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The Residential Heat Balance 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" (1199-RP), developed two new residential load 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 RHB and its development. For calculation of sensible cooling load, RHB applies the general approach of the ASHRAE heat balance (HB) method, based on room-by-room 24-hour design-day simulation. The 24-hour procedure eliminates issues of gain diversity that are troublesome in prior single-condition methods. RHB includes algorithms for calculating sensible cooling loads with temperature swing (temperature excursion above the cooling setpoint) and to handle master/slave control (room cooling controlled by a thermostat in another room). RHB is implemented in the ResHB FORTRAN 95 application, developed by modification and extension of the ASHRAE Loads Toolkit. The paper documents RHB/ResHB models and modeling assumptions. Because RHB is a first-principles heat balance procedure, it can be directly validated and refined using empirical data.

INTRODUCTION

The research project, "Updating the ASHRAE/ACCA Residential Heating and Cooling Load Calculation Procedures and Data" (1199-RP), 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 described in this paper. The second product of 1199-RP is a simpler procedure, designated the residential load factor (RLF) method. RLF is tractable by hand or can be straightforwardly implemented using spreadsheet software and is applicable to conventional single-family detached residences. RLF procedures and data are presented in the "Residential Cooling and Heating Loads Calculation" chapter of the *2005 ASHRAE Handbook—Fundamentals* (ASHRAE 2005). RLF development is documented by Barnaby and Spitler (2005).

RHB is based on heat balance first principles as described by Pedersen et al. (1997, 1998) and chapter 29 of ASHRAE (2001). 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 1199-RP, is the reference implementation of the RHB method. ResHB is a PC-based application written in FORTRAN 95. The code is based on the ASHRAE Loads Toolkit (Pedersen et al. 2001). ResHB is a research-oriented batch program, taking input from one or more text files and producing various output reports and data files. ResHB documentation is included in the 1199-RP final report (Barnaby et al. 2004). Source code and associated developmental procedures are found on a CD that accompanies the report. An additional utility program, RHBGen, was also developed during 1199-RP. RHBGen generates and runs parametrically varied ResHB cases for testing, research, and RLF development. Validation of ResHB is underway; intermodel, analytical, and empirical test results will be reported in future publications (Xiao et al. 2005).

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The sections below describe RHB and its implementation in ResHB. References to RHB and ResHB are made somewhat interchangeably because, in many ways, ResHB *is* RHB. Detailed equation-based model descriptions are not included here; readers are referred to cited sources and the ResHB source code.

BACKGROUND AND RHB DESCRIPTION

Residential heating and cooling load calculations produce information needed for equipment selection and distribution system design. These results include design values for heating, sensible cooling, and latent cooling equipment capacity plus room-by-room heating and sensible cooling loads. Experience has shown that simple procedures are sufficient for heating and latent cooling load calculations. Sensible cooling load calculations are more problematic. Sensible load results from the combination of several load components having building- and climate-dependent profiles. Excess sensible capacity increases first cost and results in performance problems, including poor humidity control, excessive power demand, and noisy operation. Thus, using conservative estimates of load components is not acceptable, and the overwhelming focus of the 1199-RP research project was on calculation of sensible cooling loads.

Prior Methods

Prior residential load calculation 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* include 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.

These methods share many features. Their heating load procedures differ only in details; all ignore solar and internal gains and are based on summing surface UAΔT heat losses, infiltration loss, ventilation loss, and distribution loss. Sensible cooling loads are similarly derived by summing component contributions calculated using tabulated or formula-based factors incorporating temperature and solar effects as appropriate. With the exception of *Manual J*, eighth edition, all perform a single design-condition calculation, implicitly making assumptions about relative timing of various gains and the zone response that transforms the gains into load. Recent addenda to *Manual J* (eighth edition) have added an adjustment that involves evaluation of the full-day room and zone fenestration gain profiles.

The single design-condition calculation of sensible cooling load has long been problematic. Using the sum of peak component gains as the design load usually produces an excessive result because the gains generally occur at different times over the day. To account for gain diversity, factors used in prior methods were derived using semi-empirical adjustments such as multi-hour averaging. However, for situations with limited exposure (e.g., apartments), the dominant fenestration gains peak simultaneously and the sum-of-peaks estimate is more appropriate. To handle such configurations, prior methods have included alternative factors and/or adjustments variously called “multi-family” or “peak” (as opposed to “single-family” or “average”). User judgment is required to select the applicable condition.

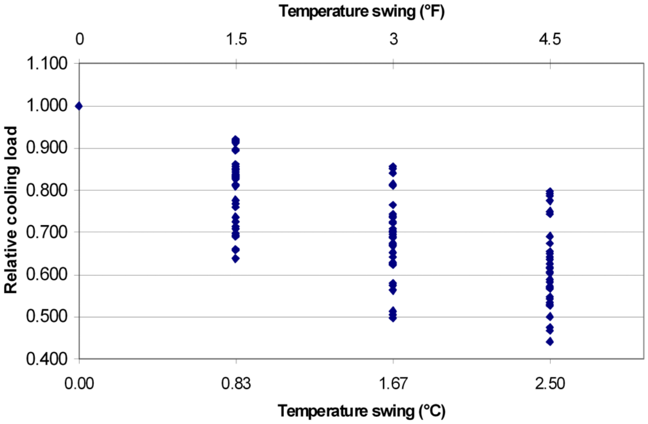

Figure 1 *Sensible cooling load reduction due to temperature swing.*

A multi-hour calculation eliminates the average/peak distinction—the design load is simply the peak of the hourly profile. The only motivation for using a single design condition is hand tractability. Implementers of past methods made the decision that an approximate method that would actually be used was preferable to a more accurate but impractically complex alternative. Given that personal computers are now ubiquitous, it is reasonable to use a 24-hour calculation for an updated procedure.

