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An Analytical Verification Test Suite for Building Fabric Models in Whole Building Energy Simulation Programs

Simon J. Rees, Ph.D.
Member ASHRAE

Dongyi Xiao
Student Member ASHRAE

Jeffrey D. Spitler, Ph.D., P.E.
Member ASHRAE

ABSTRACT

Validation and verification of whole building energy simulation programs can be attempted by a combination of experimental validation, intermodel comparison, and verification using solutions to analytical tests. An effort has recently been made to develop a comprehensive test suite for analytical testing of the building fabric models of such programs. The test suite consists of a series of sixteen tests covering convection, conduction, solar irradiation, longwave radiation, and infiltration phenomena, as well as ground-coupled floors. Standardized documentation for each test case that includes results for one or more sets of test parameters along with the derivation of the analytical solution is included. In addition, source code used to implement the analytical solutions and a user interface that drives this code have been developed. This paper discusses the objectives and design of the test suite and gives an overview of each of the tests. Results obtained from the use of the test suite with an existing building energy simulation program are presented and show its utility in verifying correct operation and diagnosing problems with such programs.

INTRODUCTION

Building energy analysis programs are, by the nature of the processes they seek to model, complex and require detailed input data involving many parameters. Demonstrating the validity of results and diagnosing deficiencies in the calculation method or its computer implementation can be correspondingly difficult. The need for some form of validation of building energy simulation codes has been long recognized. A number of attempts have been made over the last two decades to identify suitable validation procedures by a number of organizations (e.g., NREL [Judkoff et al. 1983; Judkoff and Neymark 1995], BRE [1988], and the IEA [Bloomfield et al. 1988]), but no standard procedures have been universally accepted despite the proliferation and increased use of such programs.

It is first of all helpful to define what we mean by the terms *verification* and *validation* in this context. We make the distinction between the code *verification* and *validation* following the definitions given by Boehm (1981) and Blottner (1990). They described verification as "solving the equations right" and validation as "solving the right equations." Three types of test methods applied to whole building energy simulation programs, in which results from one code are compared with results from other sources, can be identified (Judkoff et al. 1983). These are experimental data, intermodel comparison, and analytical testing. Of these approaches, analytical tests are most abstracted from the full complexities of real building simulation problems, but they offer the most certain form of reference or "truth" model with which comparisons can be made. Being slightly abstract in nature, they may be of least interest to the end user of simulation codes, but are arguably the most useful to the code developer in that they offer the clearest path to the diagnosis of specific problems with the algorithms or their implementation. In terms of our definition, such tests should probably be thought of as primarily *verification* tests.

Intermodel comparisons of results from annual energy analysis codes have been attempted by a number of groups. One notable attempt has also been made at devising a systematic diagnostic tool based on intermodel comparisons (Judkoff and Neymark 1995). A further type of intermodel comparison can be identified, which consists of a large number of test cases (of the order one thousand) where certain parameters are systematically varied. Such a study using "design day" cool-

Simon J. Rees is a visiting assistant professor, **Dongyi Xiao** is a research assistant, and **Jeffrey D. Spitler** is a professor in the School of Mechanical and Aerospace Engineering, Oklahoma State University, Stillwater, Okla.

ing load calculation methods has been completed as part of ASHRAE research project 942-RP (Rees et al. 1998; Spitler and Rees 1998).

In any type of test, where results of a given code are compared with data from another source, three things are implicitly tested, each of which may contribute to the overall "error" in the results.

- The interpretation of the input data
- The model(s) or algorithm(s)
- The computer implementation of the algorithm(s)

Where test specifications have to be interpreted in some way by a user in the formation of the input data for a particular test program, differences are likely to arise from differing interpretations of the specifications. This has been shown in the past on several projects (Allen et al. 1985). Fortunately, these problems can be minimized in the case of analytical tests due to the simplified nature of the building zone specifications and the possibility of using idealized zone constructions.

Analytical tests are (partly by necessity) simplified in nature and should usually be designed to allow only one particular feature (of the building zone model in this case) to be tested at a time. This should allow the ability of the code to model particular features to be verified on one hand and identification of particular model components or algorithms as the source of any problems on the other. (The term *analytical* is used here to mean a mathematical model of reality that has an analytically determinable solution for a given set of parameters and boundary conditions.) As noted above, in testing a building energy analysis code, it is both the underlying algorithms of the code and their implementation that are tested. Inadequacies in both the algorithms or in their implementation (code bugs) can be the source of discrepancies. It is not possible to test the algorithms without implicitly testing their coding. Therefore, developers can use analytical tests as a diagnostic tool to find bugs in the implementation as well as verify the operation of the various component models.

An analytical verification test suite for building fabric models in whole building energy simulation programs—ASHRAE research project 1052-RP, sponsored by TC 4.7 (Spitler et al. 2001)—has been developed to help verify the ability of whole building energy analysis programs to model various aspects of heat transfer through the building fabric. The tests are intended to be used in support of *ANSI/ASHRAE Standard 140-2001, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*. The test suite exists in three forms. In the first place, the tests exist as a set of documentation that defines the test zone and model parameters necessary to perform the test and includes one or two sets of test results for given sets of parameters. Although documentation in itself might adequately define a suitable set of test cases, software that implements the analytical tests has been developed in two forms. This software is first available in the form of Fortran90 subroutines that were used to calculate the analytical test results as they appear in the documentation. This source code can be compiled and used by interested users and developers. Furthermore, a user interface to the Fortran90 subroutines has been developed as a means of conveniently running the tests on personal computers. The principal advantage of the test suite software being available to users is that parameter values (e.g., convection coefficients) other than those used in the documented tests may be used to calculate specific analytical solutions.

This paper outlines the development of the analytical tests and the implementation of the test suite software and summarizes the initial testing results from an in-house comparison of BLAST to analytical solutions. Conclusions and recommendations are also presented.

