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The Radiant Time Series Cooling Load Calculation Procedure

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ABSTRACT

The radiant time series method is a new method for performing design cooling load calculations, derived from the heat balance method. It effectively replaces all other simplified (non-heat-balance) methods such as the cooling load temperature difference/solar cooling load/cooling load factor method (CLTD/SCL/CLF), the total equivalent temperature difference/time averaging method (TETD/TA), and the transfer function method (TFM).

The radiant time series method relies on a 24-term response factor series to compute conductive heat gain, and it relies on a 24-term "radiant time series" to convert instantaneous radiant heat gain to cooling loads.

This paper describes the radiant time series method and the generation of the response factors and the radiant time series coefficients and gives a brief comparison to the heat balance method.

INTRODUCTION

The radiant time series (RTS) method is a new method, derived directly from the heat balance method, for performing design cooling load calculations. It effectively replaces all other simplified (non-heat-balance) methods such as the cooling load temperature difference/solar cooling load/cooling load factor method, the total equivalent temperature difference/time averaging method, and the transfer function method.

The casual observer might well ask why yet another load calculation method is necessary. This method was developed in response to the desire of ASHRAE TC 4.1, the design load calculations technical committee, for a method that is rigorous yet does not require the user to perform the iterative calculations required by the transfer function method. In addition, for pedagogical reasons, it is desirable for the user to be able to inspect and compare the coefficients for different zone types. In all other simplified methods, the physical processes are obscured by the procedure. In the radiant time series method, it is easy to compare the radiant time factors between zone types and understand the relative zone responses.

This paper will first describe the methodology and then explain the procedures for generating the wall/roof response factors and the radiant time factors. Some comparisons will be made between the RTS method and the heat balance method. It should also be noted at the outset that this paper concerns a work in progress—it is anticipated that further refinements will be made to the method.

OVERVIEW OF THE METHOD

Figure 1 shows the RTS method computational procedure assuming the radiant time series and wall/roof response factors have already been determined. It should be noted that with the exception of the two "bold" boxes, all of the procedures are described in chapters 2 and 10 of the current ASHRAE *Cooling and Heating Load Calculation Manual* (McQuiston and Spitler 1992). Therefore, this discussion will focus on the calculation procedures that are different. Important areas that are different include the computation of conductive heat gain, the splitting of all heat gains into radiant and convective portions, and the conversion of heat gains into cooling loads. These are discussed in the following sections.

Computation of Conductive Heat Gains

Conductive heat gain is calculated for each wall and roof type with the use of 24 response factors. The response factor formulation gives a time series solution to the transient, one-dimensional conductive heat transfer problem. For any hour, θ, the conductive heat gain for the surface, q_θ, is given by the

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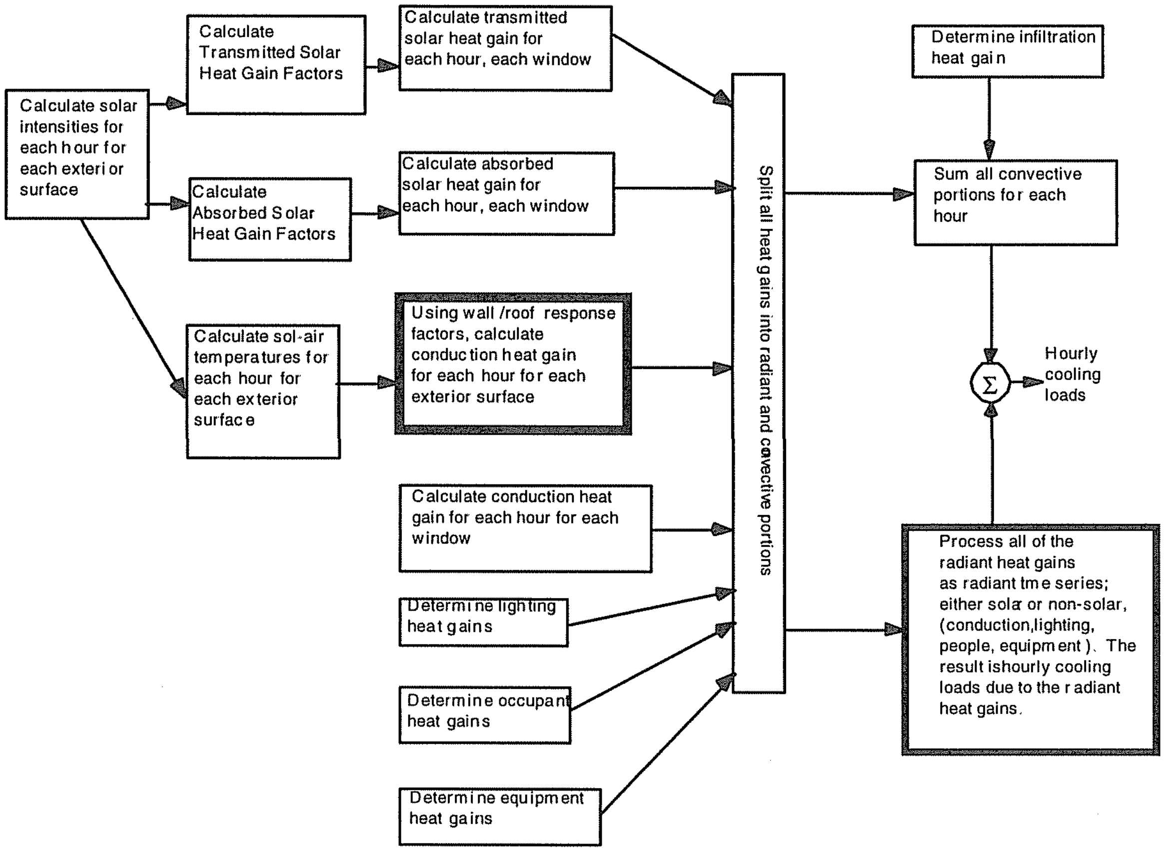

Figure 1 *Overview of the radiant time series method.*

summation of the response factors multiplied by the temperature difference across the surface, as shown in Equation 1:

$$q_\theta = A \sum_{j=0}^{23} Y_{Pj}(t_{e,\theta-j\delta} - t_{rc}) \quad (1)$$

where

q_θ = hourly conductive heat gain, Btu/h (W), for the surface;

A = surface area, ft^2 (m^2);

Y_{Pj} = jth response factor;

$t_{e,\theta-j\delta}$ = sol-air temperature, °F (°C), j hours ago; and

t_{rc} = presumed constant room air temperature, °F (°C).

