Development of the Residential Load Factor Method for Heating and Cooling Load Calculations

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ABSTRACT

The recent ASHRAE project, "Updating the ASHRAE/ACCA Residential Heating and Cooling Load Calculation Procedures and Data" (RP-1199), developed two new residential loads calculation procedures: residential heat balance (RHB), a detailed heat balance method that requires computer implementation, and residential load factor (RLF), a simplified procedure that is hand tractable and suitable for spreadsheet implementation. This paper describes RLF and its development. The form of RLF resembles prior methods. However, the sensible cooling load procedure was derived using linear regression to find relationships between design conditions, building characteristics, and peak cooling load predicted by RHB. This eliminated the need for semi-empirical adjustments, such as averaging, that have been used in the development of other methods. Results comparing RLF to RHB are presented. The RLF heating load calculation is also described; it uses the traditional UAΔT *formulation except for improvements to procedures for infiltration leakage rate and ground (slab and basement) losses.*

INTRODUCTION

The research project, "Updating the ASHRAE/ACCA Residential Heating and Cooling Load Calculation Procedures and Data" (RP-1199), had two primary products. First, a new fundamental residential heating and cooling load calculation method was developed and tested. This procedure, called the residential heat balance (RHB) method, is based on heat balance first principles as described by Pedersen et al. (1997, 1998) and ASHRAE (2001). RHB is documented by Barnaby et al. (2005). It uses a computationally intensive 24-hour design-day simulation that is practical only when implemented in software. Because of its fundamental approach, RHB can be applied with few restrictions to arbitrarily complex residential buildings, including those with large fenestration areas, novel construction features, or having non-summer peaks.

The ResHB computer program, developed as part of RP-1199, implements the RHB method as described in Barnaby et al. (2004). ResHB is a batch-driven FORTRAN-90 application derived from the ASHRAE Loads Toolkit (Pedersen et al. 2001) that operates on Windows-based PCs. Several key ResHB features are noted here. First, ResHB models room temperature swing: in addition to the standard fixed-setpoint capability, ResHB can find the sensible cooling extraction rate that results in a specified temperature swing above the thermostat setpoint. Second, ResHB incorporates the updated models identified in RP-1199 as appropriate for residential loads calculation. Third, ResHB is multi-room and multi-zone, allowing application to real buildings as well as simple test cases. Finally, ResHB can model typical residential master-slave control, where a thermostat in one room controls the cooling delivery in another, with resulting imperfect temperature control in the slave room.

The second product of RP-1199 is a simpler procedure, designated "residential load factor" (RLF) method. RLF is tractable by hand or can be straightforwardly implemented using spreadsheet software. This simplification is achieved at the expense of generality—RLF is applicable only to conventionally constructed residences with typical space-conditioning requirements. The procedures and data required to use RLF are presented in the "Residential Heating and Cooling Loads Calculation" chapter of the *2005 ASHRAE Handbook—Fundamentals* (ASHRAE 2005).

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This paper discusses the design of RLF and documents the methodology used in its development. Some testing results are also presented. While RLF includes both cooling and heating load procedures, the heating calculations rely on the traditional $UA\Delta T$ model that has proven satisfactory for decades. Improvements have been introduced in relation infiltration leakage rate and to ground heat loss.

The RLF cooling procedure resembles and builds upon prior methods but was developed using a linear regression approach that avoids some semi-empirical derivations used in the past. Prior methods have been published by the Air-Conditioning Contractors of America (ACCA), including the widely used *Manual J*, seventh edition (ACCA 1986) and *Manual J*, eighth edition (ACCA 2003). The 1989-2001 editions of the *ASHRAE Handbook—Fundamentals* included a method based on 342-RP (McQuiston 1984). Canadian Standard CAN/CSA-F280-M90 (HRAI 1996; CSA 1990) specifies a cooling method also based on 342-RP and a heating procedure that includes enhanced ground loss calculations.

RLF COOLING LOAD CALCULATION

The RLF cooling load calculation is based on the idea of independent load components, as are prior simplified methods. The load contributions from various sources are separately evaluated and then summed. The following sections summarize the method, showing both sensible and latent components as applicable. Later sections document the derivation of the component models and coefficients.

In RLF, surfaces have associated load factors (LFs) or load contribution per unit area. These are designated CFs for cooling and HFs for heating. For the most part, HF values are simply $U\Delta T$. CF values depend on surface construction, climate, and, in some cases, surface orientation, solar absorptance, or other characteristics. Each unique LF needs to be evaluated once for a given set of site and construction conditions and then is applied repeatedly to building elements of the same type. This two-step process is convenient for hand or spreadsheet application. Note that LFs are the functional equivalent of *Manual J*'s heat transfer multipliers (HTMs) but are derived differently and in general do not have the same values.

Total Cooling Load

$$q_s = \sum A_i \cdot CF_i + q_{vi,s} + q_{ig,s} \quad (1)$$

$$q_l = q_{vi,l} + q_{ig,l} \quad (2)$$

where

q_s = sensible cooling load, W (Btu/h)
q_l = latent cooling load, W (Btu/h)
A_i = area of *i*th surface, m^2 (ft^2)
CF_i = cooling factor of *i*th surface, W/m^2 ($Btu/h \cdot ft^2$)

Opaque Surfaces

The cooling load per unit area of opaque walls, ceilings, and non-slab floors is calculated as follows:

$$CF_{opq} = U \cdot (OF_t \cdot \Delta T + OF_b + OF_r \cdot DR) \quad (3)$$

where

CF_{opq} = opaque surface cooling factor, W/m^2 ($Btu/h \cdot ft^2$)
U = construction U-factor, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot °F$)
ΔT = design dry-bulb temperature difference (outdoor – indoor), K (°F)
DR = daily range of outdoor dry-bulb temperature, K (°F)
OF_t, OF_b, OF_r = coefficients from Table 1

Slab floors produce a slight reduction in cooling load, as follows:

$$CF_{slab} = 1.6 - 1.4 \cdot h_{srf} \quad (4a)$$

$$CF_{slab} = 0.51 - 2.5 \cdot h_{srf} \quad (4b)$$

where

CF_{slab} = slab cooling factor, W/m^2 ($Btu/h \cdot ft^2$)
h_{srf} = effective surface conductance, including resistance of slab-covering material such as carpet, $W/m^2 \cdot K$ ($Btu/h \cdot ft^2 \cdot °F$); $1/(R_{cvr} + 0.12)$ $W/m^2 \cdot K$ or $1/(R_{cvr} + 0.68)$ $Btu/h \cdot ft^2 \cdot °F$

Table 1. Opaque Surface Coefficients

Surface Type	Construction	OF_t	OF_b	OF_r
Ceiling or knee wall adjacent to vented attic	Wood frame	0.62	$14.1 \cdot \alpha_{roof} - 4.3$ ($25.4 \cdot \alpha_{roof} - 7.7$)	–0.23
Ceiling/roof assembly	Wood frame	1	$39 \cdot \alpha_{roof} - 6.8$ ($70.2 \cdot \alpha_{roof} - 12.2$)	–0.42
Wall	Wood frame	1	7.9 (14.2)	–0.34
Floor over ambient	Wood frame	1	0	–0.10
Floor over crawlspace	Wood frame	0.32	0	–0.46

α_{roof} = roof solar absorptance

Table 2. Fenestration Coefficients

Exposure	FFs
N	0.17
NE	0.09
E	0.17
SE	0.25
S	0.45
SW	0.54
W	0.48
NW	0.34
Horiz	0.66