THE TEST SUITE

The test suite consists of sixteen individual tests, each with the objective to test the ability of a building energy simulation program to model a particular heat transfer phenomenon. The test is applied by comparing the output of the energy simulation program to be tested with the analytical solution for a special test zone. The data to be compared may be a single zone load, heat flux, temperature, or hourly loads over one or more days of output. In this section, the organization of the tests is described first, some general concerns relevant to several of the tests are discussed, and the individual objective and analytical model used in each test are explained.

Organization of the Tests

The sixteen individual tests of the test suite are organized into groups relating to particular heat transfer phenomena as follows:

Group 1 - Convection and conduction
Group 2 - Solar gains and shading
Group 3 - Infiltration
Group 4 - Longwave radiation
Group 5 - Miscellaneous

In reality, convective heat transfer occurs at all building surfaces. Although it is possible to eliminate radiant effects from both analytical solutions and in the test program by selection of suitable surface properties, it is not generally possible to eliminate convective effects so conveniently. Consequently, convective heat transfer is involved in nearly all the test cases. This makes it important that the steady-state convection test be carried out first and its results analyzed prior to completion of the other test cases.

A complete list of test cases is given in Table 1. Each test is given an abbreviation for convenient referencing in the documentation. Group one is concerned with testing the ability of the test program to model convective and conductive heat transfer—both steady-state and transient. Three transient conduction cases with different boundary conditions and driving temperature profiles are included. Group two is concerned with solar radiation on both opaque and glazed surfaces. These tests are intended to test the program's time, solar position, glazing, and shading models. Group three is concerned with infiltration and group four with internal and external longwave

TABLE 1
Organization of the Test Suite

Test Group	Test Title	Abbreviation
Group 1	Steady-State Convection	SSConv
	Steady-State Conduction	SSCond
	Transient Conduction—Adiabatic Wall	Tc1
	Transient Conduction—Step Response	Tc2
	Transient Conduction—Sinusoidal Driving Temperature and Multi-layer Wall	Tc3
Group 2	Exterior Solar Radiation—Opaque Surfaces	ExtSolRad
	Solar Radiation— Glazed Surfaces	SolRadGlazing
	Solar Radiation—Window Shading	SolRadShade
	Solar Radiation—Window Reveal Shading	WinReveal
	Solar Radiation—Internal Solar Distribution	IntSolarDist
Group 3	Infiltration—Fixed Infiltration Rate	Infiltration-1
	Infiltration—Stack Effect	Infiltration-2
Group 4	Interior Longwave Radiation	IntRad
	External Longwave Radiation	ExtLWRad
Group 5	Internal Heat Gains—Convective and Radiant	IntHeatGain
	Ground Coupling—Slab on Ground Floor	GrdCoup

radiation. Tests associated with internal gains and ground coupling are in group five. It is acknowledged that the limitations, both in fabric models and input data structure, of some programs will mean that not all tests can be applied to every building energy simulation program.

TEST SUITE DESIGN

The tests are designed so that, whenever possible, they may be useful to and used by program users—not only by developers. To this end, the following design principles were adopted.

When possible, the tests require only simple output typically available to program users. These include annual and monthly heating and cooling loads and annual and monthly peak heating and cooling loads. However, for many tests, hourly output is also required.

Besides the unique weather files developed for this project, the tests, for the most part, require only simple input typically available to program users. This has been done by providing the user with software implementations of the analytical solutions through which users can enter custom parameter values.

- Test as few phenomena as possible with each test to expedite identification of specific problems.
- The tests are ordered to expedite identification of specific problems.

One of the concerns in the development of the analytical tests and the development of the associated software has been the verification of their derivation and implementation. The verification has been attempted by a combination of the following methods:

- manual checking of derivation by other individuals
- checking against existing published solutions
- checking the computer implementation against published results
- cross-checking one test implementation against another for similar boundary conditions and parameters
- checking against results from other computer implementations

The way in which these methods have been applied to each of the tests has depended on the availability of other sources of solutions and implementations in each case. Further details can be found in the project final report (Spitler et al. 2001).

The Test Zone

In order to make each test specific and help diagnose problems, it is necessary to minimize the number of heat transfer paths (and, hence, the number of models involved) in each test. This requires the use of test zones that are rather different in their construction and specification from normal building zones. Considerable familiarity on the part of the tester with the operation and data requirements of the program to be tested is therefore required.

The test zone common to most of the test cases is a cube shape of $3 \times 3 \times 3$ m ($9.84 \times 9.84 \times 9.84$ ft) internal size. The surfaces that are exposed or adiabatic vary from test to test. Windows may or may not be present, depending on the specific purpose of each test. Only in the tests dealing with internal longwave radiation, internal solar distribution, and the second infiltration test (IntRad, IntSolarDist, and Infiltration-2) is the aspect ratio varied. It is assumed in all the tests that the zone air has no thermal mass. This assumption is often made in whole building energy simulation programs. If the zone air is in fact modeled with thermal mass, it may be necessary for the user of the test to modify the zone geometry so that the air mass is minimized (i.e., change the depth to be very small).

Convection Coefficients

In developing analytical solutions to building heat transfer problems, one would like to identify a "truth" model for each heat transfer phenomenon that might be applied, given certain assumptions. In the case of convection coefficients, there is no one universally acceptable "right" coefficient or correlation. However, most convection correlations used for exterior and interior building heat transfer should be reducible to the form

$$h = A + C(|T_s - T_\infty|)^n, \tag{1}$$

where

h = convection coefficient, W/m^2·K (Btu/h·ft^2);

A = constant, W/m^{2}K (Btu/h·ft^2);

C = constant, units vary depending on *n;*

n = exponent non-dimensional;

T_s = surface temperature, ºC (ºF);

T_∞ = air temperature, ºC (ºF).

