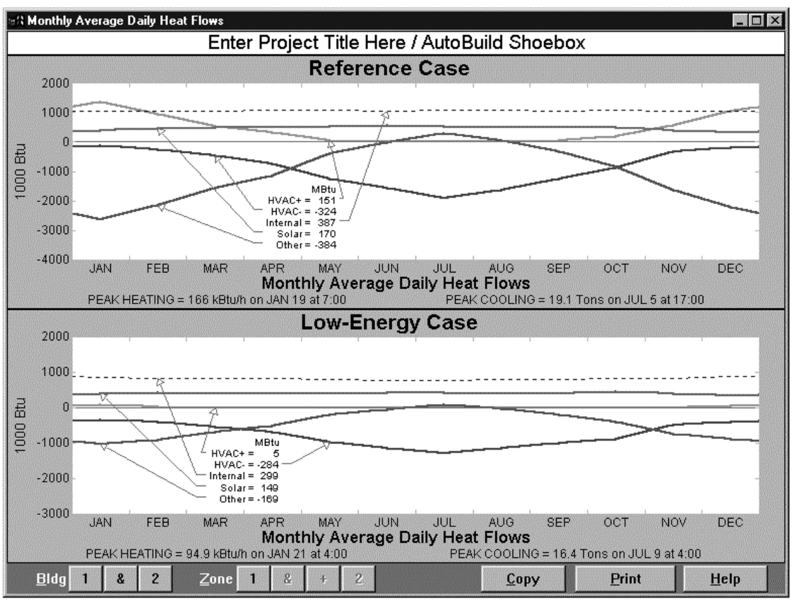

FIGURE 6.2.7 *ENERGY-10* output screen (2).

being DOE-2.1E, released in 1993. The basic DOE-2 program uses a text-based input and output procedure that is quite powerful, but unfortunately difficult and time-consuming to learn.

Mainframe and PC versions of DOE-2, as well as the FORTRAN source code, are available from the Energy Science and Technology Software Center (ESTSC) in Oak Ridge, TN (e-mail address: estsc@adonis.osti.gov). There are also more than a dozen PC versions or derivative software packages based on DOE-2 being sold by private vendors, some of whom have added graphical user interfaces to make the program easier to use. However, these interfaces generally come at the cost of some loss of modeling capability and a fundamental understanding of how the program works. They may be very helpful in introducing DOE-2 at a basic level, but may at some point hinder experienced users from tapping into more advanced features such as user-defined functions, macro expressions, or purposely tweaking the model for specific applications. A good source of information on DOE-2 (as well as BLAST) software resources, consultants, and Web sites is the *Building Energy Simulation User News*, a newsletter published quarterly by the Simulation Research Group of LBNL (e-mail address: KLEllington@lbl.gov).

The BLAST program was developed by the U.S. Army Construction Engineering Research Laboratory (CERL) with funding from various U.S. Department of Defense agencies, and first released in 1977. Since 1983, BLAST has been maintained and supported by the Building Systems Laboratory at the University of Illinois at Urbana-Champaign. The current version is BLAST 3.0, which was completed in 1980. The BLAST program contains three main subprograms — *Space Load Prediction* which calculates the building's space conditioning loads, *Air Distribution System Simulation* which models the performance and control of the air handling system to meet the previously calculated loads, and *Central Plant Simulation* which models the performance and energy usage of the boilers, chillers, and other equipment that supply the heating and cooling needed by the air handling system. In recent years, the Building System Laboratory has also developed a Windows-based graphical interface, the *Heat Balance Loads Calculator* (HBLC), which allows users to visualize the building model as it is being developed. PC versions of the BLAST program and HBLC are both available from the BSL at the University of Illinois (e-mail address: www.bso.uiuc.edu). As with DOE-2, new developments and current information about BLAST appear in the *Building Energy Simulation User News* newsletter published quarterly at LBNL.

DOE-2 and BLAST have both been maintained for close to 20 years, and can be regarded as mature software products if one accepts their 1970s software architecture and modeling techniques.

Starting in 1996, DOE began developing a new building simulation program, EnergyPlus, with a core development team consisting of staff from LBNL, the University of Illinois BSL, and CERL, thus combining the experience and expertise of the original DOE-2 and BLAST development teams. In addition to improving the simulation techniques and capabilities, other goals and characteristics of the EnergyPlus program are

- To create a modular software platform to facilitate future enhancements by other researchers and thus eliminate the bottleneck in software development found with DOE-2 and BLAST due to their arcane structure and coding
- To maintain EnergyPlus as a calculational engine and leave the development of user-interfaces to third-party private ventures. As of 2001, two beta versions of EnergyPlus were to be released to interested reviewers and a number of licensing agreements signed with potential interface developers.

The following discussion of building energy simulation programs focuses on their underlying calculation techniques, input data requirements, and output variables, using DOE-2 as an example. When talking about DOE-2, we refer to the original program with its text-based batch input procedure. This is not meant to downplay the benefits of commercial graphical interfaces, but more a reflection of the author's own experience; it also reflects more directly the operations of the basic program itself. There is no getting around the fact that making a credible computer simulation of a large building requires a sizeable amount of information and knowledge about building physics and operations, as well as equipment performance and controls, that cannot be avoided. Each portion of this input information may seem reasonable to the professionals in that discipline — the building geometry and construction materials to the architects, the HVAC equipment characteristics and operations to the mechanical engineer, the lighting schedules and operating hours to the building managers, the weather data to the meteorologist, etc. — but *in toto* may be difficult when requested of a single person attempting to put together a DOE-2 computer input file. A graphical user interface may simplify this task by using ready-made input templates, but users should at least be aware of the range of input assumptions that are required.

General Modeling Technique and Capabilities of the DOE-2 Program

Despite many similarities, there are some significant differences between DOE-2 and BLAST. Both programs simulate building energy use in sequential fashion, modeling first the building's heating and cooling loads, then the actions of the HVAC system to meet those loads, and finally the actions of the central plant to provide the energy required by the system. DOE-2 adds a further economics module that calculates the cost of the consumed energy, which can be difficult to do in places that have complicated utility tariffs. This sequential modeling approach results in a weak coupling between the three modeling steps and necessitates some simplifications. For example, because the actual zone temperature is calculated only in the systems subprogram, the loads calculations are done using a constant zone temperature and then adjusted using a steady state approximation during the systems simulation.

Whereas in the simpler degree-day or bin methods, the calculations are done for an average or a number of average conditions and then aggregated to yearly totals, in the hourly simulation method the heat flows, building conditions, system operations, etc. are tracked hour by hour through the entire year. This includes the hourly variations in heat conduction through the walls, roof, windows, doors, and floor, solar heat gain on the walls and roof and through the windows, convection due to air infiltration through cracks and leaks in the building envelope, and internal heat gain from people, lights, and equipment.