Fenestration

Fenestration cooling factors are calculated as follows:

$$CF_{fen} = U \cdot (\Delta T - 0.49 \cdot DR) + FF_s \cdot PXI \cdot SHGC \cdot IAC \quad (5)$$

where

CF_{fen} = fenestration cooling factor, W/m^2 (Btu/h·ft^2)
U = fenestration NFRC heating U-factor, W/m^2·K (Btu/h·ft^2·°F)
DR = daily range of outdoor dry-bulb temperature, K (°F)
ΔT = cooling design temperature difference, K (°F)
FF_s = load factor (see Table 2)
PXI = peak exterior irradiance, including shading modifications (see below), W/m^2 (Btu/h·ft^2)
$SHGC$ = fenestration rated or estimated NFRC solar heat gain coefficient
IAC = interior shading attenuation coefficient

Peak exterior irradiance (PXI) is the hourly maximum solar gain incident on the surface.

$$PXI = T_x E_t \qquad \text{(unshaded)} \qquad (6)$$

$$PXI = T_x(E_d + (1 - F_{shd})E_D) \qquad \text{(shaded)} \qquad (7)$$

where

PXI = peak exterior irradiance for exposure, W/m^2 (Btu/h·ft^2)
E_t, E_d, E_D = peak total, diffuse, and direct irradiance for exposure, W/m^2 (Btu/h·ft^2)
T_x = transmission of exterior attachment (see Table 4)
F_{shd} = fraction of fenestration shaded by permanent overhangs, fins, or environmental obstacles

For horizontal or vertical surfaces, irradiance values can be obtained from Table 3 for primary exposures or Algorithm 1 for any exposure. Skylights with slope less than 30° from horizontal should be treated as horizontal. Steeper slopes, other than vertical, are not supported by the RLF method.

Algorithm 1. Exterior irradiance
Horizontal surfaces

$$E_t = 970 + 6.2L - 0.16L^2 \qquad E_d = MIN(E_t, 124)$$
$$E_D = E_t - E_d$$

Vertical surfaces

$$\Psi = \left|\frac{\psi}{180}\right| \qquad \text{(normalized exposure)}$$

$$E_t = 462.2 + 1625\Psi - 6183\Psi^3 + 3869\Psi^4 + 32.38\Psi L + 0.3237\Psi L^2 - 12.56L - 0.8959L^2 + \frac{1.040L^2}{\Psi + 1}$$

$$E_d = MIN\left(E_t, 392.1 - 138.6\Psi + 2.107\Psi L - \frac{121\sqrt[4]{L}}{\Psi + 1}\right)$$

$$E_D = E_t - E_d$$

where

E_t, E_d, E_D = peak hourly total, diffuse, and direct irradiance, W/m^2 (multiply by 0.317 to convert to Btu/h·ft^2)
L = site latitude, °N or °S
ψ = exposure (surface azimuth), ° from south (–180 to +180)

The shaded fraction, F_{shd}, can be taken as 0 for fenestration in full sun and 1 for any fenestration that is shaded by adjacent structures or other obstacles during peak hours. F_{shd} for simple overhang configurations can be calculated as follows (more complex configurations should be analyzed with the RHB method):

$$F_{shd} = MIN\left(1, MAX\left(0, \frac{SLF \cdot D_{oh} - X_{oh}}{H}\right)\right) \qquad (8)$$

where

SLF = shade line factor from Table 5
D_{oh} = depth of overhang (from plane of fenestration), m (ft)
X_{oh} = vertical distance from top of fenestration to overhang, m (ft)
H = height of fenestration, m (ft)

The shade line factor (SLF) is the ratio of the distance a shadow falls beneath the edge of an overhang to the width of the overhang (Table 5). Therefore, the shade line equals the SLF times the overhang depth. The tabulated values are the average of the shade line values for 5 h of maximum solar intensity on August 1 on each wall exposure shown. Windows facing north, northeast, and northwest are not effectively protected by roof overhangs; in most cases, they should not be considered shaded.

Table 3. Exterior Irradiance (W/m²)

Exp		Latitude (°N or °S)								
		20	25	30	35	40	45	50	55	60
N	E_D	132	117	106	101	103	110	124	145	172
	E_d	136	122	109	98	88	79	70	63	55
	E_t	269	238	215	199	190	189	194	207	227
NE/NW	E_D	541	532	522	511	501	490	480	470	461
	E_d	163	154	147	140	135	130	126	123	120
	E_t	704	686	668	652	636	621	606	593	580
E/W	E_D	627	640	650	657	662	663	662	659	653
	E_d	173	169	166	163	162	161	161	161	162
	E_t	800	809	816	821	824	825	823	820	815
SE/SW	E_D	334	380	422	460	494	525	553	577	598
	E_d	174	173	174	175	177	180	183	187	191
	E_t	508	553	595	635	672	705	736	764	788
S	E_D	0	65	146	223	297	368	436	501	563
	E_d	149	171	175	180	186	192	198	205	212
	E^t	149	236	321	403	482	559	634	705	774
Hor	E_D	906	901	888	867	838	801	756	703	642
	E_d	124	124	124	124	124	124	124	124	124
	E_t	1030	1025	1012	991	962	925	880	827	766

Note: multiply value by 0.317 to convert to Btu/h·ft²

Table 4. Exterior Attachment Transmission

Attachment	Tx
Exterior insect screen	0.6
Shade screen	Manufacturer SC value, typically 0.4 to 0.6

Note: see Brunger et al. 1999 re: insect screens

Ventilation and Infiltration

Infiltration airflow is calculated as follows:

$$Q_{inf} = \frac{A_L}{1000} \cdot \left[I_0 + H \cdot |\Delta T| \cdot \left(I_1 + I_2 \cdot \frac{A_{L,flue}}{A_L} \right) \right] \qquad (9)$$

Q_{inf} = infiltration airflow rate, L/s (cfm)

A_L = building effective leakage area (including flue) at 4 Pa assuming $C_D = 1$, cm² (in.²)

$I_0 - I_2$ = coefficients, as follows:

	Cooling Windspeed— 3.4 m/s (7.5 mph)	Heating Windspeed— 6.7 m/s (15 mph)
I_0	25 (343)	51 (698)
I_1	0.38 (.88)	0.35 (.81)
I_2	0.12 (.28)	0.23 (.53)

H = building average stack height, m (ft) (approximately 2.5 m [8 ft] per story)

ΔT = indoor-outdoor temperature difference, K (°F)

$A_{L,flue}$ = flue effective leakage area at 4 Pa assuming $C_D = 1$, cm² (in.²)

The ventilation airflow rate is determined according to the installed or planned ventilation equipment that is expected to be operating at design conditions. Generally, intermittently

Table 5. Shade Line Factors (SLF)

Window Exposure	Latitude, °N						
	24	32	36	40	44	48	52
East	0.8	0.8	0.8	0.8	0.8	0.8	0.8
SE	1.8	1.6	1.4	1.3	1.1	1.0	0.9
South	9.2	5.0	3.4	2.6	2.1	1.8	1.5
SW	1.8	1.6	1.4	1.3	1.1	1.0	0.9
West	0.8	0.8	0.8	0.8	0.8	0.8	0.8

Note: Shadow length below the overhang equals the shade line factor times the overhang depth.

operated exhaust fans are not included. Overall supply and exhaust flow rates are determined and divided into "balanced" and "unbalanced" components and combined with infiltration.

$$Q_{bal} = MIN(Q_{sup}, Q_{exh}) \tag{10}$$

$$Q_{unbal} = MAX(Q_{sup}, Q_{exh}) - Q_{bal} \tag{11}$$

$$Q_{vi} = MIN(Q_{unbal}, Q_{inf} + 0.5 \cdot Q_{unbal}) \tag{12}$$

where

Q_{bal} = balanced ventilation airflow rate, L/s (cfm)
Q_{sup} = total ventilation supply airflow rate, L/s (cfm)
Q_{exh} = total ventilation exhaust airflow rate (including any combustion air requirements), L/s (cfm)
Q_{unbal} = unbalanced airflow rate, L/s (cfm)
Q_{vi} = combined infiltration/ventilation flow rate (not including balanced component), L/s (cfm)

Note that unbalanced duct leakage can produce additional pressurization or depressurization. This effect is included in distribution losses, discussed below.