For example, in the correlation for external surfaces given by Yazdanian and Klems (1994),

$$h = \sqrt{[C_t(|T_s - T_\infty|)^{1/3}]^2 + [aV_o^b]^2}, \tag{2}$$

where C_t = 0.84 for SI units and constants *a* and *b* depend on wind direction. In a correlation like this, the wind velocity can be zero so that the correlation reduces to

$$h = 0.84(|T_s - T_\infty|)^{1/3}. \tag{3}$$

In this case, *A*, *C*, and *n* of Equation 1 can be specified as 0.0, 0.84, and 0.333, respectively. In the test suite software, users are given the opportunity to enter convection correlations by specifying coefficients *A*, *C*, and *n* as defined in Equation 1. This is important, as convection correlations adopted by different energy simulation programs are not standardized. However, for the analytical tests involving transient conduction, it is not practical (in derivation of the solution) to use a nonlinear convection correlation and a constant convection coefficient must be set.

Surface Properties

In a number of the tests, it is necessary to eliminate the longwave and/or solar radiation from the interior and/or exterior surface of the zone. This requires careful specification of the zone surface properties in the test program input data. It may be possible to achieve these goals in more than one way, depending on the exact input data requirements. A common approach would be to set solar absorptivity and longwave emissivity for the relevant surfaces to zero (for numerical reasons it may in practice be necessary to set a very small number such as 1.0×10^{-06}).

Solar Data

Arriving at tests involving solar algorithms, and data that can be considered as truly "analytical," is problematic. This is because of the empirical nature of all models of diffuse solar radiation. In view of this, all of the solar radiation tests in this series involve only beam (direct) solar radiation. In each of the solar radiation tests, it is therefore necessary that diffuse radiation and radiation reflected from surroundings be eliminated. The weather files, accordingly, only contain data for direct normal radiation at ground level only.

Each of the solar radiation tests involves the testing of the program models associated with calculation of solar position. Rather than generate reference data by use of an algebraic model (of which there are several), reference data have been obtained for four sites (Atlanta, Boston, Chicago, and Los Angles) and two dates (August 21, 1999, and June 21, 1999) from the U.S. Naval Observatory (USNO 2001).

THE ANALYTICAL TESTS

Each test in the test suite has a particular objective in terms of which heat transfer path or models of the energy simulation program are to be tested. The basis and assumptions for the analytical models to realize these objectives vary with each other accordingly. The basis for each of the analytical models and the assumptions made in applying these in each group of tests is outlined in the following section.

Test Group 1: Convection and Conduction

The steady-state convection and conduction tests in this group are designed to find the response to a steady difference in dry-bulb temperature between the inside and the outside of the test zone. The heat transfer is only by convection at the inside and the outside surface and by conduction through one or more surfaces. This requires suitable choice of surface properties to eliminate longwave radiation. Steady-state results are ensured by making the zone fabric massless. As in most energy simulation programs, the heat transfer is assumed to be one-dimensional. In the steady-state convection test (SSConv), the external surface consists of a single homogeneous layer. The thermal resistance of this fabric is made negligible to ensure that the heat fluxes are most sensitive to convection at the inside and outside surfaces. The steady-state conduction test (SSCond) is similar except that the fabric is to have significant thermal resistance and may be a multi-layer construction. As noted earlier, it is not usually possible to carry out any zone heat transfer test without invoking the program's convection models (at least using the regular data input mech-

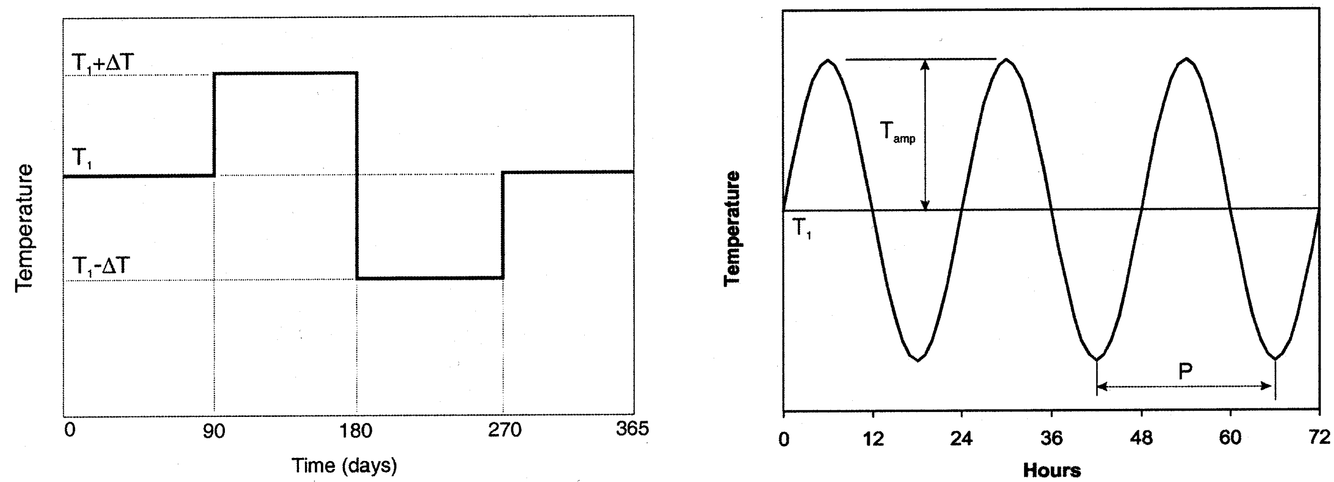

Figure 1 *Driving external dry-bulb temperature profiles used in the transient conduction tests: (a) a stepped profile used in tests TC1 and TC2, (b) the sinusoidal profile used in test TC3.*

anisms). Consequently, the steady-state convection test—although seemingly trivial—underlies all the other tests.

