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Proposals for a Building Loads Diagnostic Test Procedure

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ABSTRACT

Design cooling load calculation methods are, by the nature of the processes they seek to model, complex, and they require detailed input data involving many parameters. Diagnosing deficiencies in the calculation method or its computer implementation can be correspondingly difficult. A set of tests are proposed that are designed to exercise the principal features of any implementation of a design cooling load calculation method. Diagnosis of weaknesses of the method, or faults in its implementation, are made by making calculations with test data sets that induce a single type of heat gain or heat transfer by a particular path and comparison with a set of reference results for each test. In the tests proposed here, the ASHRAE heat balance method is used as a reference model. Details of the test input data specification are given along with the heat balance method results so that others can use the same tests. Some examples of how the tests were used in the project "Comparison of Cooling Load Calculation Methods (942-RP)" are also given.

INTRODUCTION

Design cooling load calculation software is commonly relied upon in the sizing of HVAC equipment on a wide range of building projects. Accurate sizing of equipment affects not only the proper function of the building systems but also their energy consumption and life-cycle cost. Accordingly, engineers must be able to place a high degree of confidence in load calculation methods and the computer implementations that they use.

ASHRAE has a long history of developing cooling load calculation methods. Three methods were included in the *1997 ASHRAE Handbook—Fundamentals* (ASHRAE 1997) and the *Cooling and Heating Load Calculation Manual* (McQuiston and Spitler 1992): the transfer function method (TFM), the cooling load temperature difference/solar cooling load/cooling load factor (CLTD/SCL/CLF) method, and the total equivalent temperature difference/time averaging (TETD/TA) method. Although these methods were developed and tested within ASHRAE, implementation in design software has been carried out by others. More recently, ASHRAE has funded a research project entitled "Advanced Methods for Calculating Peak Cooling Loads (RP-875)." This project has resulted in the development of two "new" methods: the ASHRAE heat balance method (Pedersen et al. 1997) and the radiant time series method (Spitler et al. 1997). At the same time, ASHRAE also commissioned the development of computer implementations of these methods. In time, third-party implementations of the heat balance and RTS methods may well appear.

In view of the importance of cooling load calculation methods and software, there is clearly a need for objective and independent assessment of the methods and quality control of the software. Design cooling load calculation methods have historically relied less heavily on computer implementation than annual energy calculation codes. For this reason systematic validation and quality control methods have mainly been developed with energy simulation programs in mind. Independent work on model validation started in the late seventies and early eighties after the growth in popularity of energy simulation after the 1973 energy crisis—see Hoellwarth (1980) and Judkoff et al. (1980) for example. Validation of energy codes has been attempted by a variety of methods that can be categorized as either (1) comparison with analytical tests, (2) inter-model comparison, or (3) comparison with empirical data.

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Ahmad (1997) has reviewed a number of such validation studies.

One of the most notable attempts at producing a systematic validation and diagnostic tool for energy simulation programs was the result of a collaborative effort organized within the International Energy Agency and is known as BESTEST (Judkoff and Neymark 1995). In this method, a number of whole year data sets, designed to test particular heat transfer submodels, are used and the success of the test judged by comparison with results from a number of well-known and widely tested codes. The data sets progressively increase in the number of model features tested. Diagnosis of particular weaknesses of the model or faults in the code is made by comparison of the results from tests with and without a particular load or feature. A number of statistical results can be compared besides the annual energy use, and a pre-defined problem diagnostic procedure has been defined for use by code developers.

Design-day cooling load calculation codes have received less attention in the way of systematic testing and problem diagnosis procedures. Recently the Comité Européen de Normalisation (CEN), the standards-making organization that includes all the major countries of Western Europe, has been in the process of developing a standard approach to load calculations. The draft CEN standard (CEN 1997) takes the form of a specification consisting of a set of heat balance equations and a set of qualification tests against which particular computer codes can be evaluated. In this case, the tests are based on a single test zone that is exposed to a combination of loads. The tests are varied by changing such things as shading, internal loads, wall construction, and system controls. In each case a number of submodels of the load calculation method are tested together. The purpose of the tests is qualification to a certain standard of accuracy and not diagnosis of particular faults.

THE APPROACH

The philosophy of the tests proposed here is rather different from that of either the CEN test procedure or BESTEST. The emphasis here is on diagnosis of deficiencies in the calculation method and/or its implementation, rather than on qualification to a particular standard. The test method seeks to do this by subjecting the test zone to a particular type of heat gain or use a particular heat transfer path in turn, rather than using different combinations of loads. In this way the results are functions of either individual (or at most only a few) submodels alone and not the whole zone heat transfer model. We have given the test procedure the name BUILDTEST, which is taken from BUILding Loads Diagnostic TEST procedure.

With computer -based cooling load calculation methods it is not possible to test the method without testing a particular implementation. Accordingly, the tests proposed here have the dual purpose of diagnosis of deficiencies in the actual calculation method and its particular implementation. The tests make use of both steady-state and dynamic boundary conditions. The authors have found that the simpler steady-state tests are most useful in diagnosing problems in the implementation of the method (i.e., programming bugs of some sort), and the dynamic tests are more useful in diagnosing deficiencies in the calculation method.

In order to apply a specific type of load in a particular test the construction of a special set of input data for each code being tested is required. The method of data input for each code tested may vary, but in the case of the methods tested by the authors this involved constructing a set of special input files. To apply a particular type of load (conduction through the walls for example) generally requires effectively “switching off” other elements of the model (radiant gain/loss at the outside surfaces, for example). The ability to do this depends first on being able to manipulate the input data to achieve the desired effect and will vary depending on the data structure of the method to be tested. A reasonably detailed knowledge of the method and the input data structure is therefore required. For example, to effectively remove radiant gain/loss at the outside surfaces in the heat balance method, it is necessary to set the external emissivity and absorbtivity to zero. Whereas, in the BREADMIT implementation of the admittance method (Bloomfield n.d.), it is necessary to set the external absorbtivity to zero and set an artificial cloudiness level to nullify the radiant loss. In some cases there may, in fact, be more than one way to switch off the required element of the calculation.