To calculate heat conduction through building surfaces, both DOE-2 and BLAST use the transfer function or response factor technique, but in somewhat different formulations. This analytical technique was developed in the 1980s to model dynamic heat flow by characterizing it as a time series of thermal responses at different faces of a building surface to a unit excitation at either the inside or outside face, either a heat flux pulse, as in DOE-2, or a temperature pulse, as in BLAST. Once the transfer functions or response factors for a building surface have been calculated, they are then used to calculate the dynamic heat flows hour by hour based on the varying excitations for each hour. Transfer functions or response factors capture the effects of thermal mass in dampening heat flows through building structures. The impact of wind on heat conduction is taken into account by varying the outside air surface coefficient depending on the wind speed shown in the weather file, with adjustments for neighborhood wind shielding effects.

To calculate solar heat gain, hourly simulation programs such as DOE-2 or BLAST need to track the position of the sun, the amount of direct and diffuse solar radiation, the orientation of the building surface, the relative position and size of shading surfaces such as overhangs, fins, neighboring buildings, as well as self-shading from other parts of the building, and in the case of windows, the transmission characteristics of the glazing depending on the sun angle. To calculate convective heat flows due to infiltration, various models are used to estimate the amount of air leakage based on temperature differences, wind speeds, and local shielding factors. To calculate internal heat gain, DOE-2 or BLAST relies on user input schedules, e.g., the number of people in a building depending on time of day and the day type, energy intensities, e.g., the amount of sensible and latent heat gain per person, and, for certain types of equipment such as stoves or boilers, the fraction of heat gain that actually remains in the space.

Perhaps the most substantial difference between DOE-2 and BLAST is in how the two programs calculate the zone heating or cooling loads. After the heat flows to a zone have been determined, DOE-2 uses the weighting factor method to compute the zone's cooling load. Weighting factors are similar to response factors but relate the thermal response of an entire space rather than that of an individual building surface. BLAST, on the other hand, uses a heat balance method that models the energy exchange between all the surfaces making up the zone. The weighting factor method is quicker but has the disadvantage that the zone properties must be constant throughout a simulation. For this reason, DOE-2 has difficulty in modeling strategies that affect the zone properties, such as movable night insulation or increased thermal coupling to the air with ventilative cooling.

The DOE-2 program was designed as a whole-building energy analysis program for large commercial buildings but has been used to model anything from single-zone residential houses to large skyscrapers with up to 128 thermal zones, hundreds of surfaces, and dozens of schedules for occupancy, equipment use, and equipment controls.

The DOE-2 *Systems* subprogram has a library of 26 system types, each with an assumed configuration and default characteristics. These are listed in Table 6.2.1. Different pieces of HVAC equipment are modeled using two performance curves, one giving its full-load performance (efficiency or coefficient of performance) as a function of outdoor air conditions, and the other its part-load performance as a

TABLE 6.2.1 HVAC Systems Types Modeled in DOE-2

Code-Word	Description of System
	Single Supply Duct Types
SZRH	Single-Zone Fan with Optional Sub-Zone Reheat
PSZ	Packaged Single-Zone
SZCI	Single-Zone Ceiling Induction
RHFS	Constructed Done, Reheat Fan System
VAVS	Variable Volume Fan
PIU	Power Induction Unit
PVAVS	Packaged Variable-Air Volume
PVVT	Packaged Variable-Volume, Variable-Temperature
PTGSD	Packaged Total Gas Solid Desiccant
CBVAV	Ceiling Bypass
EVAP-COOL	Evaporative Cooling
	Air Mixing Types
MZS	Multi-Zone Fan
PMZS	Packaged Multi-Zone Fan
DDS	Dual Duct Fan
	Terminal Units
TPFC	Two-Pipe Fan Coil
FPFC	Four-Pipe Fan Coil
TPIU	Two-Pipe Induction Unit
FPIU	Four-Pipe Induction Unit
PTAC	Packaged Terminal Air-Conditioner
HP	Heat Pump
	Residential
RESYS	Residential
RESVVT	Residential Variable-Volume, Variable-Temp
	Heating Zone
FPH	Floor Panel Heating
HVSYS	Heating and Ventilating
UHT	Unit Heater
UVT	Unit Ventilator
	Diagnostics
SUM	Sum Zone Loads

function of the part-load ratio (fraction of full-load operation during the hour). The performance curves, as well as the control and operation of the configured system, can be modified by the user, but the modeling of innovative systems or nonstandard configurations would require changes to the original source code.

The DOE-2 *Plant* subprogram models the performance and operation of large plant heating and cooling equipment, including boilers; electric, gas-fired, or engine-driven chillers; cooling towers; thermal storage systems; electric generators; and the parasitic energy use of pumps and fans. Like in the *Systems* subprogram, the full- and part-load performance of the plant equipment are modeled using various curves.

The DOE-2 *Economics* subprogram allow users to input utility rate structures, first costs, and maintenance and overhaul costs in order to compute the operational costs, energy savings, investment statistics, and overall life-cycle costs.

TABLE 6.2.2 Comparison of General Features and Capabilities of DOE-2, BLAST, IBLAST, and EnergyPlus

	DOE-2	BLAST	IBLAST	EnergyPlus
Integrated Simultaneous Solution	No	No	Yes	Yes
Integrated loads/system/plant				
Iterative solution				
Tight coupling				
Multiple Time Step Approach	No	No	Yes	Yes
User-defined time step for interaction between zones and environment (15-minute default)				
Variable time step for interactions between zone air mass and HVAC system (>1 minute)				
Input Functions	Yes	No	No	Yes
User can modify code with reprogramming				
New Reporting Mechanism	No	No	No	Yes
Standard reports				
User-definable report with graphics				

Source: From Crawley, D.B. et al. (2000). With permission.

In terms of ability to model specific heat flows, equipment types, or control strategies, in some cases DOE-2 may be more accurate, while in other cases BLAST might be more accurate. Tables 6.2.2, 6.2.3, and 6.2.4 compare a number of salient features and modeling capabilities of DOE-2, two versions of BLAST, and the new EnergyPlus program.

Overall Structure of the DOE-2 Program

DOE-2 consists of three separate programs:

doebdl — an input processor that reads the input file, checks for syntax, logic, and data completeness, supplies defaults when no input values are given, computes response factors and weighting factors, and produces an output ASCII file for debugging; if no errors are found, *doebdl* produces binary files used as input by *doesim*.

doesim — the main simulation program that models the energy use of a building for specified run-periods of up to a year; *doesim* consists of four subprograms that are run sequentially: LOADS, SYSTEMS, PLANT, and ECONOMICS.

doewth — a stand-alone weather processing program to convert raw weather data into DOE-2's required binary format.