Three transient conduction test cases are included, each using different profiles of the driving external dry-bulb temperature, and each with rather different analytical solutions. The first and second tests (TC1 and TC2) use a stepped external dry-bulb temperature profile, as shown in Figure 1a, and involve a single-layer homogeneous fabric construction. The third test uses a sinusoidal external dry-bulb temperature profile, as shown in Figure 1b, and allows multiple-layer fabric constructions. In these tests, the response in terms of zone load and wall surface temperatures is examined.

The first transient conduction test case (TC1) requires application of an adiabatic boundary condition at the inside surface of the wall. After each step change in external temperature, the external surface temperature should show a first order response and return to equilibrium with the external temperature. The external surface heat flux should be seen to return to zero as the surface temperature returns to equilibrium. This type of response is shown in Figure 2. This test is essentially the same as that used previously in the testing of building energy simulation programs by Bland (1992). Although several forms of the analytical solution exist for this test, we have used that given by Incropera and DeWitt (1990). Details of the analytical solutions to the transient conduction cases are given in a companion paper (Rees et al. 2002).

The second transient conduction test case uses the same stepped external dry-bulb temperature profile to drive the heat transfer as the first test. The boundary conditions are rather different in that convection occurs at both the outside and inside surfaces, with the inside dry bulb being kept constant. Consequently, a linear temperature gradient develops across the wall as the steady state is approached some time after each step change in external temperature. Unlike the adiabatic transient test (TC1), the transient change at the start of each step

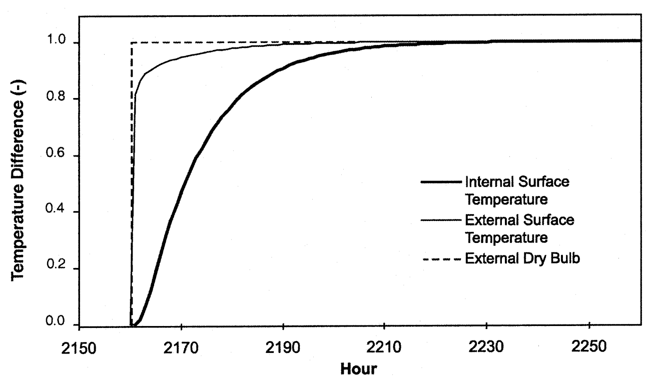

Figure 2 *The analytical response in surface temperatures in the transient conduction test case TC1. The temperatures are nondimensionalized.*

is influenced by the previous step—the initial conditions at the start of each step being different. The analytical solution is correspondingly more complex. The form of the analytical response at the first step in external temperature is shown in Figure 3.

The objective of test TC3 is to find the response to sinusoidal changes in outside dry-bulb temperature when the inside dry-bulb temperature is held constant at the mean external temperature. The analytical model for this test is based on the solution of the one-dimensional transient Fourier heat conduction equation for a multilayer slab with convective boundary conditions. Solution of this analytical model by complex representation of the temperature and use of matrix methods (Pipes 1957) allows treatment of multiple homogeneous wall layers.

The response to the driving temperature is that the inside surface temperature varies about the same mean as the outside but with reduced amplitude and a phase lag. The zone load has a similar phase lag with the driving temperature. The size of the reduction in amplitude and phase lag is dependent on the layer material properties. The inside heat flux can be described using a "decrement factor" and phase lag in the same way as in the Admittance Method load calculation procedure (Holmes and Wilson 1996) as follows:

$$q_i(t) = Uf\Delta T_o \sin(\omega(t-\phi)) \tag{4}$$

where U is the overall steady-state conductance (W/m^2·K [Btu/h·ft^2]), f is the decrement factor (nondimensional), ΔT is the amplitude of the periodic outside temperature (ºC [ºF]), ω is the period of the excitation divided by 2π, ϕ is the time lag (hours), and t is the time (hours).

Test Group 2: Solar Gains and Shading

A total of five test cases involving external solar irradiation are provided as part of the test suite. These range in complexity from a case of solar irradiation on an opaque surface to solar irradiation on a glazed surface with multiple shading devices. A simple internal solar distribution test is also included. The performance of each of these tests is assessed from the hourly load predictions over a single day. As only direct radiation data are present in the weather file and diffuse is set to zero, it is, first, the ability of the program to calculate the angle of incidence on the building fabric at each hour of a particular day and, consequently, the incident solar flux that are tested.

The ability of the test program to predict the normal solar fluxes is first tested with an opaque surface (test ExtSolRad). The analytical values of normal solar flux are calculated using the same solar fluxes that are written in the weather file and using values of solar azimuth and elevation angles from U.S.

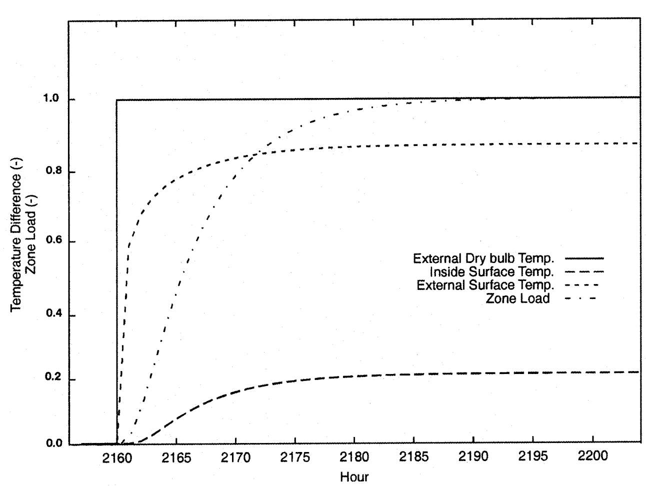

Figure 3 *The analytical solution for the transient conduction test TC2 for the 48 hours around the first step change in outside dry-bulb temperature. The temperature and zone loads are nondimensionalized.*

Naval Observatory data, tabulated every ten minutes of the test day. Angles of incidence in the analytical solution are calculated using an orthodox vector analysis. In this first solar test, a heat balance at each surface of the fabric and on the zone air is calculated using the same assumptions as the steady-state conduction test, except that an additional term is present in the outside surface heat balance due to the solar flux. No long-wave radiation at either surface is considered. The fabric is massless so that it can be assumed that the zone load is instantaneous.