The cooling (or heating) load due to ventilation and infiltration is calculated as follows, taking into account the effects of heat/energy recovery ventilation (HRV/ERV) equipment:

$$q_{vi,s} = C_s \cdot (Q_{vi} + (1 - \varepsilon_s) \cdot Q_{bal,hr} + Q_{bal,oth}) \cdot \Delta T \tag{13}$$

$$q_{vi,l} = C_l \cdot (Q_{vi} + Q_{bal,oth}) \cdot \Delta W \qquad \text{(no HRV/ERV)} \tag{14}$$

$$q_{vi,t} = C_t \cdot (Q_{vi} + (1 - \varepsilon_t) \cdot Q_{bal,hr} + Q_{bal,oth}) \cdot \Delta h \tag{15}$$

$$q_{vi,l} = q_{vi,t} - q_{vi,s} \tag{16}$$

where

$q_{vi,s}$ = sensible ventilation/infiltration load, W (Btu/h)
C_s = air sensible heat factor, 1.23 W/(L/s)·K (1.1 Btu/h·cfm·°F) at sea level
ε_s = HRV/ERV sensible effectiveness
$Q_{bal,hr}$ = balanced ventilation flow rate supplied via HRV/ERV equipment, L/s (cfm)
$Q_{bal,oth}$ = other balanced ventilation supply airflow rate, L/s (cfm)
ΔT = indoor-outdoor temperature difference, K (°F)
$q_{vi,l}$ = latent ventilation/infiltration load, W (Btu/h)
C_l = air latent heat factor, 3010 W/(L/s) (4840 Btu/h-cfm) at sea level
ΔW = indoor-outdoor humidity ratio difference
$q_{vi,t}$ = total ventilation/infiltration load, W (Btu/h)
C_t = air total heat factor, 1.2 W/(L/s)·(kJ/kg) (4.5 Btu/h·cfm·(Btu/lb)) at sea level
ε_t = HRV/ERV total effectiveness
Δh = indoor-outdoor enthalpy difference, kJ/kg (Btu/lb)

Internal Gain

The contributions of internal gains to peak sensible and latent loads are:

$$q_{ig,s} = G_{0,s} + G_{cf,s} \cdot A_{cf} + G_{oc,s} \cdot N_{oc} \tag{17}$$

$$q_{ig,l} = G_{0,l} + G_{cf,l} \cdot A_{cf} + G_{oc,l} \cdot N_{oc} \tag{18}$$

where

$q_{ig,s}$ = sensible cooling load due to internal gains, W (Btu/h)
$q_{ig,l}$ = latent cooling load due to internal gains, W (Btu/h)
G_x = coefficients, as follows:

	Sensible	Latent
G_0	136 (464)	20 (68)
G_{cf}	2.2 (0.7)	0.22 (0.07)
G_{oc}	22 (75)	12 (41)

A_{cf} = conditioned floor area of building, m^2 (ft^2)
N_{oc} = number of occupants; if not known, estimate as (number of bedrooms + 1)

Distribution Losses

The allowance for distribution losses is calculated as follows:

$$q_{dl} = F_{dl} \cdot q_s \tag{19}$$

where

q_{dl} = distribution loss, W (Btu/h)
F_{dl} = distribution loss factor, from Table 6
q_s = building sensible load, W (Btu/h)

Table 6. Duct Loss/Gain Factors

	Cooling						Heating											
							Furnace						Heat Pump					
Duct tightness	Unsealed			Sealed			Unsealed			Sealed			Unsealed			Sealed		
Duct insulation R ($m^2 \cdot K/W$ [$h \cdot ft^2 \cdot °F/Btu$])	0	0.7 (4)	1.4 (8)	0	0.7 (4)	1.4 (8)	0	0.7 (4)	1.4 (8)	0	0.7 (4)	1.4 (8)	0	0.7 (4)	1.4 (8)	0	0.7 (4)	1.4 (8)
Duct Location																		
Conditioned space	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Attic	2.01	1.35	1.23	0.83	0.42	0.35	0.68	0.46	0.41	0.41	0.20	0.16	0.78	0.57	0.53	0.40	0.22	0.18
Basement	0.20	0.17	0.16	0.09	0.06	0.05	0.43	0.31	0.28	0.25	0.13	0.11	0.35	0.27	0.26	0.18	0.11	0.09
Enclosed crawlspace	0.25	0.20	0.20	0.12	0.08	0.07	0.68	0.46	0.41	0.41	0.20	0.16	0.78	0.57	0.53	0.40	0.22	0.18

DEVELOPMENT OVERVIEW

The RLF formulation is conceptually transparent and hand-tractable: the "loads" from each wall, window, and other gain sources are calculated and summed to get the total load. Unfortunately, however, it is not possible to find invariant models for each load component because of interactions among them. For example, a major interaction occurs between opaque surfaces and fenestration—the load resulting from solar gain is lagged and moderated by differing amounts depending on surface construction. Even simple convective gains, such as infiltration and ventilation, present difficulty because they should be evaluated at the building-dependent peak hour. Note that RHB completely avoids these difficulties: 24-hour calculations allow gains to combine according to their case-specific profiles, and the heat balance procedure accurately represents component interactions.

Development of a load-component method such as RLF requires that the significant interactions be identified and addressed (via configuration-specific load-component calculations), eliminated (by restricting the configurations to which the method is applicable), or neglected if the effects are deemed small. Addressing interactive effects introduces more complexity in the method, which defeats its purpose. Given the availability of RHB to handle essentially any configuration, RLF applicability is restricted to typical residential construction.

Prior methods assumed the independence of load components and developed models for each. The component models were in many cases the obvious choice (e.g., infiltration load derived directly from an air leakage rate). However, excessive loads are predicted by simply using maximum fenestration and opaque surface heat gain rates. For these components, semi-empirical factors or adjustments were invoked to make the results consistent with experience. In particular, a common strategy was to use factors equal to multi-hour averages of calculated instantaneous gains. While the averaging approach has some intuitive appeal, it has no rigorous basis, as is acknowledged in older editions of the *ASHRAE Handbook—Fundamentals* (ASHRAE 1972).

> Averaging in this manner was found to give results compatible with measured residential loads. Hence, these are averages only in the sense that combining numbers in this manner results in accurate factors for calculating window loads of residential structures.

Room temperature swing is one reason adjustment is required. Assuming a fixed indoor temperature, as is typically done in nonresidential procedures, results in excessive loads for the residential case. Better overall system performance and cost-effectiveness results when equipment is sized to allow some temperature variation at design conditions. Averaging of gains derived assuming fixed room temperature mitigates their excessive peak.

The RLF development procedure avoided adjustments by relying on RHB cooling loads calculated with temperature swing and deriving required factors using linear regression. Equation 1 was treated as a model for which submodels and coefficients were needed. Later sections of the paper present the approaches used for each load component. The regression approach has two advantages. First, significant independent variables and efficient model forms are naturally identified by the regression process. If a model does not accurately predict load, it is revealed by poor statistical figures of merit. Second, no averaging or other semi-empirical adjustments are required.