Computation of Convective Heat Gains

The instantaneous cooling load is defined as the rate at which heat energy is convected to the zone air at a given point in time. The computation of convective heat gains is complicated by the radiant exchange between surfaces, furniture, partitions, and other mass in the zone. Radiant heat transfer introduces to the process a time dependency that is not easily quantified. Heat balance procedures calculate the radiant exchange between surfaces based on their surface temperatures and emissivities but typically rely on estimated "radiative-convective splits" to determine the contribution of internal heat sinks and sources to the radiant exchange. The radiant time series procedure simplifies the heat balance procedure by splitting the conductive heat gain into radiative and convective portions (along with lights, occupants, and equipment) instead of simultaneously solving for the instantaneous convective and radiative heat transfer from each surface. Table 1 contains provisional recommendations for splitting each of the heat gain components.

According to the radiant time series procedure, once each heat gain is split into radiative and convective portions, the heat gains can be converted to cooling loads. The radiative portion is absorbed by the thermal mass in the zone and then convected into the space. This process creates a time lag and dampening effect. The convective portion, on the other hand, is assumed to instantly become cooling load and, therefore, only needs to be summed to find its contribution to the hourly cooling load. The method for converting the radiative portion to cooling loads is discussed in the next sections.

Conversion of Radiative Heat Gains Into Cooling Loads

The radiant time series method converts the radiant portion of hourly heat gains to hourly cooling loads using radiant time factors, the coefficients of the radiant time series. Like response factors, radiant time factors calculate the cooling load for the

TABLE 1
Recommended Radiative-Convective Splits for Heat Gains

Heat Gain Type	Recommended Radiative Fraction	Recommended Convective Fraction	Comments
Occupants	0.7	0.3	Rudoy and Duran (1975)
Lighting Suspended fluorescent-unvented Recessed fluorescent -vented to return air Recessed fluorescent -vented to supply and return air Incandescent	 0.67 0.59 0.19 0.71	 0.33 0.41 0.81 0.29	York and Cappielo (1981), pp. II.83-84
Equipment	0.2-0.8	0.8-0.2	ASHRAE TC 4.1 has ongoing research aimed at evaluating the radiative/convective split for various types of equipment typically found in offices, hospitals, etc. In the meantime, use higher values of radiation fractions for equipment with higher surface temperatures. Use lower values of radiation fractions for fan-cooled equipment, e.g., computers.
Conductive heat gain through walls	0.63	0.37	The values presented here are based on standard ASHRAE surface conductances for vertical walls with horizontal heat flow and $\varepsilon = 0.9$ and for ceilings with heat flow downward and $\varepsilon = 0.9$. The computer program used to generate radiant time factors may also be used to generate better estimates of the radiative/convective split for walls and roofs.
Conductive heat gain through roofs	0.84	0.16	
Transmitted solar radiation	1	0	
Absorbed (by fenestration) solar radiation	0.63	0.37	Same approximation as for conductive heat gain through walls.

current hour on the basis of current and past heat gains. The radiant time series for a particular zone gives the time-dependent response of the zone to a single steady periodic pulse of radiant energy. The series shows the portion of the radiant pulse that is convected to the zone air for each hour. Thus, r_0 represents the fraction of the radiant pulse convected to the zone air in the current hour, r_1 in the last hour, and so on. The radiant time series thus generated is used to convert the radiant portion of hourly heat gains to hourly cooling loads according to Equation 2.

$$Q_\theta = r_0 q_\theta + r_1 q_{\theta-\delta} + r_2 q_{\theta-2\delta} + r_3 q_{\theta-3\delta} + \dots + r_{23} q_{\theta-23\delta} \quad (2)$$

where

Q_θ = cooling load (Q) for the current hour (θ),

q_θ = heat gain for the current hour,

$q_{\theta-n\delta}$ = heat gain n hours ago, and

r_0, r_1, etc. = radiant time factors.

Radiant time factors are most conveniently generated by a heat balance based procedure. A separate series of radiant time factors is required for each unique zone and for each unique radiant energy distribution function. Two different series of radiant time factors are utilized—one for transmitted solar heat gain (radiant energy assumed to be distributed to the floor only) and one for all other types of heat gains (assumed to be uniformly distributed on all internal surfaces). The section "Implementing the RTS Method" discusses the procedure for generating radiant time factors.

Because the heat gains are all known at this stage of the analysis, the cooling loads can all be calculated explicitly, eliminating the need for an iterative solution.

PROCEDURE FOR GENERATING WALL AND ROOF RESPONSE FACTORS

In order to use the methodology described above to compute conductive heat gain for walls and roofs, a set of response factors is needed for each wall and roof that is used in the building of interest. There are a number of ways to generate the response factors; the method described here uses a conventional method (Hittle and Bishop 1983) to calculate a set of 120 response factors for a single pulse. (The large set of response factors was originally developed for energy analysis where, using a weather tape, each day is different from the one before.) The response factor set for a single pulse can be reduced to a set of 24 response factors that are appropriate for a steady periodic input. These will be called *periodic response factors.*

The starting point for developing the periodic response factors for the conduction component of heat gain is the traditional response factor representation for the heat conduction through a wall:

$$q''_\theta = -\sum_{j=0}^{n} Z_j T_{i,t-j\delta} + \sum_{j=0}^{n} Y_j T_{o,t-j\delta} \quad (3)$$

where

q''_θ = heat flux at the inside surface of the wall at the current hour,

n = large number dependent on the construction of the wall,

Z_j, Y_j = response factors,

$T_{i,t-j\delta}$ = inside surface temperature j hours ago, and

$T_{o,t-j\delta}$ = outside surface temperature j hours ago.

If the boundary conditions are steady periodic within a 24-hour period, it is useful to rearrange the summations as follows:

$$\begin{aligned} q''_\theta = &-\sum_{j=0}^{23} Z_j T_{i,t-j\delta} + \sum_{j=0}^{23} Y_j T_{o,t-j\delta} \\ &-\sum_{j=24}^{47} Z_j T_{i,t-j\delta} + \sum_{j=24}^{47} Y_j T_{o,t-j\delta} \\ &-\sum_{j=48}^{63} Z_j T_{i,t-j\delta} + \sum_{j=48}^{63} Y_j T_{o,t-j\delta} + \ldots \end{aligned} \quad (4)$$

If the first term of the Z summations is separated from the rest, one obtains:

$$\begin{aligned} q''_\theta = &-Z_0 T_{i,t} - \sum_{j=1} Z_j T_{i,t-j\delta} \\ &+ \sum_{j=0}^{23} Y_j T_{o,t-j\delta} - Z_{24} T_{i,t-24} \\ &-\sum_{j=25}^{47} Z_j T_{i,t-j\delta} + \sum_{j=24}^{47} Y_j T_{o,t-j\delta} - Z_{48} T_{i,t-48} \\ &-\sum_{j=49}^{63} Z_j T_{i,t-j\delta} + \sum_{j=48}^{63} Y_j T_{o,t-j\delta} + \ldots \end{aligned} \quad (5)$$

For a steady periodic forcing function, the temperatures $T_{i,t}$, $T_{i,t-24}$, $T_{i,t-48}$, etc., are all the same. The coefficients of these temperatures can be combined to give a new set of periodic response factors (Z_{pj} and Y_{Pj}):

$$Y_{P1} = Y_0 + Y_{24} + Y_{48} + \ldots \quad (6)$$

Similarly,

$$Y_{P2} = Y_1 + Y_{25} + Y_{49} + \ldots \quad (7)$$

and so on.