Master/Slave Control, Temperature Swing, and Cooling Load

Residential air-conditioning applications rely on multi-room, constant volume systems controlled by a single thermostat in one room (master/slave control). Assuming sufficient capacity, good temperature control occurs in the master (thermostat) room. The slave rooms maintain reasonable temperatures to the extent they have load profiles similar to that of the master and/or are conditioned by air mixing with adjacent rooms. In general, their temperatures will not be held at the setpoint even when the system is operating. The resulting temperature variation, or swing, has the effect of reducing the required capacity. This has long been recognized as a major consideration in residential cooling load calculations. Its importance is confirmed by this work.

Temperature swing generally occurs in slave rooms. However, with reduced cooling capacity, a thermostat room will experience temperature swing as well. Figure 1 shows the results of 192 ResHB sensible cooling load calculations for a single room with one exterior exposure in a variety of climates and in four primary orientations. At a 1.67°C (3°F) swing, the load reduction ranges from 13% to 50%. Some of this reduction is due to the higher average room temperature when swing is allowed. However, most of the effect results from a portion of peak gains being absorbed in building mass as room temperature rises. This energy is "carried forward" and is removed at a later time when gains have moderated and the system has adequate capacity to bring the room back to the setpoint, recooling the building mass. Permitting a small, short-duration temperature excursion at design conditions usually results in a significant reduction in required sensible capacity, with associated cost reduction, moisture removal improvement (as a result of longer run times), and electrical demand reduction. Note that these are primarily capacity effects—approximately the same amount of energy is removed over the day with or without temperature swing. Second-order considerations, such as higher average part-load ratio, may result in some energy savings when swing is allowed, but their relative magnitude is much smaller than the capacity savings.

Heat Balance for Residential Applications

Over the last ten years, ASHRAE nonresidential cooling load calculation procedures have moved to the heat balance (HB) method as the fundamental procedure (Pedersen et al. 1997) and the radiant time series (RTS) method as a simplified procedure derived from HB (Spitler et al. 1997). HB and RTS were evaluated regarding their suitability as the basis for an updated residential procedure. Both are 24-hour methods. HB was selected because it can readily calculate either load at a known space temperature or a space temperature given a known extraction rate. The latter capability makes HB well suited to the residential application where room temperature swing is so important.

To handle these floating temperature cases, RTS would have to be modified. An RTS extension, designated "Period Space Air Response Factor" (PSARF), was explored during 1199-RP. PSARFs relate extraction rate to air temperature deviation from a nominal setpoint and are analogous to the space air temperature weighting factors in the transfer function method (TFM) (McQuiston and Spitler 1992). The PSARF approach was not ultimately pursued because an extended RTS method would be in essence a re-invention of TFM, which has been superseded by HB. Given that direct application of HB is now computationally practical, there is no reason to resort to simplifications.

An important goal for the updated residential procedure was simplicity of required input, preferably comparable to prior methods. Specifically, a detailed geometric building description was deemed impractical. Using a simplified geometric model, where surface areas and orientations are known but their positions are not, implies (1) exact surface-to-surface view factors are not available and (2) room adjacencies are not known. The heat balance method can model longwave radiant exchange with good accuracy without exact view factors using an MRT formulation (Liesen and Pedersen 1997). Room adjacencies are unnecessary if room loads are calculated independently. Thus, there is a good match between heat balance and the requirement of simple input.

RHB Definition

The residential heat balance method is a specialized application of the ASHRAE heat balance method. The following HB changes and extensions define RHB:

- *Multi-room, multi-zone, and multi-system.* The fundamental RHB modeling unit is the room. Independent heat balances are performed for each room. Zones and systems are accounting structures to which loads are accumulated to provide overall results.
- *Specialized algorithms.* Temperature swing and master/slave control can be modeled to produce realistic sensible cooling load estimates.
- *Residential models and assumptions.* Component models and assumptions used for RHB are appropriate for the residential application.
- *Simple heating and latent cooling procedures.* As discussed above, the simple UAΔT model has proved satisfactory for heating load calculations. Similarly, latent load can be estimated from moisture gain from infiltration, ventilation, duct leakage, and occupants. These simple approaches are retained in RHB.

It should be noted that RHB is not a fully elaborated cooling system design procedure. In particular, RHB does not specify how temperature swing and master/slave control should be considered during the design process. RHB can model rooms with or without swing, allowing choice on the much-debated question as to whether systems should be sized to allow swing at the thermostat on the design-day. Slave room temperature results from a case-specific combination of limited capacity and control profile mismatch, so its design implications are more complex. It may be that RHB master/slave capabilities should be used for investigation of zoning options only after primary load calculations are done on an independent room-by-room basis (with or without temperature swing).

The remaining sections of this paper provide details about the above aspects of RHB in its current form. One major advantage of a heat balance formulation is that it can be tested and refined via direct comparison to empirical data. It is expected that RHB will evolve as additional research results become available.

CALCULATION ALGORITHMS

The HB method is a design day procedure that requires iteration to find the steady-periodic solution at which all heat flows correctly balance. RHB adds the additional requirement of finding loads under floating temperature conditions in order to handle temperature swing and master/slave control, as described here.