From a processing point of view, RLF was developed using three PC applications: ResHB as described above (loads

Table 7.   Prototype Building Characteristics

Item	Value	Notes
Conditioned floor area	168 m^2 (1808 ft^2)	Typical size
Height	2.5 m (8.2 ft)	Single story
Exterior wall area	142.4 m^2 (1533 ft^2)	Average width assumed to be 8.5 m (28 ft), yielding perimeter = 57 m (187 ft)
Interior partition area	140 m^2 (459 ft^2)	83% of conditioned floor area
Nominal fenestration	27.2 m^2 (89.2 ft^2) windows 1.68 m^2 (18 ft^2) skylight clear double glazed (U = 2.73 W/m^2K (0.48 $Btu/h·ft^2·F$), SHGC = 0.76)	Window area = 16% of floor area Skylight area = 1% of floor area
Fenestration variation	All cases run with 200% nominal area. IAC values varied, $L = 0$, $M = 0.5$, $H = 1$.	
Internal mass	168 m^2 (1808 ft^2) of 12 mm (0.5 in) wood	RP-1199 default
Indoor design temperature	24°C (75.2°F)	
Indoor temperature swing	1.67 K (3°F)	
Infiltration	Leakage class E (normalized leakage = 0.34)	Reasonably tight contemporary construction (ASHRAE Standard 119, ASHRAE 1994)
Internal gain	Default	Based on Building America 2003, see below.
Surface exterior solar absorptance	Walls: 0.6	Roof: 0-1 (varied)
Surface interior absortance	Beam solar gain: floor: 0.6, internal mass: 0.3, other: 0 Diffuse solar gain: all surfaces: 0.6	
Orientation	0° and 45°	All 8 primary orientations considered.

calculations), RHBGen (parametric case generator), and the R statistics package.

RHBGen was developed to support ResHB testing and RLF development and is described by Barnaby et al. (2004). RHBGen generates and runs ResHB input files under the control of multi-character parametric codes. Fields within the code control various aspects of the case to be run, such as base prototype (fundamental building geometry), location, orientation, constructions, fenestration type and area, and so forth. RHBGen combinatorially varies code fields, allowing sets of hundreds or thousands of ResHB runs to be constructed and executed. On typical Pentium-based PCs, the RHBGen/ResHB system can complete several hundred cases per minute. ResHB writes suitable results files for regression analysis and other post-processing.

The R package (R 2004) is an open-source system with extensive statistical and data visualization capabilities. For RLF development, the linear regression and data plotting procedures were used. R is particularly suitable for RLF development because it includes a script language for automation of complex analysis sequences. The R scripts used in this work can be found in Barnaby et al. (2004).

MODELING ASSUMPTIONS

As discussed above, RLF cooling load procedures were developed by using linear regression analysis of sets of ResHB results. To generate the input data for regression, specific combinations of inputs were varied while others were maintained at typical values. For most variables, three levels were identified: L = minimum, M = typical, and H = maximum. Even with only three levels and relatively few variables, the total number of possible combinations is impractically large. To limit the number of cases, the range of RLF applicability was restricted to conventionally constructed and occupied single-family detached wood-frame buildings at latitude 20°-60° and at modest elevation. In addition, load components were analyzed separately, as is discussed below under "Regression Strategy."

Prototype Building

Cooling loads for many variations of a single prototype building were the basis for the regression analysis; Table 7 summarizes the prototype characteristics and Table 8 shows construction details. The floor plan of the prototype building was square with four rooms, one in each corner. Note that ResHB surfaces need not be geometrically consistent, allowing exterior wall area to be based on an assumed typical-width rectangular plan and that area to be distributed equally on all facades. The four-room plan was chosen so there was a reasonable ratio of interior partition to floor area and to limit radiant transfer among exterior walls. The sensible cooling load used as the regression independent variable was the maximum value of the combined 24-hour profile derived by summing the room loads for each hour.

Table 8. Prototype Surface Constructions

Surface	Construction	Framing Fraction	Insulation Level	U-Factor W/m²·K (Btu/h·ft²·°F)	Insulation Description
Ceiling	Roof/ceiling, asphalt shingles, plywood deck, 2 × 8 framing, gypsum board	10%	L	1.48005 (0.26066)	None
			M	0.21835 (0.03846)	190 mm (7.5 in.) fiberglass between framing
			H	0.11879 (0.02092)	190 mm (7.5 in.) fiberglass between framing plus 140 mm (5.5 in.) overlay
	Attic/ceiling, 2 × 8 framing, gypsum board	10%	L	2.24413 (0.39523)	None
			M	0.23148 (0.04077)	190 mm (7.5 in.) fiberglass between framing
			H	0.12204 (0.02149)	190 mm (7.5 in.) fiberglass between framing plus 140 mm (5.5 in.) overlay
Wall	Wood frame, plywood, 2 × 4 framing, gypsum board	25%	L	1.57621 (0.27760)	None
			M	0.50209 (0.08843)	90 mm (3.5 in.) fiberglass between framing
			H	0.25946 (0.04570)	90 mm (3.5 in.) fiberglass between framing plus 25 mm (1 in.) foam at outside of framing
Floor	Wood frame, oak floor, plywood deck 2 × 8 framing	10%	L	0.80772 (0.31837)	None
			M	0.22512 (0.03965)	190 mm (7.5 in.) fiberglass between framing
			H	0.15737 (0.02772)	190 mm (7.5 in.) fiberglass between framing plus 50 mm (2 in.) foam at outside surface
	Slab: 100 mm (4 in.) concrete, 300 mm (12 in.) soil, adiabatic exterior boundary conditions	n/a	L	n/a	Bare slab
			M	n/a	Additional surface resistance = 0.185 (m²·K)/W (1.05 [ft²·°F·h]/Btu), light carpet
			H	n/a	Additional surface resistance = 0.370 (m²·K)/W (2.10 [ft²·°F·h]/Btu), heavy carpet

Table 9. Design Conditions

Case	Design Dry-Bulb Temperature	Daily Range of Dry-Bulb Temperature	Design Wet-Bulb Temperature
	°C (°F)	°C (°F)	°C (°F)
LL	24 (75.2)	4 (7.2)	19 (66.2)
LM	24 (75.2)	11 (19.8)	16 (60.8)
ML	33 (91.4)	4 (7.2)	29 (84.2)
MM	33 (91.4)	11 (19.8)	23 (73.4)
MH	33 (91.4)	21 (37.8)	15 (59)
HL	43 (109.4)	4 (7.2)	24 (75.2)
HM	43 (109.4)	11 (19.8)	22 (71.6)
HH	43 (109.4)	21 (37.8)	21 (69.8)

Table 10. Site Assumptions

Item	Value
Latitude	20°N, 40°N, 60°N
Longitude	75°W
Time zone	–5 hr
Elevation	50 m (164 ft)
Date	July 21
Time	Daylight savings
Clearness	1

Table 11. Regression Data Sets

Component	Fenestration	Ceiling	Wall	Floor	Total Cases (24 design conditions, 2 orientations)
q_{fen}	41 combinations of LMH on 4 facades plus skylight (Box-Behnkin 5 factor design)	Attic, M $\propto_{roof} = 0.85$	Wood frame, M	Crawlspace, M Exposed, M Slab, M	5904
q_{ceil}	Nominal	Roof/ceiling LMH, Attic LMH, each with $\propto_{roof} = 0, 0.6, 1$	Wood frame, M	Crawlspace, M Exposed, M Slab, M	2592
q_{wall}	Nominal	Attic, M $\propto_{roof} = 0.85$	Wood frame, LMH	Crawlspace, M Exposed, M Slab, M	432
q_{floor}	Nominal	Attic, M $\propto_{roof} = 0.85$	Wood frame, M	Crawlspace, LMH Exposed, LMH Slab, LMH	432

Outdoor Design Conditions

Eight combinations of outdoor design dry-bulb temperature and daily range were selected to span a broad range of design conditions. Coincident wet-bulb temperatures were chosen by inspection of actual sites having design conditions similar to those of each combination. Table 9 summarizes the temperature assumptions. Other site-related assumptions are shown in Table 10, most of which were held constant for all cases.