Thus, for the special case of a steady periodic forcing function, the generally large number of response factors can be replaced by 24 periodic response factors, and the heat flux can be expressed in terms of periodic response factors as

$$q''_\theta = -\sum_{j=0}^{23} Z_{Pj} T_{i,t-j\delta} + \sum_{j=0}^{23} Y_{Pj} T_{o,t-j\delta} \quad (8)$$

where the wall heat gain coefficients are designated to be either inside coefficients (z) or cross-coefficients (y), depending on the temperature by which they are multiplied.

Furthermore, the inside temperature is assumed constant for calculating design loads, and the sum of the Y_{Pj} coefficients is equal to the sum of the Z_{Pj} coefficients, so that Equation 8 can be rewritten as

$$q''_\theta = \sum_{j=0}^{23} Y_{Pj}(t_{e,\theta-j\delta} - t_{rc}). \quad (9)$$

By way of example, consider a specific wall, in this case made up of outside surface resistance, 4 in. (100 mm) face brick, 1 in. (25 mm) insulation, 4 in. (100 mm) lightweight concrete block, ¾ in. (20 mm) drywall, and inside surface resistance. This wall is type 10 wall, described in Table 18 of chapter 26 of the *1993 ASHRAE Handbook — Fundamentals* (ASHRAE 1993).

A large set of response factors are computed using the method described by Hittle and Bishop (1983) and are given in Table 2. Using the procedure described above, a set of 24 periodic response factors were developed as shown in Figure 2.

PROCEDURE FOR GENERATING RADIANT TIME FACTORS FROM HEAT BALANCE

A procedure analogous to the periodic response factor development demonstrates that a series of 24 radiant time factors completely describes the zone response to a steady periodic input. The 24 radiant time factors can be generated by one of two procedures. First, the radiant time factors can be generated from a zone heat balance model. Since one of the goals of this project was to develop a simplified method that was directly based on the heat balance method, it was deemed desirable to generate the radiant time factors directly from a heat balance. To this end, a heat balance program, modeled on the BLAST program (BLAST Support Office 1991) but limited to load calculations for a single day, was developed. The program is described by Pedersen et al. (1997). Second, it would be possible to generate radiant time factors directly from a set of weighting factors using the existing ASHRAE database (Sowell 1988a, Sowell 1988b, Sowell 1988c). This approach would use a computer program to read the database and transform the weighting factors to radiant time factors.

The procedure for generating radiant time factors may be thought of as analogous to the custom weighting factor generation procedure used by DOE 2.1. (Kerrisk et al. 1981; Sowell 1988b, 1988c). In both cases, a zone model is pulsed with a heat gain. In the case of DOE 2.1, the resulting loads are used to estimate the best values of the weighting factors to most closely match the load profile. In the case of the procedure described here, a unit periodic heat gain pulse is used to generate loads for

TABLE 2
Traditional Response Factors for Wall Type 10

j	Y_j	j	Y_j	j	Y_j	j	Y_j	j	Y_j
0	7.0561E-06	24	2.2210E-04	48	9.8843E-07	72	4.2703E-09	96	1.8437E-11
1	1.3174E-04	25	1.7784E-04	49	7.8787E-07	73	3.4035E-09	97	1.4695E-11
2	1.4033E-03	26	1.4230E-04	50	6.2800E-07	74	2.7127E-09	98	1.1712E-11
3	3.7668E-03	27	1.1380E-04	51	5.0056E-07	75	2.1620E-09	99	9.3348E-12
4	5.5041E-03	28	9.0955E-05	52	3.9898E-07	76	1.7232E-09	100	7.4400E-12
5	6.2266E-03	29	7.2668E-05	53	3.1801E-07	77	1.3734E-09	101	5.9298E-12
6	6.2340E-03	30	5.8037E-05	54	2.5347E-07	78	1.0946E-09	102	4.7262E-12
7	5.8354E-03	31	4.6337E-05	55	2.0203E-07	79	8.7245E-10	103	3.7668E-12
8	5.2401E-03	32	3.6986E-05	56	1.6103E-07	80	6.9536E-10	104	3.0022E-12
9	4.5768E-03	33	2.9516E-05	57	1.2834E-07	81	5.5421E-10	105	2.3928E-12
10	3.9197E-03	34	2.3550E-05	58	1.0229E-07	82	4.4172E-10	106	1.9071E-12
11	3.3088E-03	35	1.8787E-05	59	8.1533E-08	83	3.5206E-10	107	1.5200E-12
12	2.7626E-03	36	1.4985E-05	60	6.4984E-08	84	2.8060E-10	108	1.2115E-12
13	2.2871E-03	37	1.1951E-05	61	5.1794E-08	85	2.2364E-10	109	9.6557E-13
14	1.8807E-03	38	9.5309E-06	62	4.1281E-08	86	1.7825E-10	110	7.6958E-13
15	1.5383E-03	39	7.6000E-06	63	3.2902E-08	87	1.4206E-10	111	6.1337E-13
16	1.2528E-03	40	6.0598E-06	64	2.6224E-08	88	1.1323E-10	112	4.8887E-13
17	1.0166E-03	41	4.8315E-06	65	2.0901E-08	89	9.0245E-11	113	3.8963E-13
18	8.2259E-04	42	3.8519E-06	66	1.6659E-08	90	7.1927E-11	114	3.1055E-13
19	6.6399E-04	43	3.0708E-06	67	1.3277E-08	91	5.7327E-11	115	2.4751E-13
20	5.3490E-04	44	2.4480E-06	68	1.0582E-08	92	4.5691E-11	116	1.9727E-13
21	4.3019E-04	45	1.9515E-06	69	8.4343E-09	93	3.6416E-11	117	1.5723E-13
22	3.4549E-04	46	1.5556E-06	70	6.7223E-09	94	2.9024E-11	118	1.2531E-13
23	2.7715E-04	47	1.2400E-06	71	5.3578E-09	95	2.3133E-11	119	9.9877E-14

a 24-hour period. As long as the heat gain pulse is a unit pulse, the resulting loads are equivalent to the radiant time factors.