A schematic of the DOE-2 program is shown in Figure 6.2.8. The left half of the figure shows the input processing in *doebdl*, while the right half shows the simulation steps in *doesim* starting at the top. For each subprogram, i.e., LOADS, SYSTEMS, PLANT, and ECONOMICS, there is a parallel section in the *doebdl* processor. DOE-2 can be stopped after any of the subprograms. Conversely, it can skip directly to a later subprogram if the output binary files from the previous subprogram have been saved.

Weather Data for Hourly Simulations

Hourly simulation programs require detailed hourly weather data. Required are 8760 hourly observations, at the minimum: dry-bulb temperature, wind speed, and direct and diffuse solar radiation. DOE-2 and BLAST also require some moisture measure, i.e., wet-bulb or dewpoint temperature, absolute or relative humidity, along with atmospheric pressure. Useful also are wind direction and sky cover. With one notable exception, all these data are reported at major airport weather stations. Measured solar radiation, however, is available only from very few research sites, which, moreover, tend not to be major urban centers. For most sites, the only alternative is to estimate the amount of solar radiation based on the reported cloud cover and sky conditions. Estimated solar radiation on an annual basis compares well, but hourly values can be off substantially.

Weather data used in hourly simulations can be categorized as either typical or actual year. Typical year data are likely to be available in the format needed by the individual simulation programs, either from software venders or institutions maintaining the programs, while actual year data exist only in raw

TABLE 6.2.3 Comparison of Loads Features and Capabilities of DOE-2, BLAST, IBLAST, and EnergyPlus

	DOE-2	BLAST	IBLAST	EnergyPlus
Heat Balance Calculation	No	Yes	Yes	Yes
Simultaneous calculation of radiation and convection processes each time step				
Interior Surface Convection				
Dependent on temperature and air flow	No	Yes	Yes	Yes
Internal thermal mass	Yes	Yes	Yes	Yes
Moisture Absorption/Desorption	No	No	Yes	Yes
Combined heat and mass transfer in building envelopes				
Thermal Comfort	No	Yes	Yes	Yes
Human comfort model based on activity, inside dry-bulb, humidity, and radiation				
Anisotropic Sky Model	Yes	No	No	Yes
Sky radiance depends on sun position for better calculation of diffuse solar on tilted surfaces				
Advanced Fenestration Calculations	Yes	No	No	Yes
Controllable window blinds				
Electrochromic glazing				
WINDOW 4 Library	Yes	Yes	Yes	Yes
More than 200 window types — conventional, reflective, low-E, gas-filled, electrochromic				
User defined using WINDOW 4				
Daylighting Illumination and Controls	Yes	No	No	Yes
Interior illuminance from windows and skylights				
Step, dimming, on/off luminaire controls				
Glare simulation and control				
Effects of dimming on heating and cooling				

Source: From Crawley, D.B. et al. (2000). With permission.

TABLE 6.2.4 Comparison of HVAC Features and Capabilities of DOE-2, BLAST, IBLAST, and EnergyPlus

	DOE-2	BLAST	IBLAST	EnergyPlus
Fluid Loops	No	Yes	Yes	Yes
Connect primary equipment and coils				
Hot water, loops, chilled water and condenser loops, refrigerant loops				
Air Loops				
Connects fans, coils, mixing boxes, zones	No	No	No	Yes
User-Configurable HVAC Systems	No	No	No	Yes
Hardwired Template HVAC Systems	Yes	Yes	Yes	No
High-Temperature Radiant Heating	No	Yes	No	Yes
Gas/electric heaters, wall radiators				
Low-Temperature Radiant Heating	No	No	Yes	Yes
Heated floor/ceiling				
Cooled ceiling				
Atmospheric Pollution Calculation	Yes	Yes	No	Yes
CO2, SOx, NOx, CO, particulate matter and hydrocarbon production				
On-site and at power station				
Calculate reductions in greenhouse gases				
SPARK Connection	No	No	No	Yes
TRNSYS Connection	No	No	No	Yes

Source: From Crawley, D.B. et al. (2000). With permission.

form from archival sources and must be processed into the formats needed by the simulation program. Typical year weather data are useful for evaluating expected building energy performance or complying with building energy standards, but actual year data must be used for reconciling actual energy consumption records.

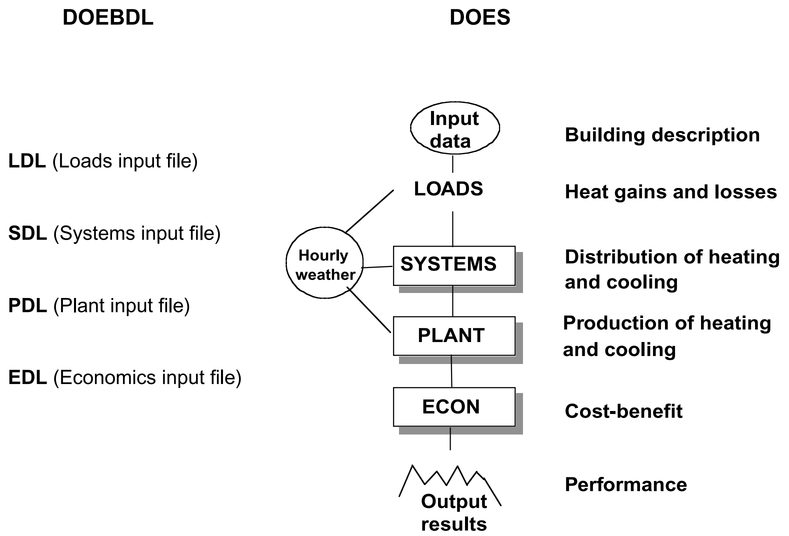

FIGURE 6.2.8 Data flow in DOE-2. (From Winkelmann, F. *The User's News*. With permission.)

Typical year weather files attempt to represent average weather conditions for a location over many years. These are often a synthetic year made up of 12 actual but typical months, as in the TMY2 (Typical Meteorological Year, 2nd version) files produced by the National Renewable Energy Laboratory (NREL, e-mail address: www.nrel.gov) for 239 U.S. sites, or the WYEC2 (Weather Year for Energy Calculations, 2nd version) files produced by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE, e-mail address: www.ashrae.org) for 55 U.S. and Canadian locations. Both the TMY2 and WYEC2 weather files have hourly solar radiation data from different cloud and sky models. An older, now less commonly used, form of typical year data are the Test Reference Year (TRY) files, available from the National Climatic Data Center (NCDC, e-mail address: www.ncdc.noaa.gov) which are actual years chosen as the most representative for nearly 60 U.S. locations. TRY weather files have no solar radiation data, only cloud cover information. TRY data are widely used in Europe.