The basic test for glazed surfaces (SolRadGlazing) involves a single pane of clear glass. By assuming a single pane of clear glazing, it is possible to avoid the complexities of specular coatings, interpane reflections, and radiation and derive an analytical solution using a conventional optical analysis to find the transmission and absorption of the incident solar flux at each hour (Duffie and Beckman 1991). The glazing is assumed to be highly conductive so that it would be at a uniform temperature. This allows a heat balance to be simply calculated on the glazing to find the thermal conduction component of the zone load. The inside of the zone is assumed to be totally absorbent of incident solar fluxes so that reflection and retransmission of the solar energy does not have to be considered.

Two tests—Test SolRadShade and Test WinReveal—are provided to assess the ability of the test program to deal with basic shading effects. The objective of the first shading test (SolRadShade) is to test the treatment of semi-infinite external shading over a glazed surface. The shading is said to be semi-infinite in that it has a finite depth (from the face of the zone exterior surface to its front edge) but is infinite in the direction parallel to the wall surface. Three types of window shading are considered—semi-infinite horizontal fin, semi-infinite vertical fin, and a combination of both semi-infinite horizontal and vertical fins.

The analytical calculation of transmission and absorption of solar radiation in all of the shading test cases is modified from the SolRadGlazing test simply by the reduction in effective glazed area by the casting of shadows from the shading devices (there is no diffuse irradiation). Shadow geometry is calculated using published shading geometric relations (Rodriquez and Alvarez 1991). Shading devices are assumed to be completely opaque and nonreflecting. No radiation is exchanged between the glazing and shading devices. The window reveal test (WinReveal) is similar to the other shading test except that the window can be shaded by both sides of the reveal as well as the top. This is geometrically the same as a combination of two vertical and one horizontal semi-infinite fins.

The last test in Group 2 (IntSolarDist) is intended to assess the treatment of internal solar distribution (i.e., how the test program redistributes solar energy that has entered the zone between the different internal surfaces). A small window on one surface of the zone is used with both horizontal and vertical shading applied. The dimensions of the window and

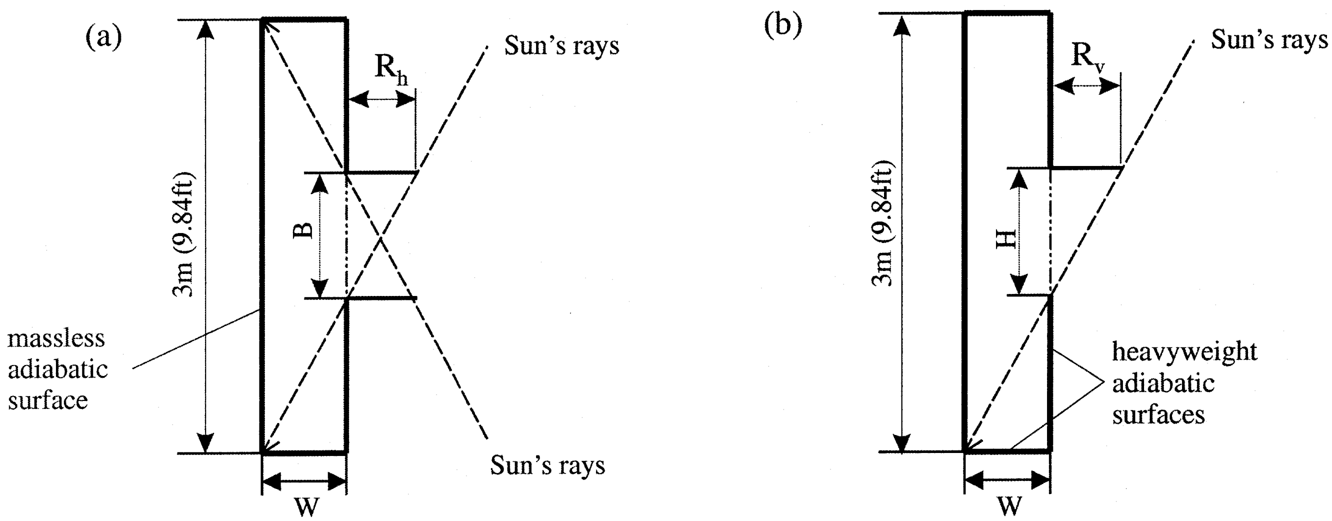

Figure 4 *Zone geometry of the internal solar distribution test: (a) plan view showing two vertical fins, (b) vertical view showing horizontal fin at the top of the window. The dimensions* W, R_v, *and* R_h *are 0.5 m (1.64 ft), and the dimensions* H *and* B *are 1.0 m (3.28 ft).*

shade and the depth of the zone are arranged such that no beam radiation should fall on any surface other than the wall opposite the window at any time of the day. By making the wall opposite the window lightweight and eliminating internal longwave radiation, the zone load corresponds to the instantaneous solar gains through the glazing. By making all other surfaces in the zone heavyweight, it should be possible to determine whether or not the test program is redistributing the solar gains to other surfaces. If solar gains are redistributed to the heavyweight surfaces, the peak zone load will be correspondingly reduced and the energy redistributed over the day. Accordingly, when the test program is set to explicitly model direct irradiation within the zone and no internal solar redistribution, the program zone loads should match those calculated with this test solution. Transmission and absorption of solar radiation and the effect of shading are calculated in the same way as the SolRadShade test. The test zone geometry for this test case is shown in Figure 4.