Specifically, in order to use the heat balance program to generate radiant time factors, the following procedure was used.

1. A zone description consisting of geometric information, construction information, etc., is provided by the user.
2. The walls are specified as "partitions," heat storage surfaces that do not interact with the outside environment.
3. The model is again pulsed with a 100% radiant unit periodic heat gain pulse at hour 1. The pulse is distributed over all the interior surfaces uniformly, that is, the radiant flux is treated as uniform over the interior. The resulting cooling loads are the radiant time factors that will be applied to the radiative portions of all internal heat gains except transmitted solar heat gain. This is equivalent to assuming that all the radiation from these internal heat gains is absorbed uniformly by all interior surfaces. This is, of course, an approximation, but one that is difficult to improve upon.
4. The model is pulsed with a 100% radiant unit periodic heat gain pulse at hour 1. This pulse represents transmitted solar heat gain. In this case, it is distributed nonuniformly. At present, it is all distributed onto the floor, but this assumption may be refined later. The resulting cooling loads are the radiant time factors that will be applied to the transmitted solar heat gain.

IMPLEMENTING THE RTS METHOD

Prior to implementing the RTS method, two sets of response factors (walls and roofs), two sets of radiant time series (internal loads and solar), sol-air temperatures, and solar heat gains must be calculated. This information is used in the computational procedure described in the following section. Assumptions and refinements to the procedure are discussed below.

j	Y_{Pj}	j	Y_{Pj}
0	2.3015E-04	12	2.7777E-03
1	3.1037E-04	13	2.2991E-03
2	1.5463E-03	14	1.8903E-03
3	3.8811E-03	15	1.5459E-03
4	5.5954E-03	16	1.2589E-03
5	6.2995E-03	17	1.0215E-03
6	6.2923E-03	18	8.2646E-04
7	5.8819E-03	19	6.6708E-04
8	5.2773E-03	20	5.3736E-04
9	4.6064E-03	21	4.3215E-04
10	3.9433E-03	22	3.4705E-04
11	3.3276E-03	23	2.7839E-04

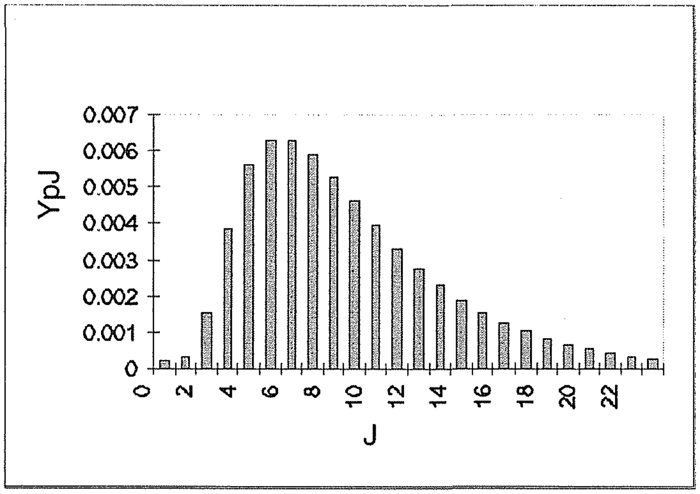

Figure 2 Periodic response factors for type 10 wall.

Computational Procedure

The computational procedure that was described above in "Procedure for Generating Wall and Roof Response Factors" can be summarized as follows.

- Calculate hourly conductive heat gains using response factors.
- Split hourly conductive heat gains into radiative and convective portions.
- Calculate hourly solar heat gains using the standard ASHRAE procedure (McQuiston and Spitler 1992).
- Sum hourly internal heat gains into radiative and convective portions.
- Convert radiative portion of internal heat gains to hourly cooling loads using radiant time factors.
- Convert solar heat gains to hourly cooling loads using radiant time factors.
- Sum convective portion of conductive and internal heat gains with hourly cooling load from radiative portions and solar heat gains.

Calculate and Split Hourly Conductive Heat Gains Hourly conductive heat gains are calculated for each exterior wall and roof according to Equation 1. Wall and roof response factors are used in conjunction with hourly sol-air temperatures as shown in the following pseudo-code algorithm.

```
For each exterior wall
  For each hour in the day
    For each of the 24 wall response factors
      Calculate fractional heat gains:
     ((Wall Area) × (Response Factor) × (Sol-air
     Temp - Zone Temp))
  next Response Factor with previous Sol-air Temp
  Sum fractional heat gains to obtain hourly heat
   gain for wall
Sum wall heat gains to obtain total heat gain from
 walls
Split total wall heat gain into convective and
 radiative portions
```

Each response factor multiplied by the appropriate sol-air-zone temperature difference represents a fractional conductive heat gain for the hour. The total hourly heat gain for the surface is obtained by summing the fractional heat gains.

The total conductive heat gain is split into radiative and convective portions according to Table 1. The radiative portion of the conductive heat gain is included with the internal heat gains and converted to hourly cooling loads by the radiant time series. The convective portion is added directly to the cooling load.

Convert Internal and Solar Heat Gains to Hourly Cooling Loads Hourly solar heat gains and heat gains from internal sources are calculated according to established procedures. The radiant time series (internal gains and solar) account for the distribution function used to apply the radiant energy to the zone surfaces. The internal heat gain radiant time series is based on a uniform distribution; the solar radiant time series is based on distribution to the floor only. Diffuse solar energy should therefore be included with internal heat gains and the radiative portion of conductive heat gain. The solar radiant time series should be applied to absorbed beam energy only.

Heat gains are converted to cooling loads according to Equation 2. The following pseudo-code shows each of the 24 radiant time factors multiplied by the appropriate hourly solar heat gain to give a fractional cooling load for each hour. The fractional cooling loads are summed to give a total hourly cooling load due to solar heat gains.

```
For each hour in the day
 For each of the 24 Radiant Time Factors
       Calculate fractional cooling load:
        Solar Radiant Time Factor × (Hourly Solar
          Heat Gain)
     next Radiant Time Factor with previous solar
       heat gain
 Sum fractional cooling load to obtain hourly cool-
  ing load due to internal heat gains and the radi-
  ative portion of conduction
```

Likewise, the radiant portion of internal and conductive heat gains and the diffuse portion of the solar heat gain are operated on by the coefficients of the internal heat gain radiant time series to generate hourly fractional cooling loads from these sources.

```
For each hour in the day
 For each of the 24 Radiant Time Factors
       Calculate fractional cooling load:
        Radiant Time Factor X (Radiant Portion of
          Internal and conductive heat gains +
          diffuse solar heat gain)
    next Radiant Time Factor with previous heat gain
 Sum fractional cooling load to obtain hourly cool-
  ing load due to internal heat gains and the radi-
  ative portion of conduction
```

Sum Hourly Cooling Load Components The final step in the procedure is the summation of all convective portions of the hourly heat gains with the radiative portions converted by means of the radiant time series to hourly cooling loads as shown below.

```
For each hour in the day
     Sum All Contributions to Cooling Load
   Convective portion of internal heat gains
 + Convective portion of conductive heat gains
 + Beam solar heat gains converted to cooling load
 + Internal, Radiative Conductive, and Diffuse
   Solar heat gains converted to cooling load
 Sum fractional cooling load to obtain hourly cool-
  ing load due to internal heat gains and the radi-
  ative portion of conduction
```

Modeling Considerations

The full implementation of the radiant time series method can vary significantly depending upon the models selected for the calculation of sol-air temperatures, solar heat gains, and internal heat gain distribution. Both detailed and simplified models are available for calculation of sol-air temperature and solar heat gains. Ongoing ASHRAE-sponsored research (RP-822) will provide improved data for determining convective radiative splits from internal sources.