Success or failure of a particular test is intended to be judged by the user by comparison with results from a reference method. The recently introduced ASHRAE heat balance method (Pedersen et al. 1997) has been used here as the reference calculation method. The heat balance method takes the most fundamental approach of the ASHRAE methods to date and involves the solution of heat balance equations for each of the outside and inside zone surfaces, along with the zone air. This approach is similar to that of existing load and energy calculation codes such as TARP (Walton 1983) and BLAST (1986). Radiant and convective heat exchange are treated separately at both inside and outside surfaces, with interior radiant exchange being calculated using the MRT-balance algorithm of Walton (1980). Transient conduction through the zone fabric is dealt with using conduction transfer functions.

To facilitate the use of these tests by others, the test results for the heat balance method in the form of hourly cooling loads per unit floor area (W/m^2[$Btu/h \cdot ft^2$]) are given in Appendix B, Tables B1-B4. The results are also available in spreadsheet form from the authors.

THE TEST SPECIFICATION

The tests are conducted with a 3 m (9.84 ft) cube-shaped test zone. A cube shape was chosen because many simplified radiant coupling algorithms give exact results for cubes and so this source of discrepancy is eliminated (except for one test included to specifically examine the effect of large aspect ratios). The construction for the test zone is described as either lightweight or heavyweight, as defined by the fabric construction given in Appendix A, Tables A1 and A2. Where glazing is included in the test zone, it is unshaded clear glazing with properties as defined in Table A3. The test zone has a single external wall facing due south. The roof surface is also exposed to external conditions. It should also be noted that all the calculations are made on the basis of the internal air temperature being held constant.[1]

There are 24 tests in total. The first eight are steady-state tests and do not include any glazing. The test specification for these tests is outlined in Table 1. The heat transfer modes intended to be tested in the steady-state tests are:

- Steady-state conduction
- Internal radiant balance
- Internal and external convective coupling
- Infiltration of outside air
- Internal air heat balance
- Internal radiant heat balance

The first test involves applying no heat gains at all. Although this is a rather pathological case, it is worthwhile to demonstrate that all gains can be turned off before introducing individual gains in the rest of the tests. This is not as easy as it sounds. As noted earlier, the data structure of most codes does not allow the sun to be explicitly "turned off" and it may well be necessary to set external emissivities and absorptivities to zero, for example, to achieve the same effect. It is also worthwhile checking that no numerical problems are generated by having zero gains.

Steady-state conduction and convective coupling are tested (tests 2-4) by applying a steady 10 K (18°F) inside to outside dry-bulb temperature difference. A cube geometry should present no problems for even the simplest internal radiant exchange model. Differences in results may be expected, however, at other zone aspect ratios. To test this, we have included a test zone (test 3) with a 10:1 aspect ratio (the external wall is maintained as 3 m × 3 m). Admittedly, the MRT-balance algorithm (Walton 1980) used by the heat balance method does not give the same answer at this aspect ratio compared to a uniform radiosity/exact view factor radiant exchange calculation. However, Liesen and Pedersen (1997) made calculations with the heat balance method using different radiant exchange models and found differences in the predicted peak load of only 0.7% between the results of using the MRT-balance algorithm and using a uniform radiosity/exact view factor model.

To stress the convective heat transfer calculation (test 4) we have used a high U-factor wall construction, one layer of 13 mm (0.51 in.) gypsum wall board, U = 3.87 W/m^2·K (0.682 Btu/h·ft^2·°F). Doing this increases the significance of the convective conductance relative to the overall wall conductance. The values of the convective heat transfer coefficient used in the heat balance method in this case are as given in Table A4, except that at the outside the values are 6.45 W/m^2·K (11.4 Btu/h·ft^2·°F)at the wall and 7.46 W/m^2·K (13.1 Btu/h·ft^2·°F) at the roof.

The calculation of cooling load due to infiltration of outside air is tested in tests 5 and 6. In these tests we define the zone as having no external surfaces to avoid the complication of applying a conduction load at the same time. A comparative solution can be obtained using the psychrometric property formulae of *ASHRAE Fundamentals* (ASHRAE 1997, chapter 6). Here we define the room volume to be 27m^3 (953.4 ft^3) and the mass flow rate to be calculated using the air density at outside conditions. In this case ρ = 1.1327 kg/m^3 (0.0708 lb/ft^3), and the inside and outside dry air enthalpies are h_{ai} = 24.146 kJ/kg·K (5.771 Btu/lb·°F] and h_{ao} = 34.212 kJ/kg·K(8.177 Btu/lb·°F) so that the sensible loads per unit floor area A_f (given by $q_i = \rho \dot{v}\ (h_{gai} - h_{gao})/A_f$) should be 1.90 W/m^2 (0.602 Btu/h·ft^2) and 95.02 W/m^2 (30.12 Btu/h·ft^2) for tests 5 and 6, respectively.

1. Heat gains are defined as the rates at which heat enters or is generated within a space. Cooling loads are defined as the rates at which sensible heat must be removed from the space to maintain constant air temperature.