Test Group 3: Infiltration

Two tests are included in the test suite in which the only zone load is due to infiltration of outside air. Zone loads due to infiltration can be calculated analytically simply from the product of the mass flow rate and the difference in enthalpies of the incoming air and the air at the room condition. What has to be calculated in the analytical solution (and implicitly in the test program) are the mass flow rate and enthalpies at different psychrometric conditions. In the first place, it is the test program's ability to carry out the necessary psychrometric calculations that is being tested.

The difference between the two infiltration tests in group 3 (Infiltration-1 and Infiltration-2) lies in the way that the mass flow rate is specified. In the first test, the mass flow rate is simply specified as a fixed volumetric flow rate at the outside conditions. The results therefore depend only on the program's ability to find the correct air density (to get the mass flow rate) and the enthalpies at inside and outside conditions. In the second infiltration test, the flow is driven by stack effect between openings at high and low levels in the zone. In this test the zone geometry is altered to 3 m (9.84 ft) wide × 3 m (9.84 ft) deep × 10 m (32.81 ft) high. A steady-state calculation is made of the mass flow through two simple orifice openings at high and low levels in the zone. The flow is assumed to be driven by the difference in stack pressures due to the difference in height between the two openings and the difference in temperature inside and outside the zone. The analytical solution can be found by calculating a neutral pressure level and by knowing the characteristics of the orifice openings.

Test Group 4: Longwave Radiation

Two separate tests have been developed for the testing of treatment of internal and external longwave radiation. In each case, it is assumed that the surfaces are gray and isothermal. Radiation is treated in a single waveband using exact view factor-based methods. In each case, the air is assumed not to participate in the radiant exchange.

The ability of the test program to deal with longwave radiation at external surfaces is examined using a test zone with a single horizontal surface that is assumed to exchange radiation only with the sky (test ExtLWRad). It is also intended that this fabric is a massless surface so that zone loads can be assumed to be instantaneous. A single sky temperature is specified and the net steady-state heat balance on the inside and outside surfaces of the roof is calculated, assuming one-dimensional conduction through the roof, to find the surface temperatures and resultant zone load. Using this test, the sensitivity of the zone load predicted by the test program to the external longwave emissivity can be evaluated.

The internal longwave radiant exchange model of the test program can be evaluated by examining the zone loads and surface temperatures predicted with zone geometries of different aspect ratio and different surface emissivities. This is done in the second test in group four (IntLWRad). In this case, energy enters the zone through one external surface by convection from the outside air and conduction through a massless wall and enters the zone by convection to the room air and radiant exchange with all the room surfaces. Conduction through the lightweight wall is treated by a one-dimensional steady-state analysis. The radiant exchange calculation method adopted for this test is that given by Stefanizzi et al. (1988).

The aspect ratio of the test zone is changed by keeping the external wall a fixed 3×3 m (9.84×9.84 ft) and extending the length of the adjacent walls of the zone. As the aspect ratio increases, so does the internal surface area of the zone. The net radiation from the inside surface of the external wall increases with aspect ratio as the external wall radiates to a larger area (effectively less radiation returns to this surface). The analytical prediction of response to different aspect ratios and surface emissivities is shown in Figure 5. Previous work has shown that internal longwave radiation models differ in how they are able to respond to changes in zone aspect ratio and that this type of test is a robust test of such models (Stefanizzi et al. 1988).

Test Group 5: Miscellaneous

Two further tests included in the test suite deal with response to internal gains and heat transfer through slab-on-grade floors (denoted as IntHeatGain and GrdCoup). Internal gains are considered as a combination of radiant and convective heat fluxes. The convective portion of the gains is relatively easy to deal with—both in simulation programs and in the analytical solution – in that such gains can be added instantaneously to the heat balance on the room air. The response to radiant internal gains is dependent on the thermal mass of the zone, as some portion of the radiant energy will be stored in the room fabric. If the radiant gain is cyclic (e.g., scheduled on and off over a day), this stored energy is released later. The analytical solution to this problem is therefore derived from a consideration of transient conduction through the zone fabric.

The boundary conditions are rather different in this case than the other transient conduction tests in that all the surfaces are assumed to be adiabatic (at the outside surfaces that is) and have a radiant flux and convective boundary condition at the internal surfaces. As in current energy simulation programs, we assume that the radiant gains can be treated explicitly as a flux at the zone surfaces and are not associated with real surfaces at which a heat balance could be calculated. As to the distribution of fluxes within the zone, we assume the radiant fluxes are distributed to each surface of the cube equally. All of the zone fabric is assumed to be of the same homogeneous single-layer construction and a fixed convection coefficient is applied. In the test, the heat gains are simply scheduled on for a 168-hour period, and then removed.

Although most energy simulation programs have only simplified methods of dealing with heat transfer from ground-coupled floors, in the interests of completeness and in the expectation that such programs will become more sophisticated, we have included an analytical test that deals with this mode of heat transfer.

In this test, the response to the three-dimensional steady-state heat transfer from a ground-coupled floor is assessed. The analytical solution adopted for this case is that developed by Delsante et al. (1983), but it uses the calculation method given by Davies (1993). It is assumed that the thermal conductivities of the slab and the soil are equal so that the floor and the ground can be treated as a uniform semi-infinite solid. As shown in Figure 6, the floor is rectangular of area $L \times B$ and is bounded (but not penetrated) on each side by four equal width external walls of thickness W. It is assumed that the effect of the walls is to change the ground/slab surface temperature linearly over their thickness (the walls have a finite conductance but its actual value is unimportant). The ground surface temperature is taken to be the same as the deep ground temperature. The inside air temperature is held constant and the inside floor surface temperature calculated. Heat flux to the floor is via a single convective resistance only. All surfaces of the test cube are adiabatic except the floor, and no windows are present.