Calculating Sol-Air Temperatures Sol-air temperatures may either be calculated directly from a heat balance procedure or calculated using the simplified equation presented in the *Cooling and Heating Load Calculation Manual.* The simplified formulation includes an estimated longwave correction term that is solved for directly in the heat balance procedure.

Sol-air temperature formulations are strongly dependent on the selection of exterior convective heat transfer coefficients. Available outside convection models are described in detail by McClellan (1997).

Solar and Fenestration Models Solar and fenestration models also vary widely, both in complexity and required inputs. Modern window systems with suspended films and reflective coatings require detailed models such as those provided in certain programs (LBL 1992). Chorpening (1997) compares results of simplified and detailed models.

Splitting Heat Gains Currently, conductive and internal heat gains are arbitrarily split into convective and radiative portions. The heat balance procedure can be used to approximate the radiative portion of conductive heat gains for various surface constructions and interior convection models. As previously stated, the radiative portion of internal heat gains must be empirically determined.

COMPARISON TO HEAT BALANCE TEST CASES

The Zone Models

Three mid-floor offices were selected as examples. All have floor areas of 388 ft^2 (36 m^2). The first example is for an interior zone. The second example is a southwest corner office with 10% windows in each of the two exterior walls. The third example is a southwest corner office with 70% windows in each of the two exterior walls. Construction details are shown in Table 3.

To simplify the example, a single scheduled internal heat gain was specified as "electric equipment" with a peak of 2 W/ft^2 (22 W/m^2). The equipment was operated according to the schedule shown in Figure 3.

Solar heat gains were calculated for a location of 40 degrees N latitude and 88 degrees longitude. The calculations were made for the 21st day of July. Figure 4 shows the daily outdoor dry-bulb temperature profile; the indoor temperature was controlled to 75°F (24°C) for all hours.

Cooling Load Due to Internal Heat Gains

For each hour, the internal heat gain was split into radiant and convective portions. For this example, a split of 30% radiant and 70% convective was used. The convective portion was added directly to the hourly cooling load.

The radiant portion of the hourly heat gain was converted to an hourly cooling load by the procedure described in "Conver-

TABLE 3
Construction Details of Example Zone

Layer	Exterior Wall	Partition	Ceiling
(outside) layer 1	4 in. (100 mm) brick	8 in. (100 mm) concrete block	4 in. (100 mm) concrete
layer 2	2 in. (50 mm) insulation		ceiling air space
layer 3	4 in. (100 mm) block		acoustic tile
layer 4	3/4 in. (19 mm) plaster		
Layer	**Floor**	**Window**	
(outside) layer 1	acoustic tile	single pane	
layer 2	ceiling air space		
layer 3	4 in. (100 mm) concrete		
layer 4			

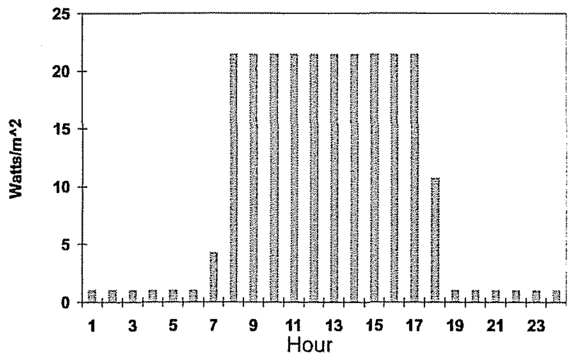

Figure 3 *Electric equipment heat gain schedule.*

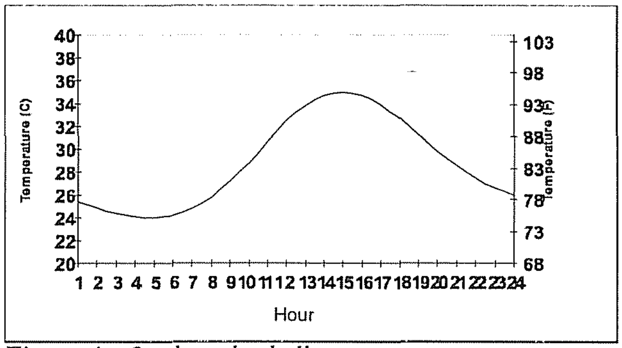

Figure 4 *Outdoor dry-bulb temperature.*

sion of Radiative Heat Gains into Cooling Loads" above. The model details were inputs to the heat balance program. In order to generate the radiant time series, the scheduled electric load was replaced by a single 1000-watt "pulse," repeated every 24 hours, as shown in Figure 5a. The radiant-convective split was set to 100% radiant, and the boundary conditions of the zone model were adjusted to eliminate the conductive and solar heat gains. The resulting cooling load shows the response of each zone to the radiant pulse. The cooling load profiles were normalized to sum to one; the sample radiant time factors are shown in Figure 5b. (Shown alongside are the radiant time factors for the solar heat gains, discussed below.)

The radiative portion of the hourly heat gains were then operated on by the radiant time series according to Equation 2 to obtain the hourly cooling load due to the radiative portion of the scheduled electric equipment load.

Cooling Load Due to Solar

Solar heat gains are converted to hourly cooling loads in an analogous manner. However, whereas the radiative portion of internal heat gains is uniformly distributed in the zone, the transmitted solar beam energy is usually assumed to fall entirely on the floor. This will result in a slightly different set of radiant time series, as shown in Figure 5b.

Cooling Load Due to Conduction

The response factor procedure for calculating conductive heat gain is amenable to a number of refinements when the procedure is closely coupled to a heat balance program. These refinements, which are included here for the sake of comparison, include the following.