The ResHB application uses these inputs to generate 24-hour design sequences that drive the heat balance simulation. Hourly incident solar radiation was calculated using the ASHRAE clear sky model (ASHRAE 2001) with updated coefficients (Machler and Iqbal 1985).

The combination of 8 design conditions and 3 latitudes resulted in 24 runs for each prototype variant.

REGRESSION STRATEGY

It was not practical to perform one regression analysis to identify all RLF coefficients because of the overwhelming number of case combinations that would have been required. Instead, an iterative series of linked regressions was performed. Equation 1 was applied to ResHB loads results and rearranged to isolate the envelope load component:

$$q_{env} = q_{s,rhb} - q_{ig,rhb} - q_{vi,rhb} \tag{20}$$

where

q_{env} = envelope cooling load component = $\sum A_i \cdot CF_i$ in Equation 1, W (Btu/h)

$q_{s,rhb}$ = ResHB sensible cooling load, W (Btu/h)

$q_{ig,rhb}$ = ResHB sensible internal gain at peak hour (simultaneous with $q_{s,rhb}$), W (Btu/h)

$q_{vi,rhb}$ = ResHB sensible ventilation/infiltration at peak hour (simultaneous with $q_{s,rhb}$), W (Btu/h)

The envelope cooling load is the sum of the load components from the various envelope elements:

$$q_{env} = q_{fen} + q_{ceil} + q_{wall} + q_{floor} \tag{21}$$

Each component term of Equation 21 was estimated using a separate data set described in Table 11. Each data set contains ResHB loads based on varying inputs relating to the term under consideration while fixing other inputs at M or nominal values. The component regressions were performed in the sequence shown in Equations 22 to 25, and the results of each were applied to the next step. (The details of each component model are discussed below.) Initial (iteration 0) estimates were set by hand using suitable prior results. It was determined by trial and error that five iterations achieved essentially complete convergence.

$$\hat{q}_{fen}^{i+1} = q_{env} - \hat{q}_{ceil}^{i} - \hat{q}_{wall}^{i} - \hat{q}_{floor}^{i} \tag{22}$$

$$\hat{q}_{ceil}^{i+1} = q_{env} - \hat{q}_{fen}^{i+1} - \hat{q}_{wall}^{i} - \hat{q}_{floor}^{i} \tag{23}$$

$$\hat{q}_{wall}^{i+1} = q_{env} - \hat{q}_{fen}^{i+1} - \hat{q}_{ceil}^{i+1} - \hat{q}_{floor}^{i} \tag{24}$$

$$\hat{q}_{floor}^{i+1} = q_{env} - \hat{q}_{fen}^{i+1} - \hat{q}_{ceil}^{i+1} - \hat{q}_{wall}^{i+1} \tag{25}$$

where

$\hat{q}_x^i$ = ith iteration estimated load component for fenestration, ceiling, wall, or floor, W (Btu/h)

COMPONENT MODELS

Ventilation and Infiltration

As discussed above, typical infiltration was included in the ResHB runs used to generate regression data, but the cooling load induced by this air leakage was subtracted from the load used in the envelope regressions. Thus, the loads

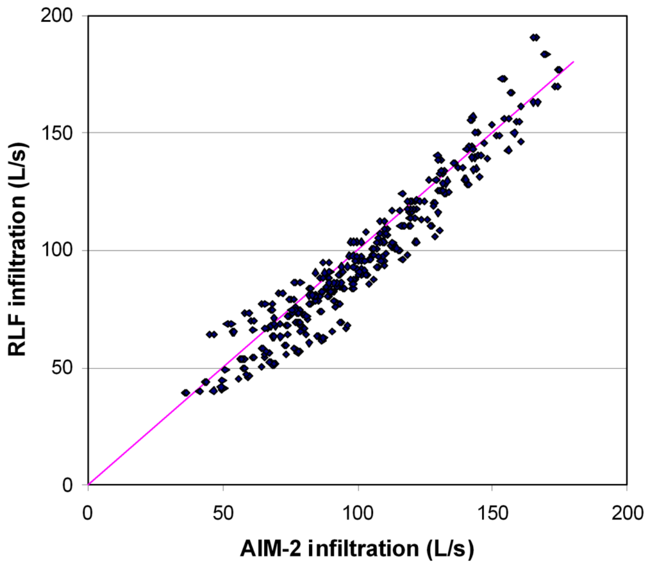

Figure 1 *Predicted infiltration leakage rates, AL = 1000 cm² (155 in.²), and representative range of stack height, temperature difference, and flue fraction. RLF values from Equation 9; see text (1 L/s = 2.12 cfm).*

predicted by the regression models implicitly assume 0 air leakage.

Equation 9 was developed to provide a simple method for estimating infiltration leakage for RLF. ResHB calculates infiltration using the AIM-2 model (Walker and Wilson 1990, 1998), which is too complex for practical hand application. The AIM-2 model was exercised over a range of temperature differences and building heights. Other assumptions included shelter class 4, flue shelter class 2, and wind speed multiplier values from Table 10, Chapter 26, ASHRAE (2001). Leakage distribution was assumed to be walls = 0.5, ceiling = 0.25, floor = 0.25 ($R = 1$, $X = 0$), all proportionately reduced if flue is present. The maximum flue leakage fraction considered was 0.5. Regression was used to find the form of Equation 9 and the I_x coefficients. The underlying functional form of the AIM-2 model is not linear, but the simple form of Equation 9 was maintained for ease of application. The regression model yielded an adjusted R^2 of 0.94. Figure 1 compares results from the regression to those from AIM-2. Because of minimal air density dependence, Equation 9 is valid at any elevation.

The procedure for combining mechanical ventilation with infiltration airflows, shown in Equations 10 to 12, follows (Palmiter and Bond 1991; Sherman 1992).

Internal Gains

RHB internal gains are based on Building America (2003), which specifies gain intensities and schedules for residential appliances, lighting, and occupants. Experiments with these gains and schedules in ResHB revealed that the sensible cooling load attributable to internal gains is generally approximated by the total sensible internal gain during the peak cooling hour. This is not necessarily expected, since a significant fraction of the gain is radiant and has a delayed load impact. The removal of load due to internal gain in Equation 20 is based on this approximation.

For RLF, Equations 17 and 18 are the aggregated Building America gains using 4 PM schedule values, that time being a common peak cooling hour for typical residential construction. Consideration was given to developing a model that predicts the peak cooling hour so a more accurate internal gains formulation could be included. However, such an addition to RLF was deemed excessively complex.