TABLE 1

The Specification for the Steady-State Test Cases*

Test No.	Feature Tested	Load Conditions	Zone Features			
			LW	HW	LG	HG
1	Zero load case	Zero heat gain	X			
2	Steady conduction	Steady conduction ($T_{ao} - T_{ai}$ = 10 K [18°F])	X			
3	Surface - surface radiation	3 × 3 × 30 m zone, steady conduction ($T_{ao} - T_{ai}$ = 10 K [18°F])	X			
4	Convective coupling	Steady conduction ($T_{ao} - T_{ai}$ = 10 K [18°F]), high "U-factor"	X			
5	Infiltration	Steady infiltration of 0.2 ACH ($T_{ao} - T_{ai}$ = 10 K [18°F])	X			
6	Infiltration	Steady infiltration of 10.0 ACH (T_{ao} - T_{ai} = 10 K [18°F])	X			
7	Internal air heat balance	Steady convective internal load of 50 W/m^2 (15.85 Btu/h·ft^2)		X		
8	Internal radiation balance	Steady radiant internal load of 50 W/m^2(15.85 Btu/h·ft^2)		X		

* LW = lightweight construction; HW = heavyweight construction; LG = low (10%) glazing; HG = high (90%) glazing

Test 7, where a 100% convective internal load of 50 W/m^2 (15.85 Btu/h·ft^2) is applied, has a trivial "analytical" solution. A 50 W/m^2 (15.85 Btu/h·ft^2) load on the airstream should result. In test 8, where the same load is 100% radiative in nature, the solution is not so obvious. Although the internal and external air temperatures are the same, there is a net heat loss from the zone. This is because a 100% radiative gain will effectively be applied at the zone internal surfaces causing a rise in their surface temperature and, hence, a temperature gradient across the external wall.

Tests 9-20 are dynamic in nature. The response of the test zone to the following types of heat gain are intended to be tested:

- Dynamic internal gains
- Dynamic conducted gains
- Solar gain through opaque surfaces
- Solar gain through glazed surfaces

Although the sources of heat gain are various in this series of tests, it is the modeling of the dynamic storage of energy in the zone fabric that is also implicitly tested. There are variations on each test with different zone construction and, where applicable, high and low proportions of glazing.

Tests 9-12 involve the application of internal gains of different convective/radiant proportions in a stepped schedule ("on" for the middle 12 hours of the day). As the cooling load is calculated on the airstream, a 100% convective load (test 9) should have as straightforward an outcome as the equivalent steady-state test (test 7). Application of a stepped internal load with some radiant portion results in the charging/discharging of the thermal mass via the internal surfaces (tests 10-12). The cases with equal radiant/convective proportions are intended to be more indicative of real building loads.

Two tests, with differing zone construction, are included where transient conduction is driven by the difference between inside and outside air temperature. These are tests 13 and 14 in which a sinusoidally varying outside temperature is applied (43°C [109.4°F] maximum at 3 p.m., 28°C [82.4°F] minimum). As the temperature difference is defined between two air temperatures, the results are also partly a function of

TABLE 2
The Specification for the Dynamic Test Cases*

Test No.	Feature Tested	Load Conditions	Zone Features			
			LW	HW	LG	HG
9	Internal air heat balance	100% convective internal load of 50 W/m^2 (15.85 Btu/h·ft^2) with stepped schedule		X		
10	Dynamic response to radiant gains	100% radiant internal load of 50 W/m2 (15.85 Btu/h·ft^2) with stepped schedule		X		
11	Dynamic response to internal gains	Internal load of 50 W/m^2 (15.85 Btu/h·ft^2), 50% radiant component, stepped schedule	X			
11	Dynamic response to internal gains	Internal load of 50 W/m^2 (15.85 Btu/h·ft^2), 50% radiant component, stepped schedule		X		
13	Dynamic response to conduction, opaque surfaces	Cyclic (sinusoidal) conduction load	X			
14	Dynamic response to conduction, opaque surfaces	Cyclic (sinusoidal) conduction load		X		
15	Solar transmission, opaque surfaces	Cyclic solar irradiance (weather data), no glazing	X			
16	Solar transmission, opaque surfaces	Cyclic solar irradiance (weather data), no glazing		X		
17	Solar transmission, glazed surfaces	No solar through opaque surfaces, cyclic solar irradiance (weather data)	X		X	
18	Solar transmission, glazed surfaces	No solar through opaque surfaces, cyclic solar irradiance (weather data)	X			X
19	Solar transmission, glazed surfaces	No solar through opaque surfaces, cyclic solar irradiance (weather data)		X	X	
20	Solar transmission, glazed surfaces	No solar through opaque surfaces, cyclic solar irradiance (weather data)		X		X

* LW = lightweight construction; HW = heavyweight construction; LG = low (10%) glazing; HG = high (90%) glazing

the inside and outside convective heat transfer models. In the heat balance method, inside convection coefficients are fixed according to *ASHRAE Fundamentals* (ASHRAE 1997) values (see also Table A4), and the Mowitt model (Yazdanian and Klems 1994) is used to define outside convection coefficients.

Response to cyclic heat fluxes driven by absorption of solar irradiation on the outside of zone opaque surfaces is tested in 15 and 16. Solar flux data for June 21 at Phoenix (latitude 33.43°, longitude 112.02°) have been used for this purpose. The results of these tests are partly dependent on the solar insolation model used. Although the user of most codes cannot usually change this type of data explicitly, the heat balance code (HBFORT) does usefully provide details of the incident solar fluxes in its output (see Pedersen et al. 1998), which may also be useful when comparing results.

The gains to the zone in tests 17-20 are entirely via glazing. The window is very simple in design. It has no frame or recess and has a 3 mm pane of clear glass. The heat balance method uses the solar heat gain coefficient (SHGC) to calculate the overall heat flux transferred through the window (see chapter 29 of *Fundamentals*) after taking account of the change in transmittance with incidence angle. This model has some simplifications but gives accurate results for this type of window.