Actual year weather data are routinely available for several hundred major airports from the NCDC going back many decades. These weather files also have no solar radiation, which must be estimated from the cloud and sky cover information either by hand or, more typically, by the weather processing utility programs that accompany a simulation program.

Starting in 1997, a new problem has arisen with U.S. and Canadian weather data due to the decision by the meteorological authorities, such as the National Weather Service and the Federal Aviation Authority in the U.S., to replace manual observations with Automated Surface Observing Stations (ASOS). The new ASOS weather stations promise more consistent and reliable weather recordings, but these data lack even the cloud and sky condition records needed for estimating solar radiation. Consequently, until new procedures or additional instrumentation are added that record solar radiation, the new ASOS weather data will not be usable in hourly building energy simulations. The installation of ASOS in major U.S. airport locations was planned to be completed by the end of the year 2000.

DOE-2 Building Input File

The primary interaction between the user and DOE-2 is through a building input file written in DOE-2's Building Description Language, or BDL. BDL is a pseudo-English text-based input format consisting of a DOE-2 keyword followed by the user input, which could be either numeric, such as *HEIGHT*=10 or *HEIGHT* 10 (the = sign is optional), or a user-defined character name followed by a DOE-2 keyword, such as WEST_WALL= *EXTERIOR-WALL*. All DOE-2 input commands are terminated by a double period (..). For example, the inputs for an example building wall in DOE-2 BDL is shown next (in English units), with the DOE-2 keywords indicated in italics:

STUCCO *MATERIAL*
THICKNESS 0.073 *CONDUCTIVITY* 0.4167 *DENSITY* 166 *SPECIFIC-HEAT* 0.20 ..
CONCRETE *MATERIAL*
THICKNESS 0.633 *CONDUCTIVITY* 0.80 *DENSITY* 144 *SPECIFIC-HEAT* 0.14 ..
EXT-WALL-LAY *LAYER*
MATERIALS (STUCCO, CONCRETE) ..
EXT-WALL-CON *CONSTRUCTION*
LAYER = EXT-WALL-LAY ..
WEST_WALL *EXTERIOR WALL*
HEIGHT 10 *WIDTH* 35
X 10 *Y* 120 *Z* 0
CONSTRUCTION EXT-WALL-LAY ..

The first two inputs describe the thermal properties of stucco and concrete. The third composes these two materials into a layer, which in turn is referenced as a construction. The remaining inputs describe the dimensions of the wall, locates it in the building's coordinate system, and assigns it to the wall construction just mentioned.

Figure 6.2.9 shows a sample complete DOE-2 input file for a simple box-shaped house. For any DOE-2 simulation, the input file has to define not only the thermal characteristics and geometrical layout of the physical building, but also the hour-by-hour variations in the internal conditions and the operational characteristics and control of the HVAC system and plant. Key input items include the internal loads or heat gains produced by occupants, lights, and equipment, the thermostat settings and schedules for the HVAC system, and its full-load and part-load performance.

It is not the intention of this discussion to explain the DOE-2 input file in detail, but to give a general sense of what inputs are needed to do a DOE-2 simulation of a building. The "$" indicates comments which are concluded with another "$."

DOE-2 Outputs

A DOE-2 simulation can produce more than 20 verification and nearly 50 different output files. The verification reports summarize the input building parameters, such as the number, orientation, area, and U-values of walls and windows in the building, and useful primarily for checking that the input data have been correctly entered.

The output files in *Loads* give the peak and monthly heating and cooling loads of the building, and their breakdown by building component or heat flow path. Figure 6.2.10 shows a sample *Loads* output report giving the peak heating and cooling loads of a building, while Figure 6.2.11 shows the monthly breakdown of heating and cooling loads by building component. These loads are approximate, as they are calculated at an assumed constant zone temperature, and categorized as heating whenever there is a net heat loss from the building, and as cooling whenever there is a net heat gain to the building. These loads bear only approximate similarity to the actual heating and cooling loads computed in the *Systems* subprogram, which takes into account actual thermostat settings and deadband and free cooling through economizers or natural ventilation. These *Loads* reports, however, are still useful in showing the relative magnitude of heat flows through different parts of a building and identifying possible areas of concern.

The output files in *Systems* give, among others, the design specifications for the space conditioning system, the actual peak and seasonal heating and cooling loads imposed on the system, and the energy used to meet these loads. If the building is modeled with a central plant, most of the *System* loads will be passed to the plant, and only energy used for zone-level heating and cooling will appear in the *System* reports. Since the *System* simulation considers only the zone- or building-level loads, the load breakdowns by building component shown in the *Loads* report do not appear in the *Systems* reports.