Opaque Surfaces

The model forms for opaque surface *CF*s were found by experimentation. Prior methods—both residential and nonresidential—have used an equivalent temperature difference (ETD) or cooling load temperature difference (CLTD) form, where ETD or CLTD = $A + \Delta T - DR/2$, where A is a constant, ΔT is the outdoor-indoor temperature difference, and DR is the daily range). This was taken as a starting point for RLF. A coefficient was added for ΔT, and multipliers other than 0.5 were allowed for DR. In some cases, the ΔT coefficient was found to be a value very close to 1, in which case it was dropped from the regression and forced to be 1. In other cases, coefficients were found to be not significant and dropped. The DR coefficient takes many values, indicating that the traditional 0.5 is perhaps not ideal. The final coefficient values are shown in Table 1. Adjusted R^2 values for all regressions were above 0.96.

A major design consideration was how many surface types to include. It was decided to limit RLF to conventional wood-frame construction. That led to inclusion of one type of wall (wood frame), two types of ceilings (ceiling/roof and ceiling/attic combinations), and three types of floors (exposed, crawlspace, and slab). Surface orientation was not a variable (all wall orientations are combined) and solar absorptance was treated as a variable only for roofs. It is believed that additional surface types could be added via straightforward extension of the current procedures.

Fenestration

A goal for the fenestration model was the separation of latitude-dependent exterior effects from building-dependent effects. It was determined by experimentation that this is achieved by factoring out peak hour irradiance incident on the fenestration exterior, leading the PXI formulation shown in Equation 5. As with the opaque surface models, this form is similar to prior residential and nonresidential methods. Many combinations of effective window aperture were included in

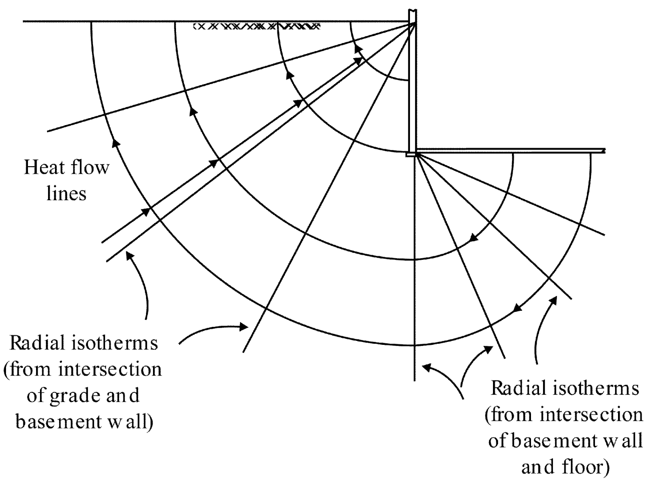

Figure 2 *Heat flow from basements (ASHRAE 2001).*

the regression data set used to find the FF_s coefficients. The final adjusted R^2 value was over 0.995.

An attempt was made to eliminate exposure-specific FF_s values, leaving PXI as the only exposure-dependent input. This produced significantly worse regression results. The FF_s coefficients (Table 2) show a physically reasonable relationship with exposure. East surfaces produce less cooling load per unit irradiance than do west surfaces, as is expected. Prior methods that relied on averaging show a less plausible E/W and SE/SW symmetry.

Distribution Losses

Duct losses can be calculated using models specified in ASHRAE (2004) and Palmiter and Francisco (1997). These models are fully implemented in the ResHB. Using typical input values, ResHB was exercised to produce Table 6 suitable for use with RLF hand calculations.

HEATING LOADS

The RLF procedure for heating loads calculation is identical, in most respects, to previously published ASHRAE (2001) residential heating load calculation procedures. The heating load calculation is based on a steady-state $UA\Delta T$ calculation, with no solar radiation and no internal heat gains. Infiltration leakage rate is based on Equation 9. The calculation procedure for heat losses from surfaces in contact with the ground has been revised as described in the following sections.

Basement Wall Heat Losses

For basement wall and floor heat transfer, the *ASHRAE Handbook—Fundamentals* has incorporated a procedure described by Latta and Boileau (1969) for a number of years. The Latta and Boileau method has the advantage of simplicity. One check of its accuracy was described by Sobotka et al. (1994), who showed that the Latta and Boileau method underpredicted the peak heating load of one basement by 16%. Correlation-based methods (Krarti and Choi 1996; Beausoleil-Morrison and Mitalas 1997) have been developed that offer significantly improved accuracy. However, these later methods have a large number of coefficients, which complicates presentation in a handbook. Therefore, the RLF procedure has incorporated a revised version of the Latta and Boileau procedure with the suggestion that buildings where the heating loads are significantly impacted by ground heat transfer should be analyzed with one of the more accurate methods.

The Latta and Boileau method is based on the assumptions that the surface temperature of the ground is at a calculable winter design temperature and that the heat flow paths may be approximated as circumferential with radial isotherms (see Figure 2). It also assumes that the thermal resistance of the ground may be estimated based on the path length of the heat transfer. In the original Latta and Boileau (1969) paper, tabulated U-factors included inside thermal resistance, thermal resistance of a concrete wall, thermal resistance of insulation (if any), and thermal resistance of the soil. The tabulated values were based on a coarse numerical integration and were specific to single combinations of soil thermal conductivity and insulation thermal resistance. The approach taken in the tables also depends on the interval value for the numeric integration being one foot. This presentation has been, at times, somewhat confusing. In fact, the values in the SI version of the *2001 ASHRAE Handbook—Fundamentals* are wrong, apparently having been misconverted due to the dependence on the interval. In addition, at some point, the original Latta and Boileau recommendation to use a ground temperature calculated as the mean ground temperature minus the annual amplitude, A, was re-expressed to use a ground temperature calculated as the average winter air temperature minus the annual amplitude. This results in significant overprediction of the ground heat loss.

In the RLF procedure, the original Latta and Boileau work was revisited and reformulated in a more flexible manner. The revised procedure allows for variation of the soil thermal conductivity and, if desired, partial wall insulation with any thermal resistance. Furthermore, an analytical expression for the average U-factor has been developed, along with new tables. This may be summarized as follows.

In cases where the basement wall is partially insulated, it will be desirable to calculate the heat loss separately for portions of the wall with differing amounts of insulation. Consider the region between depth z_1 and z_2 in Figure 3. (Here z_1 and z_2 can be any region of the wall, including the entire wall.)

For the region of interest, in steady-state heat transfer, there are several thermal resistances of interest—the soil, the concrete wall, the insulation (if any), and the inside surface resistance. If all thermal resistances besides the soil are

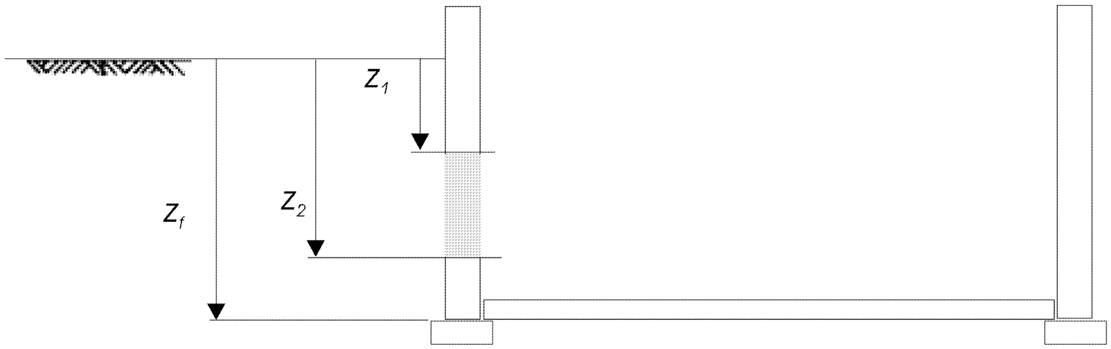

Figure 3 *Definition of basement wall and floor dimensions.*

lumped into a single value, R_{other}, the average U-factor between the basement air and the ground temperature is

$$U_{avg,bw} = \frac{2k_{soil}}{\pi(z_2 - z_1)}\left[\ln\left(z_2 + \frac{2k_{soil}R_{other}}{\pi}\right) - \ln\left(z_1 + \frac{2k_{soil}R_{other}}{\pi}\right)\right], \quad (26)$$

where

$U_{avg,bw}$ = average U-factor between basement air and ground temperature over region of interest shown in Figure 3, W/m^2·K (Btu/h·ft^2·°F);

k_{soil} = soil thermal conductivity, W/m·K (Btu/h·ft·°F);

z_1 = depth of upper bound of region of interest (see Figure 3), m (ft);

z_2 = depth of lower bound of region of interest (see Figure 3), m (ft); and

R_{other} = combined resistance of wall, insulation, and surface conductance, m^2·K/W (ft^2·h·F/Btu).