The final tests (22-25) specify a combination of loads that are intended to be representative of typical office building conditions. These tests are not intended to diagnose particular faults but allow the user to evaluate the overall significance of any particular deficiencies in the method being tested. In a situation with a combination of loads such as this, deficiencies in over- or underpredicting particular elements of the load highlighted in earlier tests may well appear less significant.

Sample Test Results

The heat balance method results for the steady-state tests are given as the constant hourly cooling load per unit floor area in Table B1. The results for the dynamic tests are given as hourly cooling loads per unit floor area in Tables B2 and B3 and the results for the final tests with a combination of loads in Table B4.

The authors have previously completed a parametric study comparing the RTS method and the BRE-ADMIT (Bloomfield n.d.; Danter 1986) implementation of the admittance method (Loudon 1968; CIBSE 1986) to the heat balance method in which several thousand test zone calculations were made (Rees et al. 1998). Although the parametric study showed particular trends in the performance of the simplified methods, the tests described here were used to diagnose “bugs” in the implementations and highlight particular submodels of the methods as the cause of certain deficiencies. For example, although the steady-state tests appear simple, we were able to find errors in the calculation of gains through roof surfaces in one method and calculation of infiltration in another (Spitler et al. 1998).

Some further differences were found in the results of the steady-state tests. An “analytical” solution to the infiltration tests 5 and 6 was given earlier. There are small differences between these values and those calculated using the heat balance method. This is due to the fact that the air enthalpy difference was found from values taken from the tables of *Fundamentals* (ASHRAE 1997, chapter 6, Table 2) rather than from $C_p \Delta T$ in the heat balance method. There are larger differences between these values and that given by the BREADMIT implementation of the admittance method, as this code uses a constant of 1.2 for the value of ρCp of air.

TABLE 3
The Specification for the Combined Load Test Cases*

Test No.	Feature Tested	Load Conditions	Zone Features			
			LW	HW	LG	HG
21	Combination of loads	3 m cube; stepped internal load of 50 W/m^2 (15.85 $Btu/h \cdot ft^2$) with 50% radiant component; cyclic conduction load; 0.2 ACH infiltration; cyclic solar irradiance (weather data)	X		X	
22	Combination of loads	3 m cube; stepped internal load of 50 W/m^2 (15.85 $Btu/h \cdot ft^2$) with 50% radiant component; cyclic conduction load; 0.2 ACH infiltration; cyclic solar irradiance (weather data)	X		X	
23	Combination of loads	3 m cube; stepped internal load of 50 W/m^2 (15.85 $Btu/h \cdot ft^2$) with 50% radiant component; cyclic conduction load; 0.2 ACH infiltration; cyclic solar irradiance (weather data)		X	X	
24	Combination of loads	3 m cube; stepped internal load of 50 W/m^2 (15.85 $Btu/h \cdot ft^2$) with 50% radiant component; cyclic conduction load; 0.2 ACH infiltration; cyclic solar irradiance (weather data)		X	X	

* LW = lightweight construction; HW = heavyweight construction; LG = low (10%) glazing; HG = high (90%) glazing

It is also worth noting that where a steady 50 W/m² (15.85 Btu/h·ft²) radiant load was applied (test 8), the heat balance method results indicate a slight loss of energy (Q_a = 47.7 W/m² [15.12 Btu/h·ft²]), whereas the RTS method predicts zero loss (i.e., Q_a = 50 W/m² [15.85 Btu/h·ft²]). This is indicative of the fact that all radiant energy is entirely conserved in the zone in the RTS method calculation (this is discussed further in Rees et al. 1998). The BREADMIT code predicts a larger loss for this case (Q_a = 45.9 W/m² [14.55 Btu/h·ft²]).

In the admittance method, the radiant and convective components of internal loads are apportioned to either the inside air or environmental temperature nodes of the room model (see CIBSE 1986, Section A8). The overall load in this method is worked out as the sum of a mean and fluctuating component. The response to the fluctuating component is determined by the room's overall "admittance." The results of tests 10 - 12 show that this gives a very simplified response to dynamic radiant gains. The results of these tests are plotted hourly in Figure 1. It can be seen that although the effect on the mean load is correctly represented, the effect of storage of the radiant energy on the peak load is not. This is interestingly true in the lightweight zone case as well as the heavyweight zone case.

The results of tests 18 and 20, where a solar gain is introduced via 90% glazing to a test zone of lightweight and heavyweight construction, respectively, are shown in Figure 2. The response in the lightweight case is notably symmetrical due to the window being oriented due south and the zone being of low thermal mass. There is reasonably good agreement in the prediction of peak load. There is, however, a notable difference in results in the night hours. The heat balance and RTS method results show an overall loss of energy from the zone during the night hours due to radiation to the night sky. The admittance method results show a steady cooling load during these hours. In the implementation of the admittance method tested here, the overall solar gain at a particular hour $G_{eS\theta}$ is given by