Figure 6.2.12 shows a sample *System* report listing the design parameters of the space conditioning system. The capacities of the heating and cooling equipment and the fan system are determined in one of three ways — (1) specified by the user, (2) sized by DOE-2 based on design-day conditions specified by the user, or (3) sized by DOE-2 based on the peak loads from the *Loads* simulation. Because DOE-2 is a

```
INPUT LOADS ..
TITLE     LINE-1 *SINGLE FAMILY RESIDENCE*
          LINE-2 *SAMPLE DOE-2.1E INPUT FILE *  ..

ABORT                ERRORS ..
          DIAGNOSTIC          WARNINGS  ..
          RUN-PERIOD          JAN 1 2000 THRU DEC 31 2000 ..
          LOADS-REPORT        SUMMARY=(LS-C,LS-D)  ..

          BUILDING-LOCATION
                   SHIELDING-COEF=.19        $Site parameters for$
                   TERRAIN-PAR1=.85          $building obstructions$
                   TERRAIN-PAR2=.20          $and ground roughness$
                   WS-TERRAIN-PAR1=.85       $used in Sherman-Grimsrud$
                   WS-TERRAIN-PAR2=.20 ..    $infiltration method$

$ ------Schedule----- $
SCH-1     =DAY-SCHEDULE        (1) (.024)  (2) (.022)  (3,5) (.021)
                               (6) (.026)  (7) (.038)  (8) (.059)
                               (9) (.056) (10) (.060) (11) (.059)
                              (12) (.046) (13) (.045) (14) (.030)
                              (15) (.028) (16) (.031) (17) (.057)
                           (18,19) (.064) (20) (.052) (21) (.050)
                              (22) (.055) (23) (.044) (24) (.022)  ..
INT-LDS-1 =SCHEDULE            THRU DEC 31 (ALL) SCH-1 ..

$ -----Materials----- $
STUD-2    =MAT      TH=.4583 COND=.0667 DENS=32  S-H=.33 $2X6 Stud$ ..
R19WALL   =MAT      TH=.4583 COND=.0337 DENS=7.6 S-H=.23 $R-19 w/0.20 Stud$ ..
INSUL-1   =MAT      TH=.2917 COND=.0265 DENS=1.5 S-H=.2  $R-11 Insulation$ ..
INSUL-3   =MAT      TH=.7917 COND=.0264 DENS=1.5 S-H=.2  $R-30 Insulation$ ..
SHEATH-1  =MAT      TH=.0417 COND=.0382 DENS=22  S-H=.31 $1/2-in Sheathing$ ..
DRYWALL-1 =MAT      TH=.0417 COND=.0926 DENS=50  S-H=.26 $1/2-in Drywall$ ..
AL-SIDE-1 =MAT      TH=.0104 COND=.0171 DENS=170 S-H=.29 $Alum Siding$ ..
AS-SHG-1  =MAT      TH=.0208 COND=.0473 DENS=70  S-H=.30 $Asphalt Shingle$ ..
PLYW-1    =MAT      TH=.0417 COND=.0667 DENS=34  S-H=.29 $1/2-in Plywood$ ..
AT-AIR-1  =MAT      RES=1.3                              $Attic Air Space$ ..
EXP-POLY-1=MAT      TH=.0833 COND=.0177 DENS=2.2 S-H=.29 $1-in Polystyrene$ ..
EXP-POLY-2=MAT      TH=.1667 COND=.0177 DENS=2.2 S-H=.29 $2-in Polystyrene$ ..
CONCRETE-1=MAT      TH=.3333 COND=.7576 DENS=140 S-H=.2  $4-in concrete$ ..
CONCRETE-2=MAT      TH=.6667 COND=.7576 DENS=140 S-H=.2  $8-in Concrete$ ..
CARP/PAD-1=MAT      RES=2.08                             $Carpet and pad$ ..
DRYSOIL   =MAT      TH=.5    COND=.5    DENS=125 S-H=.2  $Dry Soil$ ..

$ ------Glazing----- $

WINDOW-1  =GLASS-TYPE        GLASS-TYPE-CODE=2002
                             FRAME-ABS=0.9
                             SPACER-TYPE-CODE=0 ..

$ ------Constructions----- $

IWLAY-1   =LAYERS           MAT=(AL-SIDE-1,SHEATH-1,R19WALL,DRYWALL-1) ..
INS-WL-1  =CONS             LAYERS=IWLAY-1  ROUGHNESS=3 ..
IRLAY-1   =LAYERS           MAT=(AS-SHG-1,PLYW-1,AT-AIR-1,INSUL-3,
                                DRYWALL-1)  I-F-R=.61 ..
INS-RF-1  =CONS             LAYERS=IRLAY-1  ABS=.86 ..
SRLAY-1   =LAYERS           MAT=(AS-SHG-1,PLYW-1,AT-AIR-1,INSUL-1,STUD-2,
                                 DRYWALL-1)  I-F-R=.61 ..
STUD-RF-1 =CONS             LAYERS=SRLAY-1  ABS=.86 ..
CRLAY-1  =LAYERS            MAT=(PLYW-1,PLYW-1,CARP/PAD-1)
                                 I-F-R=0.92 ..
```

FIGURE 6.2.9 Sample DOE-2 input file for single-family house (part 1).

```
CRL-1 =CONS                 LAYERS=CRLAY-1 ..
BWLAY-1   =LAYERS           MAT=(DRYSOIL,EXP-POLY-2,CONCRETE-2)
                                 I-F-R=0.68 ..
BASE-WL-1 =CONS             LAYERS=BWLAY-1 ..
DIRLAY-1  =LAYERS           MAT=(DRYSOIL) ..
DIRT-1    =CONS             LAYERS=DIRLAY-1 ..
DR-1      =CONS             U=.7181  ABS=.78  ROUGHNESS=4 ..

$ ------Space Description----- $
COND-1    =SPACE-CONDITIONS   SOURCE-SCHEDULE=INT-LDS-1
                              SOURCE-TYPE=PROCESS
                              SOURCE-BTU/HR=56000
                              SOURCE-SENSIBLE=1
                              SOURCE-LATENT=.225
                              INF-METHOD=S-G
                              HOR-LEAK-FRAC=.4
                              FRAC-LEAK-AREA=.0005
                              FLOOR-WEIGHT = 0
                              FURNITURE-TYPE=LIGHT
                              FURN-FRACTION=.29
                              FURN-WEIGHT=8
                              EQUIP-SCHEDULE=INT-LDS-1
                              EQUIPMENT-W/SQFT=2.51
                              EQUIP-SENSIBLE=0.0
                              EQUIP-LATENT=0.0 ..

$ -----Zone-1 - Crawl Space (unvented)---- $
CRAWL-1     =SPACE            A=1540  V=3080
                              INF-METHOD=S-G
                              FRAC-LEAK-AREA=.0005
                              FLOOR-WEIGHT=0
                              Z-TYPE=UNCONDITIONED  T=(65) ..
GROUND-1    =U-F              CONS=DIRT-1  A=1540  U-EFF=.196  ..

$ -----Zone-2 - House (conditioned)---- $
HOUSE-1     =SPACE            A=1540  V=12320  S-C=COND-1 ..
SOUTH-WL-1  =E-W              H=8  W=42  AZ=180  CONS=INS-WL-1 ..
SOUTH-WIN-1 =WI               W=1.7292  H=3.6667 G-T=WINDOW-1
                              FRAME-WIDTH=0.1667  X=12  Y=2.875  M=7 ..
S-DOOR-1    =DOOR             H=7  W=1.4285  CONS=DR-1  X=30.5 ..
EAST-WL-1   =E-W              H=8  W=36.667  AZ=90  X=42  Y=0
                              CONS=INS-WL-1 ..
EAST-WIN-1  =WI               LIKE SOUTH-WIN-1  ..
E-DOOR-1    =DOOR             LIKE S-DOOR-1 ..
NORTH-WL-1  =E-W              LIKE SOUTH-WL-1  X=42  Y=36.667  AZ=0 ..
NORTH-WIN-1 =WI               LIKE SOUTH-WIN-1  ..
N-DOOR-1    =DOOR             LIKE S-DOOR-1 ..
WEST-WL-1   =E-W              LIKE EAST-WL-1  X=0   Y=36.667  AZ=270 ..
WEST-WIN-1  =WI               LIKE SOUTH-WIN-1  ..
W-DOOR-1    =DOOR             LIKE S-DOOR-1 ..
SOUTH-RF-1  =ROOF             H=18.333  W=42  Z=8  AZ=180  TILT=22.62
                              M=.9  CONS=INS-RF-1 ..
SOUTH-RF-2  =ROOF             H=18.333  W=42  Z=8  AZ=180  TILT=22.62
                              M=.1  CONS=STUD-RF-1 ..
NORTH-RF-1  =ROOF             LIKE SOUTH-RF-1  X=42  Y=36.667  AZ=0 ..
NORTH-RF-2  =ROOF             LIKE SOUTH-RF-2  X=42  Y=36.667  AZ=0 ..
FLOOR-1     =I-W              CONS=CRL-1  H=36.667  W=42  Z=0  TILT=180
                              N-T=CRAWL-1  ..
END ..
COMPUTE LOADS ..
INPUT SYSTEMS ..
          SYSTEMS-REPORT      VERIFICATION=(SV-A)
                              SUMMARY=(SS-A,SS-H) ..
```