Calculation Sequence and Convergence Criteria

The fundamental RHB load calculation sequence is:

```
repeat swing
  repeat day
    for hour = 1 to 24
      for all rooms
        repeat
          for all surfaces
            perform surface heat balance
          end for surfaces
          perform air heat balance
        until room convergence for current hour
      end for rooms
    end for hours
  until day convergence
  determine room supply airflow rates for next swing iter
  ation
until swing convergence
```

The convergence criteria are discussed below. The sequence was modified several times during development and its logic is worth examining:

- The outer loop handles temperature swing (discussed below). Temperature swing occurs when cooling capacity is less than required to hold a room at the setpoint. The swing search algorithm adjusts each room supply air flow rate and repeats the entire calculation until the specified swing is achieved.
- The hour loop is outside the room loop. This means that current hour conditions are available for all rooms (either from the current day iteration or, at worst, from the prior day iteration), allowing inter-room references.

One of the issues with a design-day heat balance procedure is determining when the solution has converged. A common technique is to continue iteration until calculated temperatures change a very small amount between iterations. The difficulty is to determine a "small amount" that truly represents convergence. Unfortunately, there are cases that change very little, iteration to iteration, but will continue to change, resulting in significant drift in results. Various convergence criteria were attempted for ResHB and the following are the best found to date:

- *Hour.* For each room, the current hour calculations are repeated until the sum of the absolute change in surface temperatures plus air temperature is less than 0.0005 K (0.0009°F), indicating that a fully simultaneous solution has been closely achieved.
- *Day.* The day calculations are repeated until *all* rooms meet (a) the fractional difference between daily total inside and outside surface flux is less than 0.005 and (b) the area-weighted total absolute temperature change for all surfaces plus air is less than 0.0002 K (0.00036°F). Note that the all-room requirement means that some rooms will be iterated beyond this point.
- *Swing.* The swing search is continued until swings for *all* rooms are within 0.01 K (0.018°F) of specified. Each room has a specified swing. This allows different swings in master and slave rooms, for example. Again, the all-room requirement means extra iteration for some rooms.

In addition to these basic criteria, there are various safety checks that detect oscillation or excessive iteration and attempt to find an adequate result.

The criteria have been tuned to balance reasonable performance against successful convergence. In spite of this, there remain cases that converge slowly or not at all. For example, heavy buildings that are well insulated at the outside surface take hundreds of days to converge. These cases are the subject of ongoing attempts to find better initialization and/or iteration strategies.

One discovery is that hour and day convergence strongly interact with the swing search algorithm (discussed below). An initial implementation used relaxed criteria during early swing search steps, the idea being that approximate results were adequate during the early going. However, this resulted in unstable estimates for next step supply airflow rate. The current stringent day and hour criteria were found to be necessary for correct swing convergence.

The criterion of equal total daily heat flux on the inside and outside faces of all surfaces is useful because it is absolute. Given the periodic nature of the calculation and the fact that there are no heat sources within surfaces, all heat going into one face of a surface must come out the other. There was some concern that although this criterion is true in theory, the numeric methods used in the Toolkit CTF formulation would not be sufficiently precise to allow this test to be effective. These worries are groundless—inside and outside face fluxes readily balance within 1 part in 10^7 in a well-converged room.

Temperature Swing

ResHB uses a secant method search algorithm to search for the load when temperature swing is permitted. Note that the calculations are based on varying system air volume flow rate with an assumed supply temperature. This means the maximum extraction rate varies as the room temperature changes and subcooling is self-limiting. If the modeling were done in terms of heat extraction, room air temperature could be driven below the supply air temperature, which is impossible except under naturally floating conditions.

The following calculation sequence is used:

- The required cooling airflow rate is found first for the 0 swing situation (that is, maximum available air supply volume is unlimited and room temperature held at the setpoint or floating below it with no supply airflow).

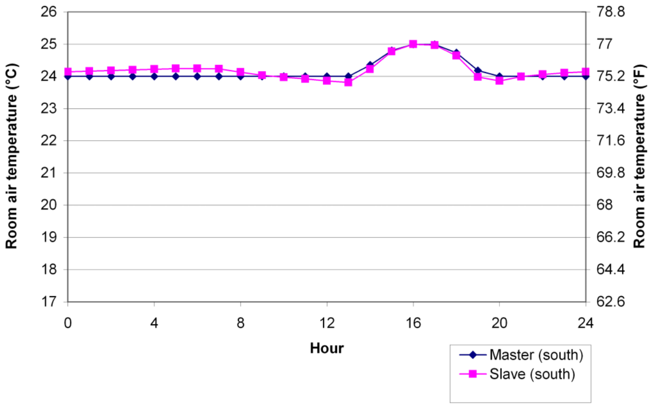

Figure 2 *Master/slave room temperatures with similar load profiles.*

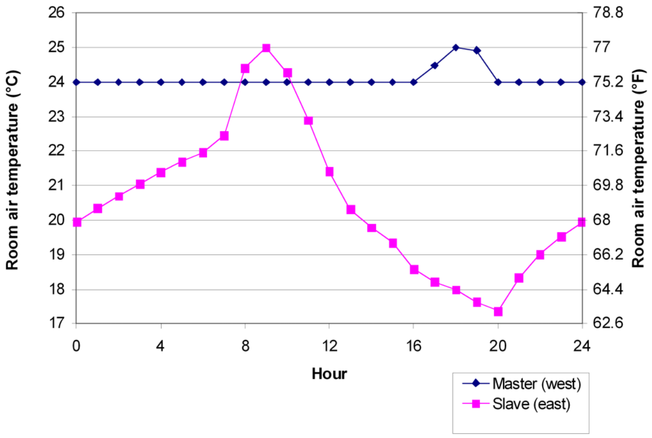

Figure 3 *Master/slave room temperatures with mismatched load profiles.*

- This maximum supply airflow rate is then reduced by 20% per K (11% per °F) of target swing and the room is calculated again. Generally, this reduction in supply airflow rate will produce a significant temperature swing.
- The supply airflow rate is iteratively adjusted in proportion to the error in temperature swing, as indicated by the secant method.