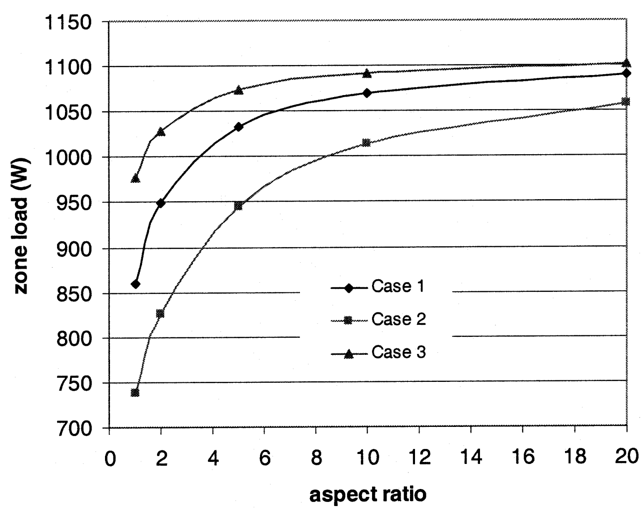

Figure 5 *Zone load variation with zone aspect ratio and different surface emissivities. The emissivities are: Case 1, external surface 0.9, opposite surface 0.1, other surfaces 0.3; Case 2, external surface 0.9, all other surfaces 0.1; Case 3, all surfaces 0.9.*

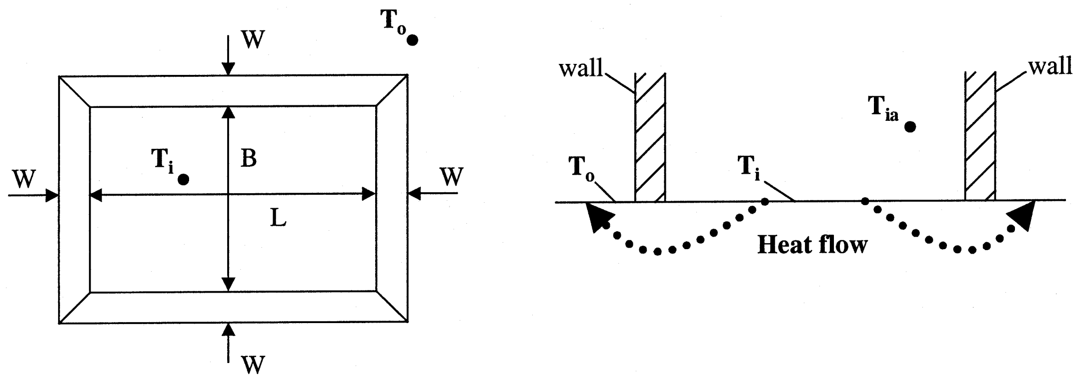

Figure 6 *A plan view (left) and section view (right) of the ground and wall geometry.* T_{ia} *is the inside air temperature,* T_i *is surface temperature of the floor, and* T_o *is temperature of the outside ground.*

The Test Suite Software

Although each of the analytical solutions can, in principle, be calculated "by hand" (with a calculator) or with the aid of a spreadsheet, the tests have been implemented in the form of a series of subroutines written in Fortran90. These, in turn, have been compiled as dynamic link libraries ("DLLs") that can be called from an interface. The interface allows users to easily enter custom values of the test parameters. The software basically takes the input test parameters and runs the analytical test and produces a result file along with an accompanying weather file. The interface has a number of convenient features, such as unit conversions, and allows saving of custom parameter values. Output of the test results is designed to be easily read into a spreadsheet, and weather file output can be in either TMY2, WYEC2, or IWEC formats. The procedure by which each test is intended to be carried out can be summarized as follows:

1. Choose the test parameters and enter them into the test suite software.
2. Run the test suite software and save the results and weather file produced.
3. Set up the input for the program to be tested to comply with the test specification.
4. Convert the weather file to the necessary format for input to the test program if required.
5. Run the test program for the test zone with the test weather file.
6. Compare and analyze the program results and analytical test results.

If it is convenient to run the test suite software, the tests may be run with a variety of parameter values; otherwise, the tests may be run using the parameter values and results given in the documentation.

THE TEST DOCUMENTATION

The value of the test suite is heavily dependent on the quality of the documentation. It is important that the documentation be clear and unambiguous if differences in results due to different interpretations of the test conditions are to be avoided. The documentation is designed to follow a common format for each test and so that the documentation for each test is largely self-contained. The function of each section of the documentation can be summarized as follows.

Objective: This sets out the aim of the particular test in terms of which heat transfer path or submodel of the energy simulation program is to be tested. It also summarizes the basis for the test and any assumptions made.

Analytical Model: This is provided to summarize the basis of the analytical model and its assumptions. It also shows how the analytical model is being applied to represent the behavior of the test zone.

Zone Description: This sets out the definition of the test zone to be used. Particular geometric, construction, and surface properties may be specified. Any heat transfer paths to be eliminated may also be specified.

Test Parameters: The particular parameters relevant to the test are given in this section of the documentation for each test. In addition, the parameter values used to get the results published in the "Results" section are tabulated. The input screen from the test suite software is illustrated in this section.

Test Results: Results of applying the analytical solution for one or more sets of test parameters are given in tabular and/or graphical form. These have been generated using the test suite software.

Analytical Solution: The derivation of the analytical solution that forms the basis of the test is given, along with any assumptions and limitations.

References: References are given at the end of the documentation for each test. These are the references relating to either the analytical solution or parameter values that have been cited in the documentation for that test alone.