$$G_{eS\theta} = \bar{I}\bar{S}_e + \tilde{I}_\theta \tilde{S}_e \tag{1}$$

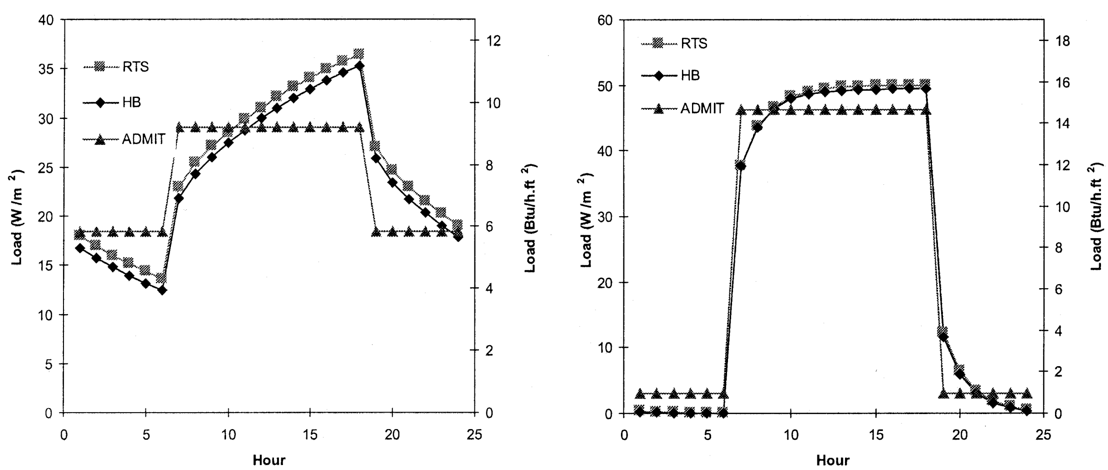

Figure 1 *Results from tests 10 (left) and 11 (right) for stepped radiant loads with 100% in a heavyweight zone and 50% radiant components in a lightweight zone.*

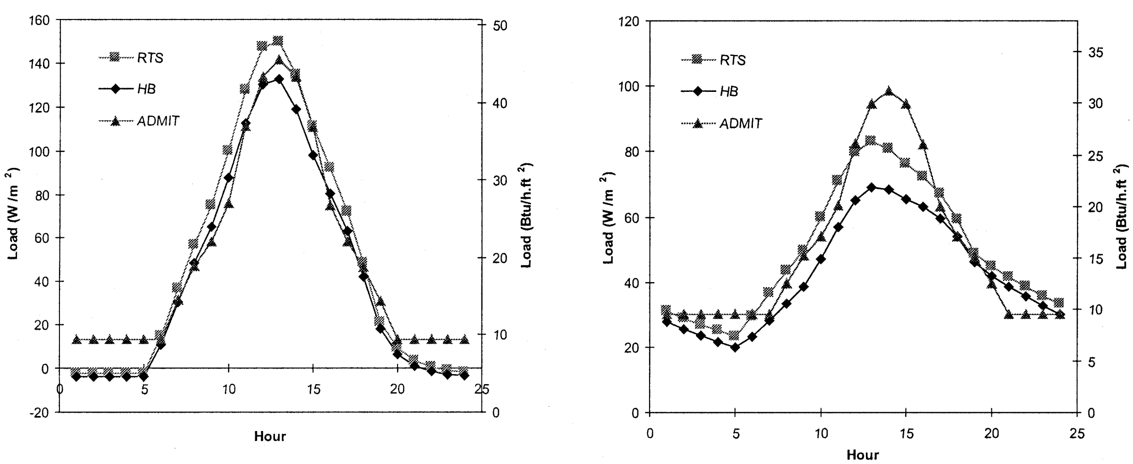

Figure 2 *Results for tests 18 and 20 with 90% glazing and a lightweight (left) and heavyweight (right) zone construction.*

In this model the solar gain factors $\bar{S}_e$ and $\tilde{S}_e$ are constants that multiply $\bar{I}$ and $\tilde{I}_\theta$, the mean and alternating components of the solar fluxes, respectively. These factors are tabulated in the CIBSE (1986) Guide and were calculated using an admittance method room model with London weather data and a southwest-facing window but using a detailed window model. However, with other window orientations and locations, these factors do not give both the correct peak load and zero load at night hours, as can be seen in the results of the tests.

The last four tests of the series employ a combination of loads. The results for tests 23 and 24 with heavyweight construction and 10% and 90% glazing for the three methods are shown in Figure 3 (note the different vertical scales). It is interesting to note here how some deficiencies in certain submodels can counteract each other where there are a variety of gains. In the case with 10% glazing, the admittance method results show an underprediction of the peak load, whereas with 90% glazing, there is an overprediction at the peak. With the knowledge of the other test results, this can be explained. With only 10% glazing, the internal gain is the most significant component, and the BREADMIT code was noted above as generally underpredicting its effect on the load. With 90% glazing, the solar gain is much more significant and the tendency to overpredict solar gains in heavyweight zones counteracts the underprediction of the effect of the internal gains.

CONCLUSIONS

A series of simple tests has been developed that can be used to test design cooling load calculation methods and their computer implementations. This series of steady-state and dynamic tests can be used to usefully diagnose problems that are the result of coding errors and deficiencies in submodels used in the cooling load calculation method.

Examples have been given from the authors' own experience how such tests can be used to diagnose errors in method implementations and highlight some deficiencies in the calculation models. The test series is proposed as a diagnostic tool for use by cooling load calculation tool developers and testers for testing other methods against the reference model results presented here.

The tests are admittedly not completely comprehensive in the model features they test. For example, there are no tests of any shading devices or ground-coupled slabs. Also, a test with a more sophisticated window test could be added. This has been because these features were not in the scope of the original research project. The intention, however, has been that the test method could be easily extended by others to include such tests.