This algorithm is extremely efficient because local linearity allows each subsequent estimate of supply airflow rate to be much better than the prior one. Convergence to within 0.01 °K (0.018°F) of the target swing usually occurs in less than ten cycles. However, specific room characteristics can cause the search to fail. As noted above, if room convergence is not essentially perfect, the secant method can produce wildly unstable supply flow rate estimates. Several limits have been implemented to reduce the number of cases that fail. Also attempted was an alternative algorithm based on a least-squares fit to the last several points (as opposed to only the last two in the secant method); this approach did not work as well as the secant method.

Master/Slave Control

The modeling of master/slave control is handled by the RHB temperature swing algorithm. By definition, a slave room has the same air supply flow rate profile as its master, so the problem reduces to finding the peak slave room supply air volume flow rate such that the maximum room temperature is the setpoint (plus allowed swing if any). At each swing iteration, the peak flow rate is adjusted up or down using the temperature swing search described above (the search is used even if the specified swing is 0). Then the flow rates for all hours are set by applying the master room profile and the next day iteration proceeds without any further adjustment of airflow.

In situations where the master and slave rooms have significantly different load profiles, subcooling can occur in the slave room. This is illustrated in Figure 2 and Figure 3. These plots show room temperatures for a two-room building. The cooling setpoint is 24°C (75.2°F) and a 1°C (1.8°F) temperature swing is allowed. In the first case, both rooms have a 10 m^2 (107.6 ft^2) window facing south; the master and slave rooms have essentially the same temperature profile. In the second case, the master room has a west-facing window and the slave room has an east-facing window. When the master room load peaks in the late afternoon, the slave room is uncomfortably cold.

Because RHB models rooms independently (neglecting air mixing between rooms), the subcooling effect shown in Figure 3 is exaggerated. However, it is clear that the ResHB master/slave capability can be used to identify the need for zoning and, with further development, allow optimization of zoned designs.

MODELS

RHB development involved review, refinement, and extension of Loads Toolkit models, as described in the following sections.

Inside Surface Convection Coefficients

In the heat balance method, the load is the total convective transfer from all space surfaces plus convective gain from other sources. Thus, the choice of surface convective coefficient values is particularly crucial when implementing the procedure. The toolkit offers a number of convective models and additional alternatives are found in the literature. Several models are summarized in Table 1. The Toolkit ASHRAE,

Table 1. Inside Surface Convection Coefficient Values ($W/m^2 \cdot K$) for Model Alternatives (*ta* = Room Air Temperature [°C], *ts* = Surface Temperature [°C], *ach* = Air Change Rate (h^{-1}); 1 $W/m^2 \cdot K$ = 0.176 $Btu/h \cdot ft^2 \cdot °F$)

Model		Ceiling			Floor	
		Heat Flow Up	Heat Flow Down	Wall	Heat Flow Up	Heat Flow Down
Toolkit ASHRAE		1.25		4.68	4.37	
TARP simple	Sys on	6.14		6.14	6.14	
	Sys off	4.043	.920	3.078	4.043	.920
TARP detailed		$1.52 \cdot \sqrt[3]{\lvert ta - ts \rvert}$	$0.76 \cdot \sqrt[3]{\lvert ta - ts \rvert}$	$1.31 \cdot \sqrt[3]{\lvert ta - ts \rvert}$	$1.52 \cdot \sqrt[3]{\lvert ta - ts \rvert}$	$0.76 \cdot \sqrt[3]{\lvert ta - ts \rvert}$
Fisher		$0.49 \cdot ach^{0.8}$		$0.19 \cdot ach^{0.8}$	$0.13 \cdot ach^{0.8}$	
RHB (see text)	Sys on	5		5	5	
	Sys off	4.043	.920	3.078	4.043	.920

TARP detailed, and Fisher models are documented in the Loads Toolkit (Pedersen et al. 2001). The TARP simple model description and additional information about TARP detailed are found in Section III of Walton (1983).

Comparison studies were done for a range of conditions, with the expected result that loads depend strongly on coefficient model. The Toolkit ASHRAE model was eliminated because it lacks sensitivity to heat flow direction. The Fisher correlations are appropriate for ceiling diffuser configurations that are typical in only a fraction of residential buildings.

The model selected for RHB is a variant of TARP simple. The "sys off" values are ASHRAE-based natural convection values. To improve convergence stability, the transition between heat flow up and heat flow down values is made linearly over 2°C (3.6°F), rather than abruptly. The "sys on" value is enhanced due to air motion in the room. A value of 5 $W/m^2 \cdot K$ (0.88 $Btu/h \cdot ft^2 \cdot °F$) was chosen as the "sys on" value based on analysis of experimental data from ASHRAE research projects 529-RP and 664-RP for air change rates of approximately 8 ACH (typical for residential systems). For each hour, the coefficient used in the heat balance is the system-run-fraction-weighted combination of the "sys on" and "sys off" values.