FIGURE 6.2.9 (continued) Sample DOE-2 input file for single-family house (part 2).

```
                      $ ------Schedules----- $
HEAT-1     =SCHEDULE        THRU DEC 31 (ALL)  (1,6)  (70)  (7,24)  (70) ..

COOL-1     =SCHEDULE        THRU DEC 31 (ALL)  (1,24)  (78) ..
VENT-1     =SCHEDULE        THRU DEC 31 (ALL)  (1,24)  (-1) ..
VTEMP-1    =SCHEDULE        THRU MAY 14 (ALL)  (1,24)  (-4)
                            THRU SEP 30 (ALL)  (1,24)  (-4)
                            THRU DEC 31 (ALL)  (1,24)  (-4) ..
                                 $Natural ventilation type - enthalpic$
                                  $temp. based on previous 4 day's loads$
VOPEN-1    =SCHEDULE        THRU DEC 31 (ALL)  (1,6)   (0)
                                               (7,23)  (1)
                                               (24)    (0) ..

HOUSE-1    =ZONE               DESIGN-HEAT-T=70
                               DESIGN-COOL-T=78
                               ZONE-TYPE=CONDITIONED
                               THERMOSTAT-TYPE=TWO-POSITION
                               HEAT-TEMP-SCH=HEAT-1
                               COOL-TEMP-SCH=COOL-1 ..

CRAWL-1    =ZONE               ZONE-TYPE=UNCONDITIONED ..

              $ ------Air Conditioner and Furnace parameters----- $
AIR-1      =SYSTEM-AIR         VENT-METHOD=S-G
                               FRAC-VENT-AREA=.011
                               MAX-VENT-RATE=20
                               NATURAL-VENT-SCH=VENT-1
                               VENT-TEMP-SCH=VTEMP-1
                               OPEN-VENT-SCH=VOPEN-1 ..
SYS-1      =SYSTEM             SYSTEM-TYPE=RESYS
                               ZONE-NAMES=(HOUSE-1,CRAWL-1)
                               SYSTEM-AIR=AIR-1
                               FURNACE-HIR=1.42     $Eff.=0.78 +10% duct losses
                               COOLING-EIR=.370     $SEER=10, COP=3.0 +10% duct$
                               MAX-SUPPLY-T=110
                               MIN-SUPPLY-T=55 ..
END ..
COMPUTE SYSTEMS ..
STOP ..
```

FIGURE 6.2.9 (continued) Sample DOE-2 input file for single-family house (part 3).

dynamic simulation that takes into account the building's thermal inertia and the noncoincidence of peak load components, the design parameters from either the second or third procedures tend to be small compared to those derived from standard engineering sizing calculations. Although "right sizing" can lead to higher operational efficiencies and capital cost savings, the designer should evaluate whether the building and weather files contain the appropriate design conditions. There is an optional input in the *System* subprogram for a SIZING-RATIO if a safety factor is desired.

Figure 6.2.13 shows a sample *System* report of the heating, cooling, and electrical loads by month, as well as the monthly peak loads and the coincident outdoor air conditions. In contrast to the approximate loads shown in the *Loads* report, these are the true heating and cooling loads being met by the system. Since the example shown is for a residential house, there is no central plant and the heating gas and cooling electricity energy uses appear on a *System* report shown in Figure 6.2.14. For large buildings with central plants, this *System* report would show only the zone-level energy use, with additional *Plant* output reports showing the monthly and peak energy uses of plant equipment such as boilers, chillers, cooling towers, and pumps.

Figure 6.2.15 shows the summary BEPS (Building Energy Performance Summary) report that gives the annual energy used by the building broken down by major end uses. In addition to these summary reports, DOE-2 also allows users to select from several hundred hourly variables at the global and subprogram levels and print out hourly reports for a selected time period in either ASCII or binary

```
SINGLE FAMILY RESIDENCE    SAMPLE DOE-2.1E INPUT FILE    DOE-2.1E-097  Tue May  2 04:18:59
REPORT- LS-C BUILDING PEAK LOAD COMPONENTS                             WEATHER FILE- STERLING, VA
WYEC2
-----------------------------------------------------------------------------------------------
-

 *** BUILDING ***


                     FLOOR  AREA      1540  SQFT       143   M2
                     VOLUME          12320  CUFT       349   M3

                                       COOLING  LOAD                       HEATING  LOAD
                                   ==========================
==========================
     TIME                                JUL 24   5PM                       JAN   5  5AM

     DRY-BULB TEMP                93 F              34 C           18 F              -8 C
     WET-BULB TEMP                82 F              28 C           14 F             -10 C
     TOT HORIZONTAL SOLAR RAD    199 BTU/H.SQFT    627 W/M2         0 BTU/H.SQFT      0
W/M2
     WINDSPEED AT SPACE          6.3 KTS           3.2 M/S       13.1 KTS           6.8 M/S
     CLOUD AMOUNT 0(CLEAR)-10      5                                 6


                              SENSIBLE           LATENT                      SENSIBLE
                        (KBTU/H)     ( KW )  (KBTU/H)   ( KW )          (KBTU/H)   ( KW )
                        --------     ------  --------   ------          --------   --------
   WALL CONDUCTION        2.039      0.597     0.000    0.000            -2.722     -0.797
   ROOF CONDUCTION        3.391      0.993     0.000    0.000            -2.226     -0.652
   WINDOW GLASS+FRM COND  4.352      1.275     0.000    0.000            -6.086     -1.783
   WINDOW GLASS SOLAR     8.232      2.412     0.000    0.000             0.125      0.037
   DOOR CONDUCTION        0.985      0.288     0.000    0.000            -1.193     -0.349
   INTERNAL SURFACE COND -1.419     -0.416     0.000    0.000            -1.419     -0.416
   UNDERGROUND SURF COND  0.000      0.000     0.000    0.000             0.000      0.000
   OCCUPANTS TO SPACE     0.000      0.000     0.000    0.000             0.000      0.000
   LIGHT     TO SPACE     0.000      0.000     0.000    0.000             0.000      0.000
   EQUIPMENT TO SPACE     0.000      0.000     0.000    0.000             0.000      0.000
   PROCESS   TO SPACE     2.602      0.762     0.718    0.210             1.197      0.351
   INFILTRATION           2.907      0.852     6.741    1.975           -12.978     -3.803
                      --------   --------   --------   ------          --------   --------
   TOTAL                 23.088      6.765     7.459    2.186           -25.301     -7.413
   TOTAL / AREA           0.015      0.047     0.005    0.015            -0.016     -0.052

   TOTAL LOAD            30.547 KBTU/H        8.950   KW         -25.301 KBTU/H       -7.413   KW
   TOTAL LOAD / AREA     19.84  BTU/H.SQFT   62.559   W/M2        16.430 BTU/H.SQFT   51.816
W/M2


                      ****************************************************************
                      *                                                              *
                      *  NOTE  1)THE ABOVE LOADS EXCLUDE OUTSIDE VENTILATION AIR     *
                      *  ----    LOADS                                               *
                      *        2)TIMES GIVEN IN STANDARD TIME FOR THE LOCATION       *
                      *          IN CONSIDERATION                                    *
                      *        3)THE ABOVE LOADS ARE CALCULATED ASSUMING A           *
                      *          CONSTANT INDOOR SPACE TEMPERATURE                   *
                      *                                                              *
                      ****************************************************************
```