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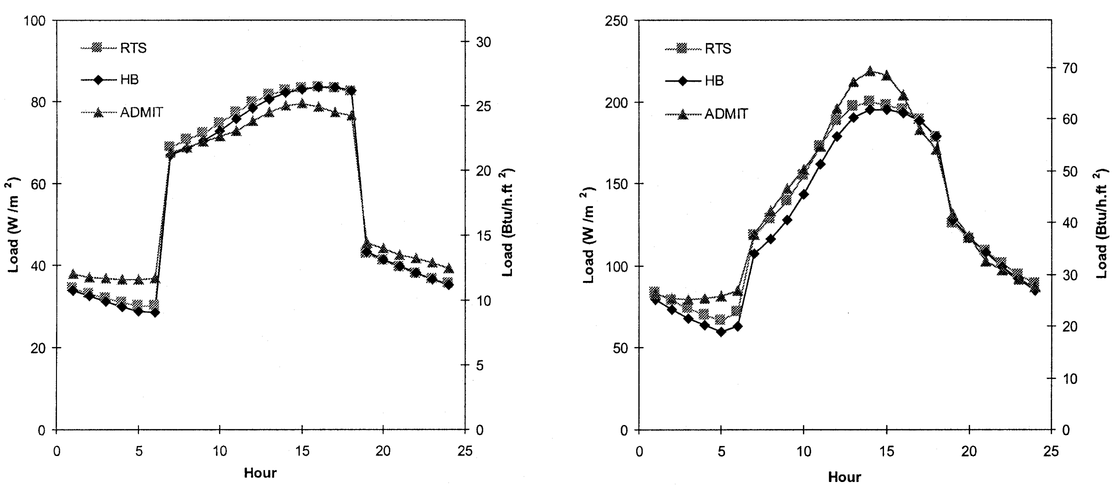

Figure 3 *Results for tests 23 and 24 using a heavyweight zone construction, 10% (left) and 90% (right) glazing, respectively, and a combination of heat gains.*

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APPENDIX A

Test Zone Construction

TABLE A1
Lightweight Test Zone Fabric Construction (Listed Outside to Inside by Layers)

Layer Material	Thickness, mm	Thickness, inches	ρ Kg/m^3 (lb/ft^3)	C_p kJ/kg·K (Btu/lb·°F)	k W/m·K (Btu/h·ft·°F)
EXTERIOR WALL: LIGHTWEIGHT TIMBER CLAD					
Cedar wood planks	15	0.59	400 (25)	1.63 (0.39)	0.11 (0.064)
Air gap	19	0.79	1.2 (0.075)	1.005 (0.24)	
Plywood	9	0.35	540 (34)	1.21 (0.29)	0.12 (0.069)
Insulation	150	6	32 (2)	0.71 (0.17)	0.04 (0.092)
Vapor barrier	1	0.04	1860 (116)	0.84 (0.20)	0.35 (0.20)
Plaster board & skim	13	0.5	800 (50)	1.09 (0.26)	0.16 (0.092)
PARTITION WALL: STUD WALL INTERNAL PARTITION					
Gypsum wall board	13	0.5	800 (50)	1.09 (0.26)	0.16 (0.092)
Insulation	100	4	32 (2)	0.71 (0.17)	0.04 (0.092)
Gypsum wall board	13	0.5	800 (50)	1.09 (0.26)	0.16 (0.092)
FLOOR: WOOD FLOOR WITH GYPSUM BOARD CEILING					
Gypsum wall board	13	0.5	800 (50)	1.09 (0.26)	0.16 (0.092)
Air gap	190.5	7.5	1.2 (0.075)	1.005 (0.24)	
Pine	20	0.79	640 (50)	1.63 (0.39)	0.15(0.087)
ROOF: STEEL DECKING INSULATED					
Membrane	10	0.4	1121 (70)	1.67 (0.40)	0.19 (0.11)
Insulation	150	6	32 (2)	1.21 (0.29)	0.04 (0.092)
Steel pan	2	0.08	7689 (481)	0.42 (0.1)	45 (26)
Ceiling air space	1000	39	1.2 (0.075)	1.005 (0.24)	
Ceiling tile	10	0.4	370 (23)	0.59 (0.14)	0.06(0.035)

TABLE A2
Heavyweight Test Zone Fabric Construction (Listed Outside to Inside by Layers)

Layer Material	Thickness, mm	Thickness, inches	ρ Kg/m^3 (lb/ft^3)	C_p kJ/kg·K (Btu/lb·°F)	k W/m·K (Btu/h·ft·°F)
EXTERIOR WALL: HEAVYWEIGHT BLOCKWORK & CAVITY INSULATION					
Facing brick	100	4	1600 (100)	0.79 (0.19)	0.84 (0.49)
Air gap	100	4	1.2 (0.075)	1.005 (0.24)	
Insulation	50	2	32 (2)	0.71 (0.17)	0.04 (0.02)
Solid concrete block	215	8.5	2100 (131)	0.92 (0.22)	1.63 (0.94)
Plaster	13	0.5	720 (45)	0.84 (0.20)	0.16 (0.16)
PARTITION WALL: BLOCKWORK INTERNAL PARTITION					
Plaster	13	0.5	720 (45)	0.84 (0.20)	0.16 (0.09)
Concrete block	100	4	2100 (131)	0.92 (0.22)	1.63 (0.94)
Plaster	13	0.5	720 (45)	0.84 (0.20)	0.16 (0.09)
FLOOR: IN-SITU CONCRETE SLAB & TILE FINISH					
Cast concrete	200	8	2300 (144)	0.9 (0.22)	1.73 (1.0)
Screed	70	2.75	1920 (120)	0.88 (0.21)	1.4 (0.81)
Vinyl tiles	5	0.2	800 (50)	1.26 (0.30)	0.6 (0.35)
ROOF: CONCRETE SLAB INSULATED					
Stone chippings	13	0.5	881 (55)	1.67 (0.4)	1.436 (0.83)
Felt & membrane	10	0.4	1121 (70)	1.67 (0.4)	0.19 (0.11)
Insulation	50	2	40 (205)	0.92 (0.22)	0.025 (0.01)
Cast concrete	150	6	2300 (144)	0.9 (0.22)	1.73 (1.0)