Elevation Effects on Convective Heat Transfer

In ResHB, care has been taken to adjust air volumetric heat capacity as a function of site elevation. This adjustment results in significant changes in predicted infiltration, ventilation, and HVAC heat transfers. Thus, the question arises as to the effect of elevation on convection coefficients. The convection correlation given by Clear et al. (2001) for horizontal roofs was implemented in a spreadsheet with air pressure and density as variables. A 10 m by 15 m (32.8 ft by 49.2 ft) roof was modeled with a surface temperature of 60°C (140°F) and ambient air at 30°C (86°F). Two cases were analyzed: (1) forced convection, 3.35 m/s (7.5 mph) wind parallel to the short roof dimension of the roof (Gr/Re^2 0.02) and (2) natural convection, 0.045 m/s (0.1 mph). Elevation was varied from 0 m to 2250 m (7382 ft) and standard atmospheric relationships were used to derive pressure and density from elevation. The convective coefficients predicted by the Clear et al. (2001) correlation were normalized to their 0 elevation values, yielding the results shown in Figure 4 (where P is the site atmospheric pressure and P_0 is sea level atmospheric pressure).

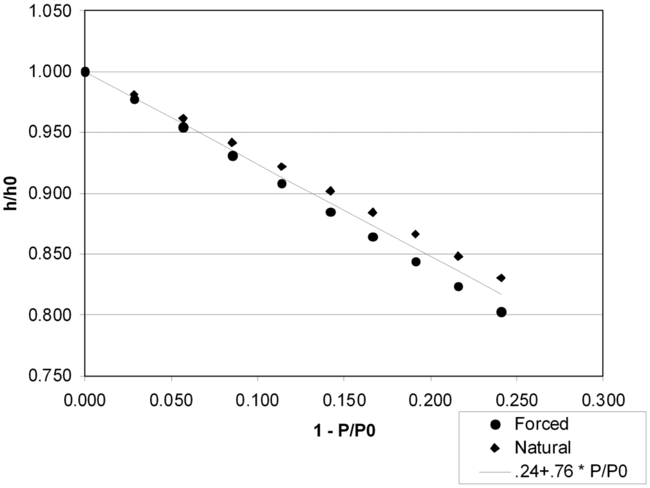

***Figure 4** Effect of pressure on convection coefficient (see definitions below).*

Given the magnitude of this effect (about 13% for Denver), applying an elevation correction to convection coefficients has a significant effect on predicted loads for high-elevation locations. A simple linear approximation was developed and used in RHB (and also shown in Figure 4):

$$h = h_0 \cdot \left(0.24 + 0.76\frac{P}{P_0}\right) \qquad (1)$$

where

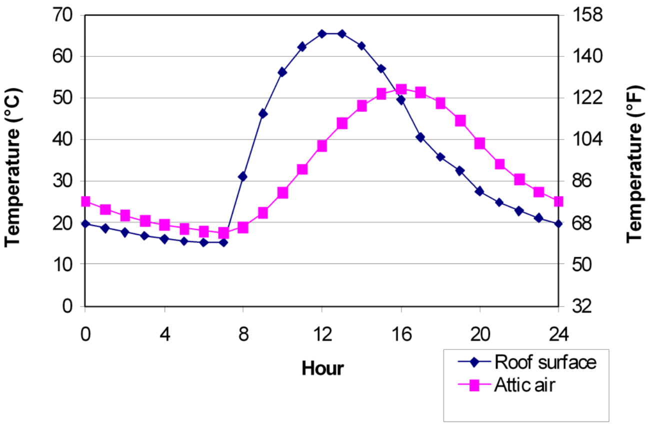

Figure 5 *Roof surface and attic air temperatures predicted by ResHB.*

h = convective coefficient at pressure P (units consistent with h_0)

h_0 = convective coefficient at sea level pressure

P = atmosphere pressure at site elevation (units consistent with P_0)

P_0 = sea level atmospheric pressure

Buffer Spaces

One of the many advantages of the heat balance approach is that buffer space temperatures can be predicted by simply modeling an unconditioned room. These temperatures can be used as outside boundary conditions for surfaces of adjacent conditioned spaces. Figure 5 shows typical ResHB results for an attic with a dark asphalt roof. Changes in roof solar absorptance and inside surface longwave emissivity (to represent radiant barriers) have the expected effects on predicted temperatures.

Infiltration

After review of available models, the AIM-2 model was selected for RHB (Walker and Wilson 1990, 1998; “enhanced model” in Chapter 26, ASHRAE 2001). As with other simplified residential models, AIM-2 requires several input values that are difficult to determine, including effective leakage area, leakage area distribution, and wind shelter parameters. ResHB provides typical default values for these inputs. Leakage area can be specified based on pressurization test or defaulted based on leakage classes defined by ANSI/ASHRAE Standard 119-1988 (RA 94) (ASHRAE 1994).

AIM-2 is a single-zone model. Infiltration leakage is determined for the entire building. In RHB, this overall rate is allocated to rooms in proportion to volume—that is, the same air change rate is assumed to apply to all rooms. Prior methods have variously allocated infiltration in proportion to exposed surface or window area. Actual room leakage can be inward or outward and depends on room position relative to the building neutral level and wind-induced pressure field. Thus, there is no simple method for allocating overall leakage other than using the average for all rooms.

Modeling of the interaction between mechanical ventilation and infiltration follows Palmiter and Bond (1991) and Sherman (1992).

Distribution Losses

ResHB duct losses are calculated using models specified in *ANSI/ASHRAE 152-2004, Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems* (ASHRAE 2004) and Palmiter and Francisco (1997). These models are fully implemented in the RHB method, allowing room-specific losses and gains to be included in estimates of air requirements and equipment capacity.