While values of soil conductivity vary widely with soil type and moisture content, a typical value of 1.4 W/m·K (0.8 Btu/h·ft·°F) was used in past editions of the *ASHRAE Handbook—Fundamentals* to tabulate U-factors. R_{other} is the sum of the resistance of the concrete wall, insulation (if any), and the inside surface resistance. In past editions of the *ASHRAE Handbook—Fundamentals*, R_{other} was approximately 0.25 m^2·K/W (1.47 ft^2·h·°F/Btu) for uninsulated concrete walls. For these parameters, $U_{avg,bw}$ is tabulated for a range of depths and insulation levels in Table 12.

Basement Floor Heat Losses

The RLF procedure uses an analogously updated version of the Latta and Boileau procedure for basement floors. For cases where the entire basement floor is uninsulated or has uniform insulation, the average U-factor is

$$U_{avg,bf} = \frac{2k_{soil}}{\pi W_b}\left[\ln\left(\frac{W_b}{2} + \frac{z_f}{2} + \frac{k_{soil}R_{other}}{\pi}\right) - \ln\left(\frac{z_f}{2} + \frac{k_{soil}R_{other}}{\pi}\right)\right], \quad (27)$$

where

$U_{avg,bf}$ = average U-factor between basement air and ground temperature for entire basement floor, W/m^2·°K (Btu/h·ft^2·°F);

k_{soil} = soil thermal conductivity, W/m·K (Btu/h·ft·°F);

W_b = basement width, which should be taken to be the shortest dimension, m (ft);

z_f = depth of slab bottom (see Figure 3), m (ft); and

R_{other} = combined resistance of floor, insulation and surface conductance, m^2·K/W (ft^2·h·°F/Btu).

For a soil conductivity of 1.4 W/m·K (0.8 Btu/h·ft·°F), $U_{avg,bf}$ for uninsulated basement floors are tabulated in Table 13.

Slab-on-Grade Floor Heat Losses

Concrete slab floors have been previously approximated as having heat losses solely proportional to the perimeter length by Wang (1979) and Bligh et al. (1978). More recent work (Bahnfleth and Pedersen 1990) has shown a significant effect of the area-to-perimeter ratio. The correlation-based methods for basement wall and floor heat transfer described above (Krarti and Choi 1996; Beausoleil-Morrison and Mitalas 1997) also have procedures for dealing with a wide range of slab-on-grade configurations. Again, if slab heat loss is a significant factor in the building heating load, one of these procedures should be used. However, for Handbook presentation, the previous approach was retained, with the exception that the table that showed some dependence of the perimeter heat loss factor on the number of degree-days was simplified by eliminating the degree-day dependence.

The simplified approach gives heat loss for both unheated and heated slab floors with the following equation:

Table 12a. Average U-Factor for Basement Walls with Uniform Insulation (SI Units)

$U_{avg,bw}$ from Grade to Depth, $W/m^2 \cdot K$*				
Depth (m)	**Uninsulated**	**R-0.88**	**R-1.76**	**R-2.64**
0.3	2.468	0.769	0.458	0.326
0.6	1.898	0.689	0.427	0.310
0.9	1.571	0.628	0.401	0.296
1.2	1.353	0.579	0.379	0.283
1.5	1.195	0.539	0.360	0.272
1.8	1.075	0.505	0.343	0.262
2.1	0.980	0.476	0.328	0.252
2.4	0.902	0.450	0.315	0.244

* Soil conductivity is 1.4 W/m-K; insulation is over entire depth. For other soil conductivities and partial insulation, use equations.

Table 12b. Average U-Factor for Basement Walls with Uniform Insulation (I-P Units)

$U_{avg,bw}$ from Grade to Depth, $Btu/h \cdot ft^2 \cdot °F$*				
Depth (ft)	**Uninsulated**	**R-5**	**R-10**	**R-15**
1	0.432	0.135	0.080	0.057
2	0.331	0.121	0.075	0.054
3	0.273	0.110	0.070	0.052
4	0.235	0.101	0.066	0.050
5	0.208	0.094	0.063	0.048
6	0.187	0.088	0.060	0.046
7	0.170	0.083	0.057	0.044
8	0.157	0.078	0.055	0.043

* Soil conductivity is 0.8 Btu/h·ft·°F; insulation is over entire depth. For other soil conductivities and partial insulation, use equations.

Table 13a. Average U-Factor for Basement Floors (SI Units)

	$U_{avg,bf}$, W/m^2K*			
	W_b (shortest width of basement), m			
z_f (depth of foundation wall below grade), m	**6**	**7**	**8**	**9**
0.3	0.370	0.335	0.307	0.283
0.6	0.310	0.283	0.261	0.242
0.9	0.271	0.249	0.230	0.215
1.2	0.242	0.224	0.208	0.195
1.5	0.220	0.204	0.190	0.179
1.8	0.202	0.188	0.176	0.166
2.1	0.187	0.175	0.164	0.155

* Soil conductivity is 1.4 W/m·K; floor is uninsulated. For other soil conductivities and partial insulation, use equations.

Table 13b. Average U-Factor for Basement Floors (I-P Units)

z_f (depth of foundation wall below grade), ft	$U_{avg,bf}$, Btu/h-ft^2-F*			
	W_b (shortest width of basement), ft			
	20	24	28	32
1	0.064	0.057	0.052	0.047
2	0.054	0.048	0.044	0.040
3	0.047	0.042	0.039	0.036
4	0.042	0.038	0.035	0.033
5	0.038	0.035	0.032	0.030
6	0.035	0.032	0.030	0.028
7	0.032	0.030	0.028	0.026

* Soil conductivity is 0.8 Btu/h·ft·°F; floor is uninsulated. For other soil conductivities and partial insulation, use equations.

Table 14a. Heat Loss Coefficient F_2 of Slab Floor Construction (SI Units)

Construction	Insulation	F_2 (W/K-m)
200 mm. block wall, brick facing	Uninsulated	1.17
	R-0.95 K-m^2/W from edge to footer	0.86
200 mm. block wall, brick facing	Uninsulated	1.45
	R-0.95 K-m^2/W from edge to footer	0.85
Metal stud wall, stucco	Uninsulated	2.07
	R-0.95 K-m^2/W from edge to footer	0.92
Poured concrete wall with duct near perimeter[a]	Uninsulated	3.67
	R-0.95 K-m^2/W from edge to footer	1.24

[a]Weighted average temperature of the heating duct was assumed at 43ºC during the heating season (outdoor air temperature less than 18ºC)

Table 14b. Heat Loss Coefficient F2 of Slab Floor Construction (I-P Units)

Construction	Insulation	F_2 (Btu/h-ft-F)
8 in. block wall, brick facing	Uninsulated	0.68
	R-5.4 from edge to footer	0.50
4 in. block wall, brick facing	Uninsulated	0.84
	R-5.4 from edge to footer	0.49
Metal stud wall, stucco	Uninsulated	1.20
	R-5.4 from edge to footer	0.53
Poured concrete wall with duct near perimeter[a]	Uninsulated	2.12
	R-5.4 from edge to footer	0.72

[a]Weighted average temperature of the heating duct was assumed at 110ºF during the heating season (outdoor air temperature less than 65ºF).