TABLE A3
Window Properties

GLAZING TYPE 1: SINGLE-PANE CLEAR GLASS, NO FRAME		
Layer Material	**Thickness mm (in.)**	**Coating**
Clear glass	3 (0.118)	None
Property		
U-factor W/m^2 (Btu/h·ft^2)		6.31 (1.11)
Shading coefficient		1.0
Solar heat gain coefficient		0.86
Normal solar transmittance		0.84
Normal solar absorptance		0.15
Inside emissivity		0.84
Outside emissivity		0.84
Surface-to-surface thermal conductance. W/m^2·K (Btu/h·ft^2)		300 (52.8)

TABLE A4
Miscellaneous Data

Convective heat transfer coefficients, W/m^2·K (Btu/ft^2·°F)	
Inside: walls	4.679 (0.824)
Inside: floor	4.37 (0.769)
Inside: ceiling	1.25 (0.220)
Outside: wall	6.33 (1.11)
Outside: roof	7.46 (1.31)
Wind, m/s (ft/s)	3.6 (11.8) Northerly
Barometric pressure, KPa (in. Hg)	101.325 (30.0)
External wet bulb, °C (°F)	20.0 (68.0)
Weather day	Phoenix, June 21
Max/Min. dry bulb (tests 21-25), °C (°F)	43.0 / 28.0 (109.4/82.4)
External LW emmissivity	0.9
External solar absorptivity	0.93
Internal LW emissivity	0.9
Internal SW emissivity	0.65
Ground reflectivity	0.2

APPENDIX B

Test Results

TABLE B1
Test Results for the Steady-State Test Series

Test Number	1	2	3	4	5	6	7	8
Hourly cooling load, W/m^2 ($Btu/h \cdot ft^2$)	0.0 (0.0)	4.33 (1.37)	4.37 (1.39)	49.67 (15.74)	1.91 (0.605)	95.64 (30.31)	50.0 (15.85)	47.7 (15.11)

TABLE B2
Hourly Cooling Load Results for Dynamic Tests 9 - 14

Hour	Test Number											
	9		10		11		12		13		14	
	W/m^2	$Btu/h \cdot ft^2$	W/m^2	$Btu/h \cdot ft^2$	W/m^2	$Btu/h \cdot ft^2$	W/m^2	$Btu/h \cdot ft^2$	W/m^2	$Btu/h \cdot ft^2$	W/m^2	$Btu/h \cdot ft^2$
1	0	0	16.71	52.72	0.22	0.69	8.36	26.38	4.64	14.64	10.64	33.57
2	0	0	15.72	49.60	0.12	0.38	7.86	24.80	3.93	12.40	10.63	33.54
3	0	0	14.8	46.69	0.07	0.22	7.4	23.35	3.3	10.41	10.6	33.44
4	0	0	13.94	43.98	0.03	0.09	6.98	22.02	2.79	8.80	10.53	33.22
5	0	0	13.16	41.52	0.02	0.06	6.58	20.76	2.43	7.67	10.44	32.94
6	0	0	12.42	39.19	0.01	0.03	6.21	19.59	2.27	7.16	10.33	32.59
7	50	157.8	21.79	68.75	37.77	119.2	35.9	113.3	2.29	7.22	10.22	32.24
8	50	157.8	24.26	76.54	43.61	137.6	37.13	117.1	2.5	7.89	10.1	31.87
9	50	157.8	25.96	81.90	46.47	146.6	37.98	119.8	2.89	9.12	9.99	31.52
10	50	157.8	27.41	86.48	47.9	151.1	38.7	122.1	3.43	10.82	9.88	31.17
11	50	157.8	28.71	90.58	48.62	153.4	39.36	124.2	4.09	12.90	9.8	30.92
12	50	157.8	29.89	94.30	48.99	154.6	39.94	126.0	4.81	15.18	9.74	30.73
13	50	157.8	30.98	97.74	49.19	155.2	40.49	127.7	5.56	17.54	9.72	30.67
14	50	157.8	31.98	100.9	49.29	155.5	40.99	129.3	6.27	19.78	9.73	30.70
15	50	157.8	32.9	103.8	49.34	155.7	41.44	130.7	6.9	21.77	9.77	30.82
16	50	157.8	33.74	106.4	49.37	155.8	41.88	132.1	7.41	23.38	9.83	31.01
17	50	157.8	34.54	109.0	49.39	155.8	42.27	133.4	7.76	24.48	9.92	31.30
18	50	157.8	35.28	111.3	49.4	155.9	42.63	134.5	7.92	24.99	10.03	31.64
19	0	0	25.9	81.71	11.63	36.69	12.94	40.83	7.9	24.92	10.16	32.05
20	0	0	23.43	73.92	5.79	18.27	11.71	36.95	7.69	24.26	10.27	32.40
21	0	0	21.73	68.56	2.93	9.24	10.87	34.29	7.3	23.03	10.39	32.78
22	0	0	20.29	64.01	1.51	4.76	10.14	31.99	6.76	21.33	10.49	33.10
23	0	0	18.99	59.91	0.79	2.49	9.49	29.94	6.1	19.25	10.57	33.35
24	0	0	17.8	56.16	0.41	1.29	8.9	28.08	5.38	16.97	10.62	33.51