Framed constructions

The Loads Toolkit CTF-based conduction model assumes one-dimensional heat flow and thus requires layer-by-layer construction descriptions as input. Framed constructions are common in residential buildings. ResHB includes an algorithm that derives fictitious material properties for a homogeneous layer that corresponds to a framed layer. The resistance of the layer is chosen to preserve the overall U-factor of the construction. Density and specific heat are the volumetric averages of the framed layer components. Heat fluxes calculated with equivalent-construction CTFs were compared to those calculated with CTFs found with detailed three-dimensional methods (Carpenter et al. 2003). Differences of 5% or less were found.

Fenestration and Solar Gain Distribution

The Loads Toolkit fenestration model requires input of angular SHGC and absorptance values. This is not practical for routine use. ResHB implements fenestration class, which can be thought of as a family of fenestration types that exhibit common behavior. The fenestration class embodies the ratio of transmission to absorption and the angular characteristics of the fenestration system. An actual fenestration is specified by its U-factor, SHGC, and its fenestration class. The required angular characteristics are taken from the fenestration class and are scaled by the ratio of rated SHGC to nominal (fenestration class) SHGC. ResHB includes built-in fenestration class definitions for common residential glazing types.

ResHB uses the ASHRAE interior attenuation coefficient (IAC) and exterior attenuation coefficient (EAC) models to represent interior and exterior shading treatments (chapter 30, ASHRAE 2001). Overhang and fin shading is modeled with Loads Toolkit methods. ResHB additionally allows shading scheduled by hour of the day.

The conversion of radiant solar gain into cooling load occurs when surfaces are heated by incident radiant gain and energy is transferred convectively to room air. The distribution of solar gains to the various room surfaces is thus an important determinant of cooling load. The actual distribution within a room involves multiple surface inter-reflections and is impractical to compute. RHB uses a modified version of the Loads Toolkit BLAST model, which distributes radiative gains in proportion to surface area-absorptance product. Beam gain is assumed to hit floor surfaces. The RHB enhancement to this model is that internal mass surfaces are assumed to be “half floor” with respect to beam radiation, based on the idea that furnishings typically intercept some of the incoming beam. As with the BLAST model, fenestration surfaces back-transmit some incident radiation, so a room has an overall cavity absorptance less than 1 (although typically very close to 1 except when glazing fraction is large).

Ground Heat Transfer

There is speculation that net heat flow into the ground in slab-on-grade houses can have a significant impact on sensible cooling loads. However, no truly simple ground loss models are available, and determination of soil properties is problematic. Several approaches were investigated, notably Beausoleil-Morrison and Mitalas (1997). Pending further research, in RHB slabs are modeled with 300 mm (1 ft) of earth and adiabatic boundary conditions. This construction captures some of the diurnal heat storage effects of slab construction but not net conduction to the ground. For heating load calculations, some improvements were achieved for calculation of ground losses (see Barnaby and Spitler [2005]).

MODELING ASSUMPTIONS

Practical application of the HB method requires that fixed or default values be established for as many inputs as possible, both as a practical aid to the user and to achieve consistent results. The following sections document the assumptions developed for RHB.

Outdoor Design Conditions

RHB requires hourly outdoor conditions for the design day. The Loads Toolkit requires user input of 24 hour profiles for these values, which is impractical. While ResHB retains the ability to accept full profiles for testing purposes, it can also automatically generate profiles from design dry-bulb temperature, daily range of dry-bulb temperature, coincident wet-bulb temperature, site coordinates, and site elevation, as follows:

- *Dry-bulb temperature.* The design dry bulb and daily range are expanded to 24 hours using the generic profile from Table 17, Chapter 29, of *ASHRAE Fundamentals* (ASHRAE 2001). The generic profile is shifted one hour later when daylight savings is specified.
- *Wet-bulb temperature and other moisture-related values.* The design dry bulb and coincident wet bulb are used to determine the design dew-point temperature. The hourly dew point is the minimum of the design dew point and the hourly dry bulb (that is, constant absolute humidity is assumed, limited by saturation). Other hourly psychrometric values (wet-bulb temperature, humidity ratio, and enthalpy) are derived from the hourly dry-bulb and dew-point temperatures.
- *Solar radiation*. Hourly incident solar is derived using the ASHRAE clear sky model (chapters 29 and 30, *ASHRAE Fundamentals*) with updated coefficients as in Machler and Iqbal (1985).
- *Sky temperature.* Sky temperature is required for calculation of exterior surface longwave radiant exchange. The model of Berdahl and Martin (1984) is used to calculate hourly sky temperature from hourly dry-bulb and dew-point temperatures (cloud cover assumed to be 0).

All psychrometric calculations are done using Loads Toolkit procedures (originally from Brandemuehl et. al. [1993]) assuming a constant barometric pressure determined from site elevation according to a standard atmosphere relationship (Equation 3, chapter 6, *ASHRAE Fundamentals*).

Internal Gain

RHB internal gain assumptions are based on Building America (2003), which provides gain intensities and schedules for significant residential end uses as a function of building floor area and number of occupants. When estimating residential internal gains, care must be taken to distinguish between energy consumption and space gain. For example, a clothes dryer uses significant energy, but most is exhausted outside the space. In addition, RHB requires the radiant/convective/latent split for each gain source, which Building America (2003) does not fully define. Estimates were developed from *ASHRAE Fundamentals* and other sources as needed. These values are shown in Table 2 and have been incorporated into ResHB. Note that both sensible and latent heat gains due to hot water use are neglected because they are

Table 2. Fractional Components of Internal Heat Sources

Source	Internal Gain (to Space)			Exhausted
	Radiant	Convective	Latent	
Refrigerator	0	1	0	0
Range	0.24	0.16	0.30	0.30
Dishwasher	0.51	0.34	0.15	0
Clothes washer	0.40	0.60	0	0
Clothes dryer	0.09	0.06	0.05	0.80
Lighting	0.79	0.21	0	0
Other appliances and plug loads	0.54	0.36	0.1	0
People (living)	0.33	0.22	0.45	0
People (sleeping)	0.30	0.30	0.40	0