1. Estimation of sol-air temperature directly from the heat balance. The standard sol-air procedure has an assumed longwave correction factor. When estimating the sol-air temperature from the heat balance procedure, the actual longwave radiation is used.
2. Use of surface conductances generated by the heat balance procedure. The radiative heat transfer changes every hour, depending on the interior surface temperatures. A custom surface conductance can be determined as the total heat flux leaving the wall divided by the difference between the surface temperature and the air temperature. This actually results in 24 different surface conductances for each surface. The surface conductance corresponding to the peak hour is used for all hours.

The RTS procedure that uses these two refinements will be referred to as "RTS-Custom" later in this paper; the standard

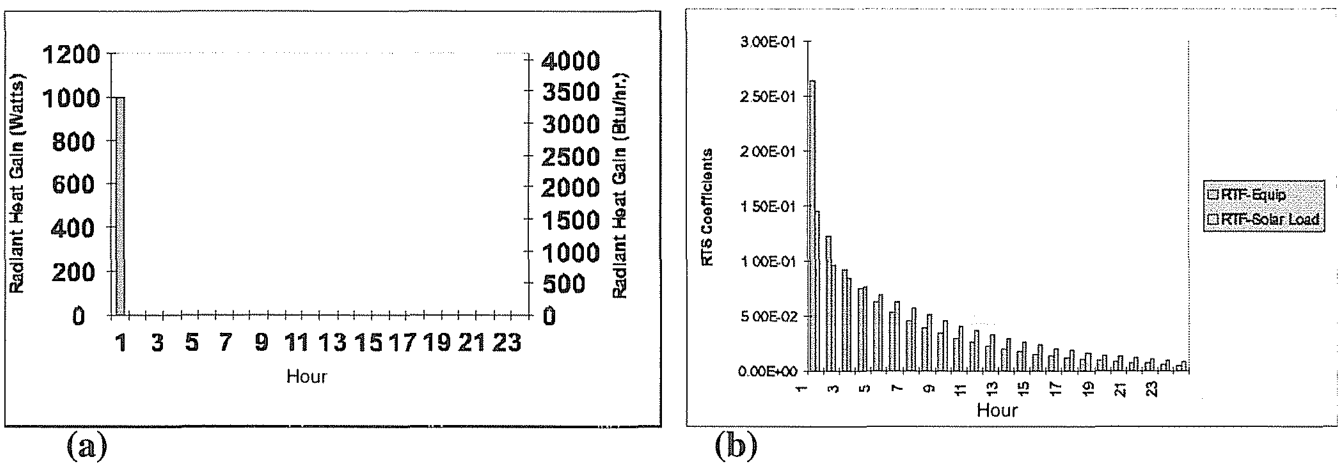

Figure 5 *One-hour internal heat gain pulse and resulting RTS coefficients.*

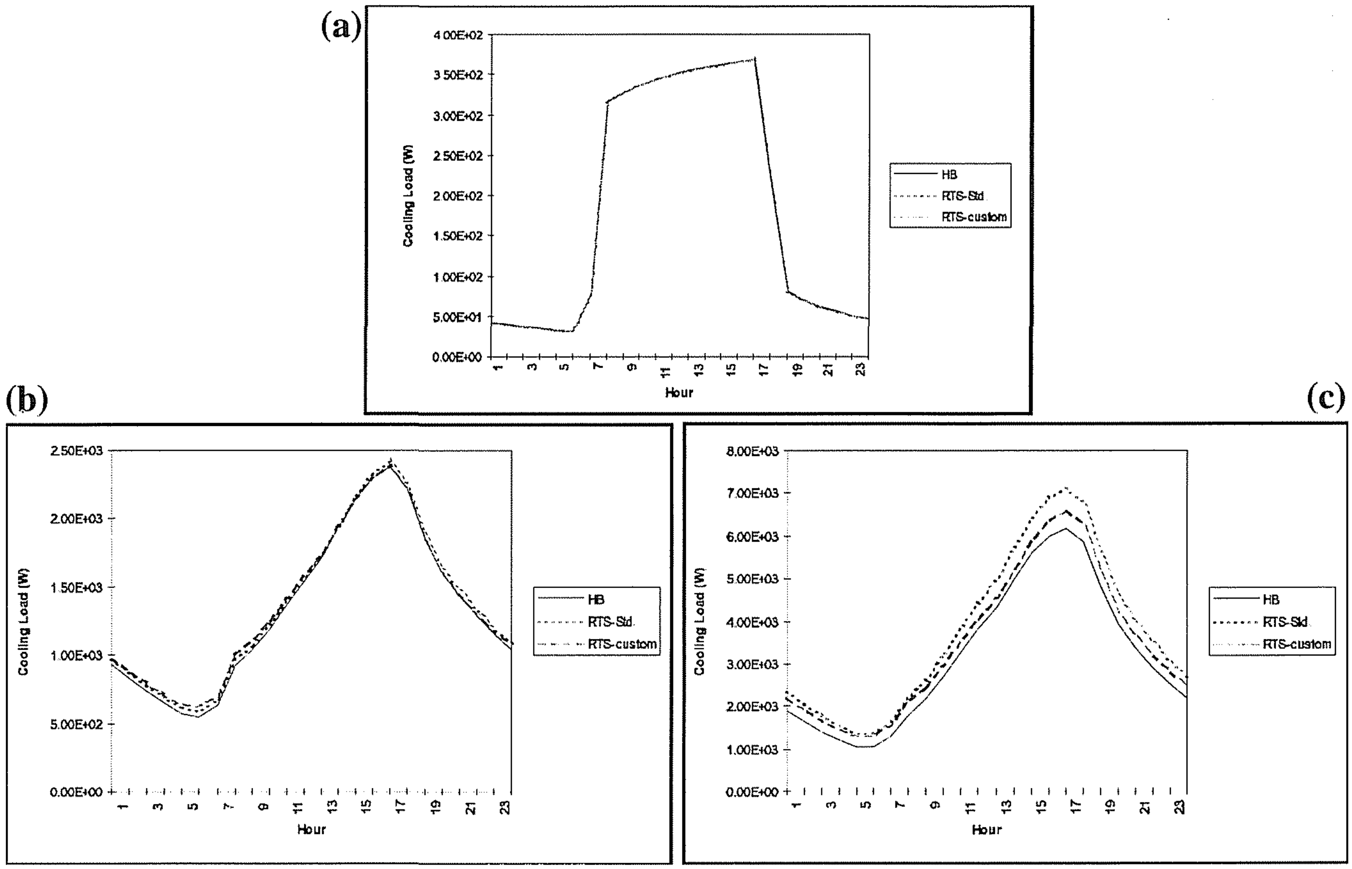

Figure 6 *Comparison between heat balance and radiant time series methods for a) the interior zone, b) the SW corner zone with 20% glazing, and c) for the SW corner zone with 70% glazing.*

procedure that uses the usual sol-air temperature estimation and standard surface conductances will be referred to as "RTS-Standard."