FIGURE 6.2.10 Loads output report on peak load components.

format. These are useful for providing a detailed look at the energy performance of the building, space-conditioning system, or control strategy on an hourly level. For example, Figure 6.2.16 shows a plot of hourly DOE-2 results for the conduction heat gains through the wall and window and the solar heat gain through the window of a typical office room over several days.

Accuracy of the DOE-2 Program

Because of the amount of and flexibility in the input data needed to do an hourly simulation with programs such as DOE-2, it is difficult to distinguish the accuracy of the program algorithms from the accuracy of the input data. In typical engineering applications, as distinguished from a research project, experienced users are able to achieve accuracies of 10–12% in monthly peak demand, 8–10% in monthly energy use, 10–15% in annual peak demand, and 3–5% in annual energy use for large commercial

SINGLE FAMILY RESIDENCE SAMPLE DOE-2.1E INPUT FILE DOE-2.1E-097 Tue May 2 04:18:59 2000LDL RUN 1

REPORT- LS-D BUILDING MONTHLY LOADS SUMMARY WEATHER FILE- STERLING, VA WYEC2

	C O O L I N G						H E A T I N G						E L E C	
MONTH	COOLING ENERGY (MBTU)	TIME OF MAX DY	TIME OF MAX HR	DRY-BULB TEMP	WET-BULB TEMP	MAXIMUM COOLING LOAD (KBTU/HR)	HEATING ENERGY (MBTU)	TIME OF MAX DY	TIME OF MAX HR	DRY-BULB TEMP	WET-BULB TEMP	MAXIMUM HEATING LOAD (KBTU/HR)	ELEC-TRICAL ENERGY (KWH)	MAXIMUM ELEC LOAD (KW)
JAN	0.20217	25	15	63.F	48.F	9.638	-7.324	5	5	18.F	14.F	-25.301	119.	0.247
FEB	0.22431	5	15	63.F	44.F	9.304	-5.675	11	6	26.F	25.F	-19.151	108.	0.247
MAR	0.93053	20	16	71.F	48.F	15.963	-4.504	22	6	28.F	24.F	-18.527	119.	0.247
APR	2.42814	27	17	86.F	64.F	21.600	-2.081	16	3	36.F	31.F	-13.724	115.	0.247
MAY	4.01552	1	14	94.F	71.F	20.610	-0.874	7	4	46.F	45.F	-9.702	119.	0.247
JUN	5.74028	27	17	85.F	64.F	20.791	-0.093	10	5	57.F	52.F	-3.581	115.	0.247
JUL	6.50512	24	16	93.F	82.F	23.088	-0.041	10	5	58.F	55.F	-3.077	119.	0.247
AUG	5.93819	16	16	93.F	73.F	23.080	-0.043	14	6	58.F	51.F	-2.902	119.	0.247
SEP	4.18373	1	16	91.F	72.F	22.172	-0.362	30	5	49.F	46.F	-6.790	115.	0.247
OCT	2.34292	10	14	81.F	62.F	17.284	-1.650	28	5	37.F	35.F	-10.594	119.	0.247
NOV	0.71645	21	13	63.F	46.F	10.815	-3.427	30	2	37.F	30.F	-14.891	115.	0.247
DEC	0.15903	3	15	57.F	46.F	8.763	-6.270	24	24	31.F	26.F	-17.740	119.	0.247
TOTAL	33.386						-32.344						1404.	
MAX						23.088						-25.301		0.247

FIGURE 6.2.11 Loads output report on monthly load components.

REPORT- SV-A SYSTEM DESIGN PARAMETERS SYS-1 WEATHER FILE- STERLING, VA WYEC2

SYSTEM NAME	SYSTEM TYPE	ALTITUDE MULTIPLIER	FLOOR AREA (SQFT)	MAX PEOPLE
SYS-1	RESYS	1.000	3080.0	0.

SUPPLY FAN (CFM)	ELEC (KW)	DELTA-T (F)	RETURN FAN (CFM)	ELEC (KW)	DELTA-T (F)	OUTSIDE AIR RATIO	COOLING CAPACITY (KBTU/HR)	SENSIBLE (SHR)	HEATING CAPACITY (KBTU/HR)	COOLING EIR (BTU/BTU)	HEATING EIR (BTU/BTU)
929.	0.119	0.4	0.	0.000	0.0	0.000	32.018	0.609	-39.709	0.37	0.37

ZONE NAME	SUPPLY FLOW (CFM)	EXHAUST FLOW (CFM)	FAN (KW)	MINIMUM FLOW RATIO	OUTSIDE AIR FLOW (CFM)	COOLING CAPACITY (KBTU/HR)	SENSIBLE (SHR)	EXTRACTION RATE (KBTU/HR)	HEATING CAPACITY (KBTU/HR)	ADDITION RATE (KBTU/HR)	MULTIPLIER
HOUSE-1	929.	0.	0.000	1.000	0.	0.00	0.00	23.09	0.00	-40.15	1.0
CRAWL-1	0.	0.	0.000	0.000	0.	0.00	0.00	0.00	0.00	0.00	1.0

FIGURE 6.2.12 System output report on system design parameters.