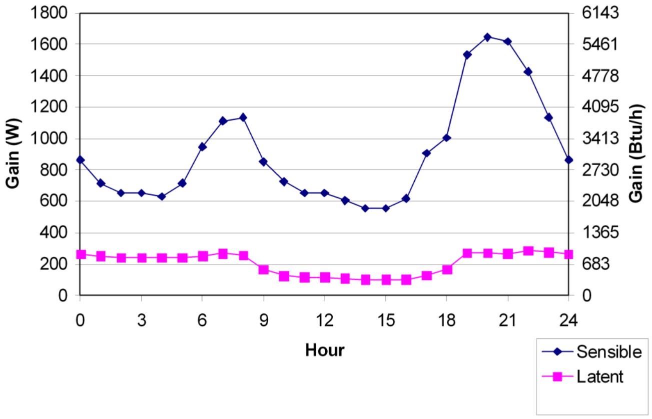

Figure 6 *Hourly internal gain (all sources) for a 186 m^2 (2000 ft^2) house with 4 occupants.*

not covered in Building America (2003); these gains are probably small due to intermittent use and shower exhaust fans but deserve further investigation.

A typical 24-hour internal gain profile is shown in Figure 6. Note that the sensible gain values during late afternoon peak cooling hours are quite moderate. This is consistent with the traditional values used in prior methods. For example, for the Figure 6 case, *Manual J*, eighth edition, specifies internal gain of 621 W (2120 Btu/h, 1200 Btu/h for appliances plus 230 Btu/h per occupant). Because of the relative timing of typical peak solar and internal gains, the contribution of the latter to the total sensible load is generally surprisingly small.

The gains specified in Building America (2003) are average values derived from energy consumption measurements. It could be argued that higher values should be used for load calculations, given that 600 W is less than the output of a single range burner. However, gains from normal residential activity are intermittent and are absorbed by small space temperature swings. Higher assumptions are appropriate only in cases where a significant gain is routinely expected. Occasional high gain situations, such as social functions, should not be considered or should be handled with a parallel system designed for that condition.

Internal Mass

The presence of internal mass (such as furniture) in a room has two effects on cooling load: the load is increased due to enhanced surface area available for convective exchange and decreased due to the storage (depending on its construction, space temperature swing, and presence of other mass such as a slab floor). The ultimate impact of internal mass depends on which of these effects dominates in a particular case. Note also that residential buildings typically have relatively small rooms and, thus, the partition-to-floor area ratio can easily exceed 1 and often exceeds 2. Partitions function as additional internal mass.

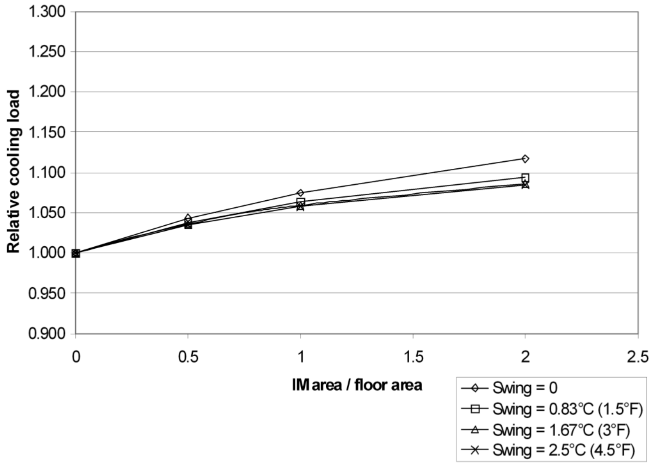

Figure 7 *Effect of internal mass, wood floor construction.*

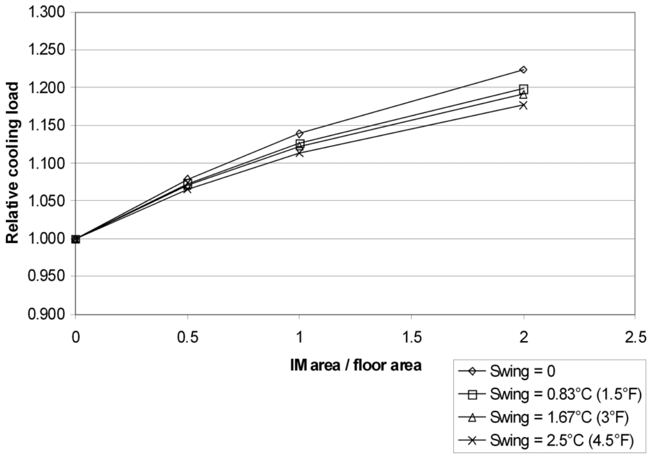

Figure 8 *Effect of internal mass, slab floor construction.*

ResHB parametric studies showed the impact of internal mass on sensible cooling load to be –2% to +23%. Typical results are shown in Figure 7 and Figure 8 for a 162.6 m^2 (1750 ft^2) house in Washington, DC, with various amounts of 12 mm (0.5 in.) wood internal mass.

No source was found for documented information about the amount or composition of internal mass found in typical residences. Using judgment, a recommended assumption was selected for RHB: each room should be modeled including internal mass having surface area equal to room floor area and consisting of 12 mm (0.5 in.) wood exposed on one side (adiabatic outside surface conditions). This surface should be radiantly coupled to all room surfaces. ResHB implements a special surface type "IM" having this behavior.