Summing the Cooling Load Components

The components of the cooling load were simply summed to obtain the total hourly cooling loads as shown in Figures 6a, 6b, and 6c. The "HB" curve represents the results from the heat balance procedure. The "RTS-Standard" curve represents the results from the RTS procedure utilizing the standard sol-air temperature equation and standard interior surface conductances. The "RTS-Custom" curve represents the results from the RTS procedure utilizing custom sol-air temperatures determined by the heat balance program and an interior surface conductance based on the results of the heat balance program.

Figure 6a shows for the interior zone all three methods giving identical answers. In this case both the RTS-Standard method and RTS-Custom method are the same, as there are no exterior walls, and hence sol-air temperature and interior surface conductances are irrelevant. The RTS method matches the heat balance method extremely well for this case, which only has an equipment heat gain.

Figure 6b shows that for the southwest corner zone, with only 20% exterior glass, both the RTS-Standard method and the RTS-Custom method slightly overpredict the cooling load. However, use of the custom surface conductances and custom sol-air temperatures make little difference in this case.

However, for the case with 70% glass in the exterior walls shown in Figure 6c, the effect of custom surface conductances and custom sol-air temperatures is more significant. This is expected, as the effect of the surface conductance and sol-air temperature on the overall (air-to-air) resistance is much higher on a window because of its low thermal resistance. Furthermore, as the disparity between the individual surface temperatures increases (with all the solar radiation incident on the floor), the RTS method cannot match the heat balance method as well. This should be understood from the fact that as interior surface temperatures rise, the radiation from the exterior surfaces to the interior surfaces naturally decreases. This effect is modeled using the heat balance procedure's radiant interchange model. However, the RTS procedure is limited to fixed surface conductances that "radiate" to the room air temperature.

PRELIMINARY VALIDATION

At this point in time, no comprehensive validation has been attempted. (Nor, to the best of the authors' knowledge, has a truly comprehensive validation of the existing simplified cooling load calculation procedures been reported. Sowell [1988b] reported a validation of the weighting factor generation program for 14 zone types. The validation compared results from the weighting factor generation program to the results from three other building simulation programs.) However, some preliminary validation work has been performed that shows that the RTS procedure satisfies the chief criterion for a simplified procedure—it closely predicts or overpredicts (but not excessively) the peak load. The preliminary validation suite was performed for nine zone orientations representing the unique zone locations in a building, as shown in Figure 7.

Both mid-floor and top-floor zones were evaluated. The first set of tests used the medium-weight zone construction shown in Table 3. An additional set of top-floor tests was run using a lightweight exterior insulation finish system construction. All zone floor areas were 388 ft^2 (36 m^2).

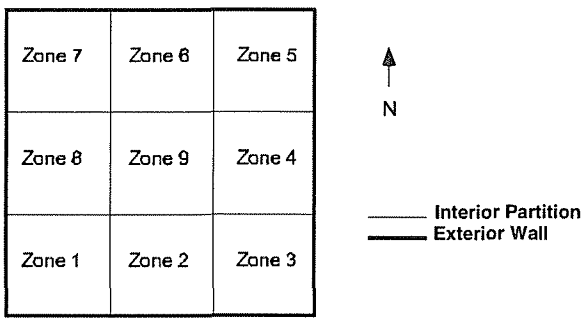

Figure 7 *Plan view showing zone locations.*

TABLE 4
Parameter Levels

Parameter	Levels
Lights (W/ft2)	0.5, 1, 1.5, **2**, 2.5, 3, 3.5, 4
Equipment (W/ft2)	0, **1**, 2, 3, 4, 5, 6
People (ft2/person)	50, **100**, 150, 200, 250, 300, 350
Infiltration (ACH)	0, **1**, 2, 3, 4, 5
Glazing (% Area)	0, 10, **20**, 30, 40, 50, 60, 70, 80, 90, 99

For these 27 zones (mid-floor/medium-weight construction, top-floor/medium-weight construction, and top-floor/lightweight construction), three internal load parameters (people, equipment, and lights) and two envelope parameters (percent glazing and infiltration) were varied one at a time from the base case over a reasonable range to yield a set of 945 test cases. The parameter ranges are shown in Table 4 with the base case values in bold.

As shown in Figure 8 the RTS method either closely predicts or slightly overpredicts the load for all cases. The only significant departure from the heat balance calculated load was for the cases with high percentages of glazing. These can be seen on the far right-hand side of Figure 8.

It should be noted that the preliminary validation exercise does not bound the range of applicability of the RTS method or examine the sensitivity of the radiant time series to various