TABLE B3
Hourly Cooling Load Results for Dynamic Tests 15 - 20

Hour	Test Number											
	15		16		17		18		19		20	
	W/m^2	Btu/h·ft^2	W/m^2	Btu/h·ft^2	W/m^2	Btu/h·ft^2	W/m^2	Btu/h·ft^2	W/m^2	Btu/h·ft^2	W/m^2	Btu/h·ft^2
1	-0.14	-0.44	11.86	37.42	-0.4	-1.26	-3.63	-11.45	3.53	11.14	27.81	87.74
2	-0.41	-1.29	11.51	36.31	-0.43	-1.36	-3.77	-11.89	3.28	10.35	25.59	80.74
3	-0.57	-1.80	11.14	35.15	-0.44	-1.39	-3.84	-12.12	3.03	9.56	23.51	74.17
4	-0.66	-2.08	10.77	33.98	-0.44	-1.39	-3.88	-12.24	2.82	8.90	21.6	68.15
5	-0.7	-2.21	10.39	32.78	-0.46	-1.45	-3.89	-12.27	2.61	8.23	19.81	62.50
6	-0.69	-2.18	10	31.55	1.23	3.88	10.79	34.04	2.98	9.40	23.21	73.23
7	-0.18	-0.57	9.64	30.41	3.52	11.11	30.27	95.50	3.53	11.14	28.17	88.88
8	1.14	3.60	9.37	29.56	5.72	18.05	48.68	153.6	4.1	12.94	33.3	105.1
9	3.21	10.13	9.21	29.06	7.71	24.33	64.99	205.0	4.69	14.80	38.62	121.8
10	5.78	18.24	9.22	29.09	10.39	32.78	87.39	275.7	5.61	17.70	46.94	148.1
11	8.66	27.32	9.38	29.59	13.43	42.37	112.7	355.6	6.72	21.20	56.91	179.6
12	11.48	36.22	9.67	30.51	15.63	49.31	130.4	411.4	7.64	24.10	65.11	205.4
13	13.83	43.63	10.08	31.80	16.04	50.61	132.7	418.7	8.1	25.56	69.08	217.9
14	15.38	48.52	10.58	33.38	14.56	45.94	119	375.4	8.03	25.33	68.37	215.7
15	15.91	50.20	11.12	35.08	12.12	38.24	97.9	308.9	7.71	24.33	65.37	206.2
16	15.39	48.56	11.67	36.82	10.02	31.61	80.43	253.8	7.46	23.54	62.98	198.7
17	14.03	44.26	12.16	38.36	7.92	24.99	63.02	198.8	7.07	22.31	59.48	187.7
18	12.07	38.08	12.56	39.63	5.41	17.07	42.26	133.3	6.44	20.32	53.82	169.8
19	9.58	30.22	12.81	40.42	2.5	7.89	17.99	56.76	5.59	17.64	46.11	145.5
20	6.78	21.39	12.91	40.73	1.02	3.22	6.49	20.48	5.12	16.15	41.9	132.2
21	4.24	13.38	12.86	40.57	0.29	0.91	1.04	3.28	4.74	14.95	38.57	121.7
22	2.36	7.45	12.7	40.07	-0.08	-0.25	-1.53	-4.83	4.4	13.88	35.57	112.2
23	1.1	3.47	12.47	39.34	-0.27	-0.85	-2.76	-8.71	4.09	12.90	32.79	103.5
24	0.32	1.01	12.18	38.43	-0.36	-1.14	-3.34	-10.54	3.8	11.99	30.21	95.31

TABLE B4
Hourly Cooling Load Results for Dynamic Tests 21 - 24 Incorporating a Combination of Load Types

Hour	Test Number							
	21		22		23		24	
	W/m^2	Btu/h·ft^2	W/m^2	Btu/h·ft^2	W/m^2	Btu/h·ft^2	W/m^2	Btu/h·ft^2
1	7.88	24.86	27.03	85.28	33.86	106.8	79.2	249.9
2	6.52	20.57	22.82	72.00	32.5	102.5	73.4	231.6
3	5.47	17.26	19.44	61.33	31.22	98.50	68.18	215.1
4	4.64	14.64	16.86	53.19	30.01	94.68	63.57	200.6
5	4.12	13.00	15.58	49.15	28.97	91.40	60.02	189.4
6	5.7	17.98	30.9	97.49	28.72	90.61	63.06	199.0
7	51.34	162.0	95.41	301.0	66.94	211.2	107.1	338.0
8	59.07	186.4	122.8	387.6	68.49	216.1	116.3	366.9
9	66.07	208.5	150.0	473.2	70.29	221.8	127.6	402.6
10	73.83	232.9	184.6	582.5	72.69	229.3	143.2	451.9
11	82.22	259.4	223.6	705.6	75.58	238.5	161.9	510.7
12	89.6	282.7	254.7	803.5	78.37	247.3	178.7	563.9
13	94.4	297.8	267.9	845.2	80.52	254.0	189.9	599.2
14	96.11	303.2	262.0	826.7	81.97	258.6	194.8	614.6
15	95.38	300.9	245.0	773.0	82.83	261.3	195.1	615.6
16	93.26	294.2	226.9	716.0	83.32	262.9	193.2	609.5
17	89.7	283.0	205.2	647.5	83.32	262.9	188.0	593.2
18	84.51	266.6	176.7	557.4	82.66	260.8	178.5	563.2
19	35.33	111.5	100.3	316.3	43.41	137.0	127.6	402.6
20	26.19	82.63	75.08	236.9	41.44	130.7	116.9	368.8
21	19.79	62.44	58.53	184.7	39.77	125.5	107.8	340.0
22	15.19	47.92	46.6	147.0	38.13	120.3	99.27	313.2
23	11.92	37.61	37.98	119.8	36.61	115.5	91.71	289.3
24	9.6	30.29	31.8	100.3	35.2	111.1	85.17	268.7