SINGLE FAMILY RESIDENCE SAMPLE DOE-2.1E INPUT FILE DOE-2.1E-097 Tue May 2 04:18:59 2000SDL RUN 1
REPORT- SS-A SYSTEM MONTHLY LOADS SUMMARY FOR SYS-1 WEATHER FILE- STERLING, VA WYEC2

	- - - - - - - - C O O L I N G - - - - - - - -						- - - - - - - - H E A T I N G - - - - - - - -						- - - E L E C - - -	
MONTH	COOLING ENERGY (MBTU)	TIME OF MAX DY	TIME OF MAX HR	DRY-BULB TEMP	WET-BULB TEMP	MAXIMUM COOLING LOAD (KBTU/HR)	HEATING ENERGY (MBTU)	TIME OF MAX DY	TIME OF MAX HR	DRY-BULB TEMP	WET-BULB TEMP	MAXIMUM HEATING LOAD (KBTU/HR)	ELEC-TRICAL ENERGY (KWH)	MAXIMUM ELEC LOAD (KW)
JAN	0.00000					0.000	-9.098	5	5	18.F	14.F	-28.900	180.	0.368
FEB	0.00000					0.000	-7.404	12	2	24.F	20.F	-22.876	162.	0.352
MAR	0.01458	25	16	76.F	53.F	6.497	-5.896	22	6	28.F	24.F	-21.582	167.	1.044
APR	0.54407	28	18	84.F	67.F	17.291	-2.619	16	4	36.F	31.F	-16.186	210.	2.224
MAY	1.00029	31	17	86.F	68.F	16.767	-0.877	7	5	46.F	45.F	-11.256	258.	2.296
JUN	3.44213	24	17	90.F	76.F	20.775	-0.027	10	6	57.F	52.F	-2.876	554.	2.628
JUL	5.51768	24	17	93.F	82.F	26.914	-0.008	9	6	59.F	56.F	-1.826	820.	3.307
AUG	4.99961	29	17	91.F	76.F	24.810	-0.002	14	7	58.F	51.F	-1.036	751.	3.069
SEP	2.12490	9	17	88.F	74.F	23.646	-0.159	30	6	49.F	46.F	-5.932	384.	2.868
OCT	0.50496	10	15	81.F	62.F	12.686	-1.080	28	6	37.F	35.F	-9.968	196.	1.630
NOV	0.00000					0.000	-3.381	30	2	37.F	30.F	-16.186	147.	0.335
DEC	0.00000					0.000	-7.341	24	24	31.F	26.F	-19.953	175.	0.341
TOTAL	18.148						-37.892						4004.	
MAX						26.914						-28.900		3.307

FIGURE 6.2.13 System output report on system monthly and peak loads.

SINGLE FAMILY RESIDENCE NFRC DOE-2.1E INPUT FILE DOE-2.1E-091 Wed May 3 02:49:02 2000SDL RUN 1
REPORT- SS-H SYSTEM MONTHLY LOADS SUMMARY FOR SYS-1 WEATHER FILE- STERLING, VA WYEC2

	--FAN ELEC---		--FUEL HEAT--		--FUEL COOL--		-ELEC HEAT--		-ELEC COOL--	
MONTH	FAN ENERGY (KWH)	MAXIMUM FAN LOAD (KW)	GAS OIL ENERGY (MBTU)	MAXIMUM GAS OIL LOAD (KBTU/HR)	GAS OIL ENERGY (MBTU)	MAXIMUM GAS OIL LOAD (KBTU/HR)	ELECTRIC ENERGY (KWH)	MAXIMUM ELECTRIC LOAD (KW)	ELECTRIC ENERGY (KWH)	MAXIMUM ELECTRIC LOAD (KW)
JAN	27.	0.087	14.704	42.802	0.000	0.000	0.	0.000	33.	0.050
FEB	22.	0.069	12.141	34.823	0.000	0.000	0.	0.000	32.	0.050
MAR	18.	0.065	9.956	33.064	0.000	0.000	0.	0.000	30.	0.891
APR	10.	0.081	4.900	25.616	0.000	0.000	0.	0.000	84.	1.900
MAY	7.	0.076	2.119	18.602	0.000	0.000	0.	0.000	132.	2.000
JUN	16.	0.090	0.635	6.235	0.000	0.000	0.	0.000	423.	2.317
JUL	25.	0.115	0.615	4.639	0.000	0.000	0.	0.000	676.	2.972
AUG	22.	0.110	0.600	3.427	0.000	0.000	0.	0.000	610.	2.738
SEP	10.	0.104	0.894	10.801	0.000	0.000	0.	0.000	258.	2.543
OCT	6.	0.063	2.493	17.031	0.000	0.000	0.	0.000	71.	1.459
NOV	10.	0.049	6.139	25.611	0.000	0.000	0.	0.000	21.	0.050
DEC	22.	0.060	12.229	30.850	0.000	0.000	0.	0.000	34.	0.050
TOTAL	196.		67.425		0.000		0.		2405.	
MAX		0.115		42.802		0.000		0.000		2.972

FIGURE 6.2.14 System output report on system monthly and peak energy use.

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SINGLE FAMILY RESIDENCE                 NFRC DOE-2.1E INPUT FILE                DOE-2.1E-091  Wed May  3 02:49:02 2000PDL RUN  1
REPORT- BEPS  BUILDING ENERGY PERFORMANCE SUMMARY                                          WEATHER FILE- STERLING, VA  WYEC2
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                                  ENERGY TYPE:   ELECTRICITY   NATURAL-GAS
                                  UNITS: MBTU

                               CATEGORY OF USE
                               ---------------
                                  MISC EQUIPMT          4.8           0.0
                                    SPACE HEAT          0.0          67.4
                                    SPACE COOL          7.6           0.0
                                  PUMPS & MISC          0.6           0.0
                                     VENT FANS          0.7           0.0
                                                 ----------    ----------
                                         TOTAL         13.7          67.4

                   TOTAL SITE ENERGY        81.09 MBTU     52.7 KBTU/SQFT-YR GROSS-AREA     52.7 KBTU/SQFT-YR NET-AREA
                   TOTAL SOURCE ENERGY     108.43 MBTU     70.4 KBTU/SQFT-YR GROSS-AREA     70.4 KBTU/SQFT-YR NET-AREA

                   PERCENT OF HOURS ANY SYSTEM ZONE OUTSIDE OF THROTTLING RANGE =  0.0
                   PERCENT OF HOURS ANY PLANT LOAD NOT SATISFIED                =  0.0
                   NOTE:  ENERGY IS APPORTIONED HOURLY TO ALL END-USE CATEGORIES.
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FIGURE 6.2.15 Plant output report on building energy performance summary.