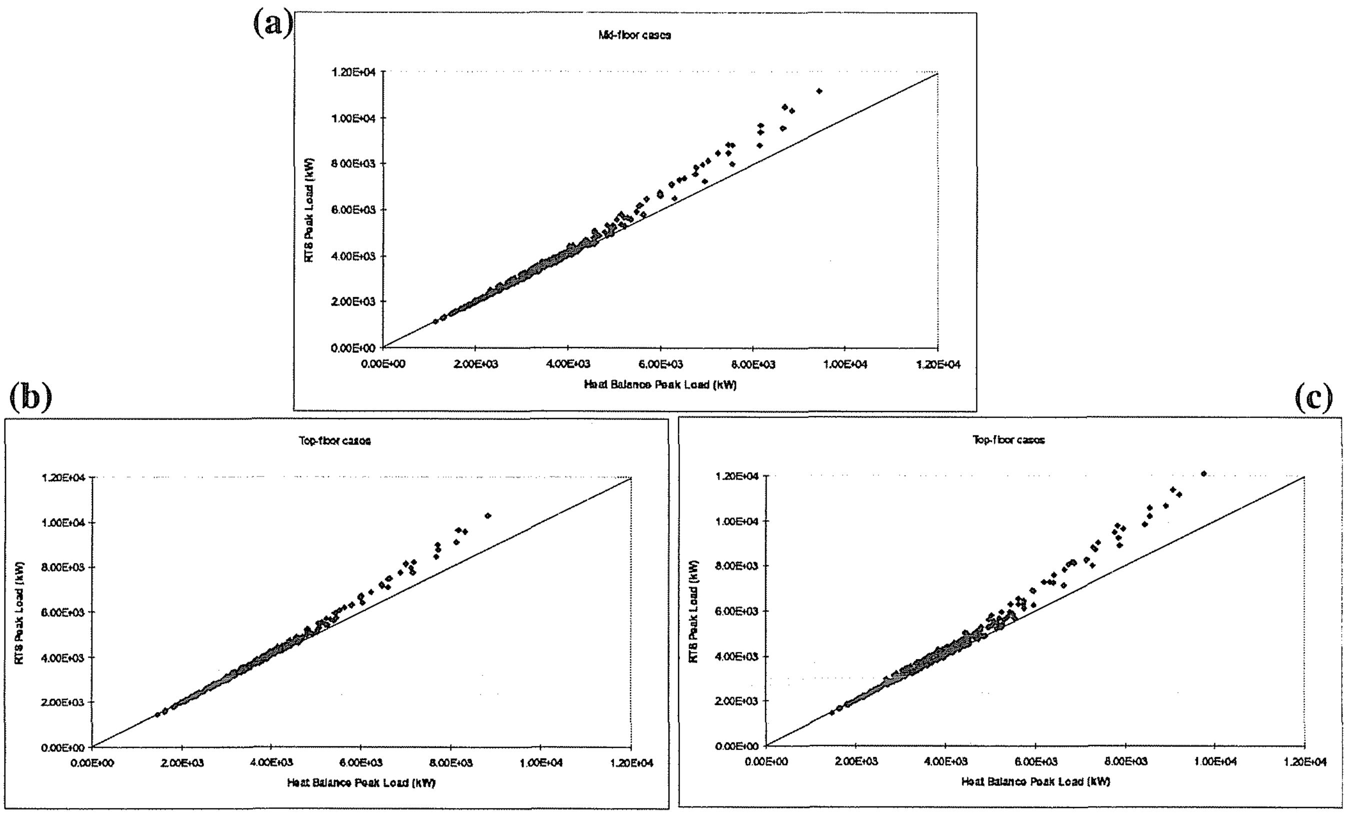

Figure 8 *Comparison of peak loads for a) mid-floor/medium-weight construction; b) top-floor/medium-weight construction; and c) top-floor/lightweight construction.*

parameters. Work in progress will address the sensitivity of the RTS calculated loads to a number of parameters, including the convective heat transfer coefficient, surface construction, flux distribution, and the radiant-convective split for conduction. In addition, the impact of the basic assumptions and inherent limitations of the method will be evaluated. Results from the RTS procedure will be compared to those from the heat balance procedure for a wider range of zone types. If necessary, improved estimations of the sol-air temperatures, interior surface conductances, and radiative-convective splits will be investigated. It is not inconceivable that the program that generates the radiant time factors for each zone could also generate recommended sol-air temperatures, interior surface conductances, and radiative-convective splits for the conductive heat gain. Alternatively, it may be possible to recommend better approximations for sol-air temperatures, interior surface conductances, and radiative-convective splits that are generally applicable.

CONCLUSIONS AND RECOMMENDATIONS

Although the current work demonstrates the viability of the RTS method under a limited set of conditions, additional data are required to determine the accuracy of the method over the full range of conditions anticipated for cooling load calculations. Important results to date include the following.

- Twenty-four-term wall and roof periodic response factors, derived using a unit periodic sol-air temperature pulse, have been derived from a larger set of response factors.
- The feasibility of generating radiant time factors directly from the heat balance method has been established.
- The radiant time series method has the potential to closely match the heat balance results; however, additional work is required to realize this potential and to characterize the error.

Based on the results to date, the following recommendations for additional research are offered.

- Using a much larger number of test cases, characterize the error of the radiant time series method when compared to the heat balance method. Besides the quantitative error estimates, additional qualitative insights into the differences between the two methods should be obtained. To some extent, these insights will also apply to some of the other simplified methods.
- Improve sol-air temperature estimation either by improving the formulation or by generating sol-air temperatures directly from a heat balance procedure.
- Improve the estimate of the radiative portion of the surface conductance. Obviously, this can be done for a specific surface and zone using a heat balance program. More general approaches should also be investigated.
- Improve the estimate for the radiative-convective split for conductive heat gain. Again, this can be done for a specific surface and zone using a heat balance program, but more general approaches should also be investigated.

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DISCUSSION

Douglas T. Reindl, Assistant Professor, University of Wisconsin-Madison, Madison, Wis.: Since the RTS is a proposed replacement method for the current simplified load calculation procedures, e.g. CLTD/SCL/CLF, TETD/TA, it seems to me that for the RTS to be "successful" it must be (1) simple; (2) be more accurate than current simplified methods; and (3) relax constraints that bound the current simplified methods. Can you comment on how the RTS compares with the current simplified method, CLTD/SCL/CLF, in the context of these criteria?

Jeffrey D. Spitler: First, the RTS is a proposed replacement procedure for all of the simplified load calculation procedures, the transfer function method (TFM), as well as the CLTD/SCL/CLF and TETD/TA methods. With respect to how the RTS procedure compares to the CLTD/SCL/CLF procedure, for the following criteria:

1. *Simplicity.* The RTS procedure requires more calculations than the CLTD/SCL/CLF procedure. However, it requires less determination of intermediate parameters, e.g., the designer does not have to find the closest primary and secondary materials for each wall nor determine whether the wall is primarily characterized by "mass located outside insulation", "mass located inside insulation", or "mass evenly distributed"; nor choose between three levels of glazing or four exterior wall types when characterizing the zone.
2. *Accuracy.* The RTS procedure is more accurate than the CLTD/SCL/CLF procedure. The accuracy of the RTS procedure is similar to that of the TFM if custom weighting factors and custom conduction transfer function coefficients were used. However, as presented in the last Cooling and Heating Load Calculation Manual (McQuiston and Spitler 1992) or the *1993 Handbood—Fundamentals* (ASHRAE 1993), the TFM uses weighting factors that were pre-calculated for specific zone configurations and then grouped so that weighting factors for a single zone were used to represent the weighting factors for a group of zones. When compared to custom weighting factors, the pre-calculation and grouping procedures introduce errors in two ways: (1) any real zone must be represented by 14 parameters that are very unlikely to fit an actual zone (this error, while thought to be small for most cases, has never, to

the authors' knowledge, been investigated) and (2) the grouping procedure introduces an error with a known maximum value. Likewise, the procedure for determining conduction transfer function coefficients introduces analogous errors. The CLTD/SCL/CLF procedure, when used with custom-generated tables, can produce results very close to the TFM, with the exception that the time-dependent nature of shading is not accounted for accurately. When the CLTD/SCL/CLF procedure is used with the tables printed in the Cooling and Heating Load Calculation Manual (McQuiston and Spitler 1992), additional errors due to grouping procedures are introduced. See Chapter 8 of the manual for a discussion of the limitations of the CLTD/SCL/CLF procedure.

3. *Relaxing constraints that bound the CLTD/SCL/CLF procedure.* Some obvious, if not quantifiable, constraints of the procedure have been eliminated-- any solar absorbability may be used for exterior surfaces; shading may be used without introducing an unknown error; and any zone specification, wall type, or roof type may be used without introducing a grouping error.