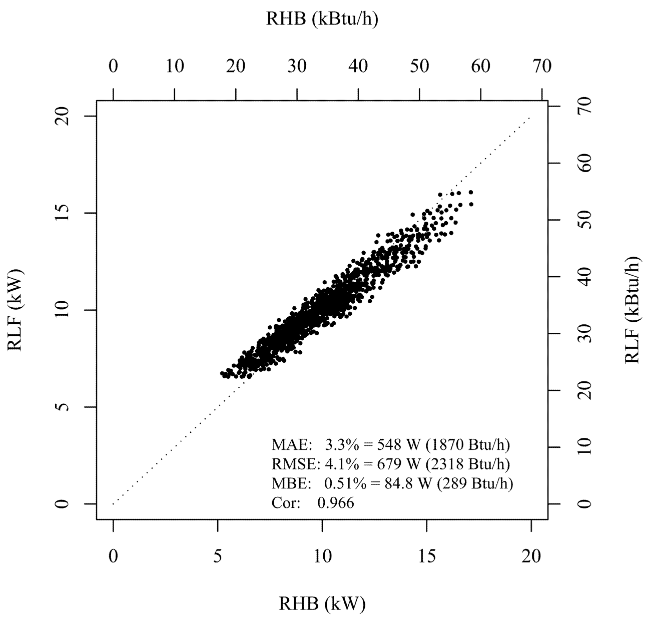

Figure 4 *RLF vs. RHB sensible cooling load comparison. Test building calculated for representative range of climate and construction conditions (1280 cases).*

$$q = F_2 \cdot P \cdot \Delta T \qquad (28)$$

where

- q = heat loss through perimeter, W (Btu/h)
- F_2 = heat loss coefficient per unit length of perimeter, W/m·K (Btu/h·ft·°F) (see Table 14)
- P = perimeter or exposed edge of floor, m (ft)
- ΔT = heating design temperature difference, K (°F)

Noting that the degree-day dependence previously given in the *ASHRAE Handbook—Fundamentals* is relatively small, the table of F_2 factors was simplified by only giving the value for 2970 Kelvin degree-day (5350 Fahrenheit degree-day) climates.

VERIFICATION OF RESULTS

The RLF method was added to the ResHB application, allowing RLF vs. RHB cooling load calculations to be performed on test cases. Figure 4 shows typical results of such a comparison for a building not involved in the regression process and using design weather data for 20 diverse US locations. As can be seen, there is generally good agreement but a trend remains in that RLF predicts too high for low loads and too low for high loads. This is being investigated and may lead to model refinement.

CONCLUSIONS

A number of conclusions can be drawn from this work:

- Linear regression is a useful tool for devising simplified building cooling load prediction models. Regression obviates the need for averaging and other semi-empirical adjustments. Further, it appears that reasonably accurate regression models can be found for virtually any building configuration.
- On the other hand, all simplified models having the RLF form (including RLF) have the distinct disadvantage that they do not give any indication of when they become inapplicable. For example, the peak cooling hour cannot be identified from the RLF procedure; if the peak is shifted, the internal gain load component could be significantly in error.
- Even within the range of applicability, uncertainty on the order of 1000 W (0.25 ton) is expected with RLF-style models. This uncertainty could be reduced via addition of model refinements. However, adding complexity to RLF defeats its purpose as a hand-tractable method while not achieving the accuracy and flexibility of RHB.

ACKNOWLEDGMENTS

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NOMENCLATURE

- A = area, m^2 (ft^2)
- A_L = building effective leakage area (including flue) at 4 Pa assuming C_D = 1, cm^2 (in.^{2})
- C_l = air latent heat factor, 3010 W/(L/s) (4840 Btu/h·cfm) at sea level
- C_s = air sensible heat factor, 1.23 W/(L/s)·K (1.1 Btu/h·cfm·°F) at sea level
- C_t = air total heat factor, 1.2 W/(L/s)-(kJ/kg) (4.5 Btu/h·cfm·[Btu/lb]) at sea level
- CF = cooling (load) factor, W/m^2 (Btu/h·ft^2)
- D_{oh} = depth of overhang (from plane of fenestration), m (ft)
- DR = daily range of outdoor dry-bulb temperature, K (°F)
- E = peak irradiance for exposure, W/m^2 (Btu/h·ft^2)
- F_2 = heat loss coefficient per unit length of perimeter (see Table 14), W/m·K (Btu/h·ft·°F)
- F_{dl} = distribution loss factor
- F_{shd} = fraction of fenestration shaded by permanent overhangs, fins, or environmental obstacles
- FF = coefficient for CF_{fen}
- G = internal gain coefficient
- h_{srf} = effective surface conductance, including resistance of slab covering material such as carpet, W/m^2·K (Btu/h·ft^2·°F). 1/(R_{cvr} + 0.12) W/m^2·K or 1/(R_{cvr} + 0.68) Btu/h·ft^2·°F
- H = height

HF = heating (load) factor, W/m^2 (Btu/h·ft^2)
I = infiltration coefficient
IAC = interior shading attenuation coefficient
k = conductivity, W/m·K (Btu/h·ft·°F)
LF = load factor, W/m^2 (Btu/h·ft^2)
OF = coefficient for CF_{opq}
P = perimeter or exposed edge of floor, m (ft)
PXI = peak exterior irradiance, including shading modifications, W/m^2 (Btu/h·ft^2)
q = heating or cooling load, W (Btu/h)
Q = air volumetric flow rate, L/s (cfm)
R = insulation thermal resistance, m^2·K/W (h·ft^2·°F/Btu)
$SHGC$ = fenestration rated or estimated NFRC solar heat gain coefficient
SLF = shade line factor
T_x = solar transmission of exterior attachment, see Table 4
U = construction U-factor, W/m^2·K (Btu/h·ft^2·°F); for fenestration, NFRC rated heating U-factor
W = width, m (ft)
X_{oh} = vertical distance from top of fenestration to overhang, m (ft)
z = depth below grade, m (ft)

Greek Symbols

α_{roof} = roof solar absorptance
Δh = indoor-outdoor enthalpy difference, kJ/kg
ΔT = design dry-bulb temperature difference (outdoor-indoor), K (°F)
ΔW = indoor-outdoor humidity ratio difference
ε = heat/energy recovery ventilation (HRV/ERV) effectiveness

Subscripts

avg = average
b = base (as in OF_b) or basement
bal = balanced
bf = basement floor
bw = basement wall
ceil = ceiling
cf = conditioned floor
d = diffuse
D = direct
dl = distribution loss
env = envelope
exh = exhaust
fen = fenestration
floor = floor
hr = heat recovery
ig = internal gain
inf = infiltration
l = latent
oc = occupant
oh = overhang
opq = opaque
oth = other
r = daily range (as in OF_r)
rhb = calculated with RHB method
s = sensible
shd = shaded
slab = slab
srf = surface
sup = supply
t = total or temperature (as in OF_t)
unbal = unbalanced
vi = ventilation / infiltration
wall = wall

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