Table 3. Default Surface Absorptances

Surface	Shortwave (Solar)		Longwave (Thermal)	
	Outside	Inside	Outside	Inside
Roof / ceiling (tilt < 60°)	0.8	0.45	0.9	0.9
Wall (60° < tilt 180°)	0.6	0.45	0.9	0.9
Fenestration	per FenClass	per FenClass	0.84	0.84
Floor (tilt = 180°)	0	0.6	0.9	0.9

Other Assumptions

Surface absorptance. Table 3 summarizes absorptance values recommended for typical load calculations. Other values should be used as appropriate, particularly for roof outside absorptance if a reflective color is specified.

Material properties. ResHB includes default material properties gathered and reconciled from multiple sources, as documented in Barnaby et al. (2004).

TOOLKIT REENGINEERING

As stated above, the starting point for ResHB was the ASHRAE Loads Toolkit (Pedersen et al. 2001). Specifically, ResHB was created via incremental reengineering of the Toolkit's successive substitution sample zone example. That module is a fully functional single-zone model that uses the conduction transfer function (CTF) calculations for building surfaces and the MRTBal radiant exchange model (Liesen and Pedersen 1997; Walton 1980). Changes were introduced one at a time. Comparison of output from each incremental change minimized the possibility of unintended changes.

The Toolkit is intended to allow exploration, understanding, and comparison of alternative loads models. Its structure emphasizes clarity and modularity over efficiency. These objectives are secondary for ResHB and ultimately an almost entirely new application resulted as the original code was adapted to the residential loads application. Some of the significant changes include:

- *Application framework*. ResHB includes various utility capabilities, such as error handling, command line processing, and common report formatting functions.
- *Streamlined input processing*. The data dictionary file (IDD) is now simplified and embedded in the application, making ResHB.exe a complete, standalone package. Unused input processing features have been removed. An INCLUDE capability is now available, allowing common input to be maintained in a single file. In addition, a rudimentary PARAMETER scheme has been added.
- *Unused models removed*. As ResHB algorithms are determined, the alternative methods provided in the Toolkit have been dropped. This makes the code smaller and eases development.
- *Residential models added*. Models not included in the Toolkit have been added for infiltration and duct losses. Other models have been enhanced.
- *RHB calculation algorithms*. Temperature swing and master/slave control algorithms were added.
- *Constant air properties*. The Toolkit performs detailed psychrometric calculations to obtain an exact energy balance on the room air. ResHB uses constant indoor air properties derived during initialization from site elevation and nominal room conditions. This change causes minor changes in results.
- *Data structure generalization*. In order to support multiple systems, zones, and rooms, global variables have been removed and replaced by arrays allocated as needed. The result is that ResHB problem size is limited only by available memory.
- *Efficient initialization*. All temperature-independent calculations are done only once in ResHB, including solar geometry, solar gains, and internal gains.
- *Refactoring constructions*. In ResHB, several changes have been made in the logical structure of surface construction. This revised structure is deemed more convenient since it does not require multiple definitions for the same material.
    - *Surfaces* can be described with a simple U-factor or with a layered construction. Absorptivities are surface properties, not construction properties. Also, surfaces may reference a "reversed" construction, eliminating the need for duplicate definition of a shared construction (a room ceiling and an attic floor, for example).
    - *Constructions* are a series of layers specified by thickness and material.
    - *Materials* are characterized by conductivity, density, and specific heat (or pure resistance). This contrasts with the Toolkit Material Layer formulation, which includes thickness. A default material thickness is available that is convenient for defined-thickness layers, such as carpet.
- *Temperatures in °C*. The Toolkit uses absolute temperature (K) for all calculations. ResHB was converted to operate in °C with appropriate conversion to absolute temperature as needed (e.g., for radiant exchange calculations).

ResHB loads calculations for multi-room buildings generally take less than one second on a 2.4 GHz PC.

CONCLUSIONS

The development of RHB shows the ASHRAE heat balance method to be the procedure of choice for residential load calculations. In particular, the ability of HB to directly handle floating temperature conditions allows straightforward and rigorous treatment of temperature swing, master/slave control, and buffer spaces. The work also proves the utility of the Loads Toolkit as a vehicle for advancing loads calculation development.

The heat balance approach has two primary drawbacks. First, it is computationally intensive. Current generation interactive load calculation applications require "instant" calculations (a small fraction of a second). Based on experience with ResHB, it appears that such speed is achievable but not without clever implementation. Second, the occasional HB convergence failure remains troublesome; additional algorithm development is needed before the method can robustly handle all cases encountered in practice.

In addition to providing accurate peak loads, the hourly, multi-room, varying temperature capabilities of RHB offer many opportunities for improved residential system design procedures. An immediate possibility is automated identification of poor zoning configurations, replacing the user judgment required in prior procedures. More ambitious, but certainly possible, are applications such as distribution system optimization and automated determination of zoning.

The largest advantage of heat balance is how it transforms the continuing improvement of load calculation methods. Direct empirical comparisons can be made between experiments and heat balance models, leading to model validation and/or refinement. Further, sensitivity studies can guide research efforts to areas where refinement is particularly important. Experience during RHB development indicates that high priority should be placed on improving models of convective heat transfer in air-cooled residential spaces, ground heat transfer during cooling season, clear-sky solar radiation, and interior shading. Additional research on residential occupancy patterns, appliance use, and interior shade operation is also needed. Some of these topics are addressed by current or proposed ASHRAE research projects. The significant point, however, is that as results become available, they can be immediately integrated into RHB and other HB methods.

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