TABLE 2
Differences in Zone Load Between the BLAST Program and Analytically Calculated Loads for the Convection and Conduction Cases

Test		Mean percentage difference in zone load	Maximum percentage difference in zone load
SSConv		0.11	0.11
SSCond		0.06	0.06
TC2	First stage	0.98	5.13
	Second stage	1.95	13.40
TC3		1.60	2.94

It is hoped that the test documentation will be used in support of *ANSI/ASHRAE Standard 140-2001, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*.

EVALUATION OF THE TEST SUITE

The development of the analytical test suite was planned to include two stages of evaluation so that any problems in the analytical tests themselves, and the documentation, could be resolved before its general release. First, evaluation was done "in house" by carrying out the whole test series with one particular whole building energy simulation program, BLAST (1995). Second, the test suite was evaluated "blind" by a third party using the EnergyPlus program. Feedback from both of these evaluation processes was used to improve the test documentation and software. A brief summary of the test results using the BLAST program follows along with a discussion of the principal problems found.

Summary of the Internal Test Results

A summary of the results of the steady-state, transient conduction, and convection tests found with the BLAST program are given in Table 2. The differences in zone load are calculated from the difference at a given hour divided by the peak zone load. The steady-state tests show very close agreement with the analytical solutions. It was important to establish that the convection coefficients stated in the BLAST documentation were verified by the test results before continuing with the other tests. The results for the transient conduction tests were very reasonable. In these cases, the greatest differences in results are found when the zone load is initially applied. Results for test TC1 are not given in Table 2, as there is no resultant load in this test. In this case, surface temperatures were examined and found to be different by a mean of 0.1ºC (0.18ºF) and a maximum of 0.5ºC (0.9ºF).

A summary of the results for the second group of tests (solar gains) found with the BLAST program is given in Table 3. The loads calculated by the test program showed the same trends as predicted by the analytical solutions, and the level of error appears acceptably small. Usually, the maximum error was found in one hour that BLAST did not show any load, while there is a very small load calculated in the analytical solution. The test program has three internal solar distribution algorithms of different complexity. As expected, the results only match closely with the analytical solution for the internal solar distribution test when the position of the "sun patch" is explicitly calculated.

TABLE 3
Differences in Zone Load Between BLAST and Analytical Result for the Solar-Related Cases

Test	Mean percentage difference in zone load	Maximum percentage difference in zone load
ExtSolRad	1.88	4.01
SolRadGlazing	1.85	4.23
SolRadShade	2.42	6.16
WinReveal	3.01	5.82
IntSolarDist	2.69	7.62

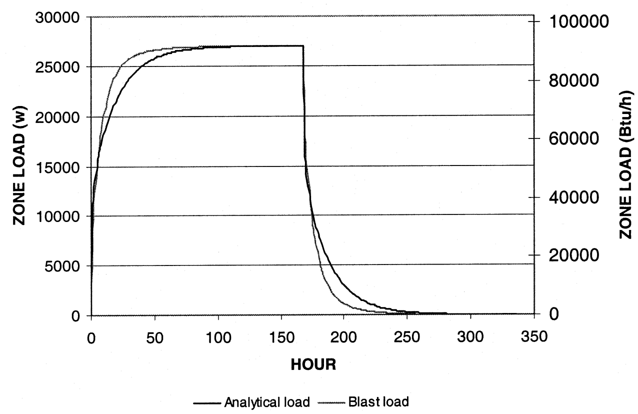

Figure 7 *Analytically calculated zone loads and those predicted by the BLAST program for the internal heat gain test.*

Two of the tests performed with the BLAST program gave disappointing results. These were the internal heat gain test (IntHeatGain) and the internal longwave radiation test (IntLWRad). In the first of these tests, the zone load response was noticeably slower than that predicted by the analytical solution (with peak error of 12.9% of peak load and mean of 2.3% [see Figure 7]). In the internal longwave radiation test, the zone loads predicted by BLAST did not show the same sensitivity to aspect ratio and surface emissivity as predicted by the analytical solution.

Satisfactory results were obtained for the BLAST program with the external longwave radiation test, with a maximum difference in the steady-state load of 2.53% for the emissivities tested. To carry out this test with BLAST, it was necessary to use the program's detailed external convection model, which is not enabled by default. It was also necessary to find the detailed convection correlations used in this mode. This would not be easy for many users, as this information is only available in a draft technical report (Walton 1981). It should also be noted that two of the tests—those concerned with infiltration by stack effect (Infiltration 2) and ground-coupled floors (GrndCoup)—were beyond the scope of the BLAST program and so results for these tests cannot be reported.

PROBLEMS DIAGNOSED DURING INTERNAL TESTING

In carrying out the tests with the BLAST program, trials with several tests revealed a number of difficulties in using BLAST. These arose mostly from lack of documentation of some features or erroneous documentation. In one case, an error in one of BLAST's models is suspected. These findings may be of interest to general users of the program as well as users of the test suite.

Convergence Criteria

Poor results were initially obtained for the first transient conduction test (TC1). It was subsequently found that these could be improved considerably by changing the convergence criteria used by BLAST. The convergence criteria used by BLAST are described in a draft technical report (Walton 1981) and are defined in terms of maximum allowable heat imbalance, maximum difference in zone temperatures, and a limit on the total number of iterations allowed. Figure 8 shows the difference in results obtained when using different values of the convergence parameters. The results obtained with the default convergence criteria show poor agreement with the analytical solution. In this case, there is a difference of internal surface temperature of 4.33ºC (7.8ºF), with 97 hours out of 100 hours having a difference of more than 0.5ºC (0.9ºF). After selecting more stringent convergence criteria, the results from the program can be seen to be much closer to the analytical solution results. In this case, the maximum difference in internal surface temperature is approximately 0.5ºC (0.9ºF), with 80 out of 100 hours having a difference less than 0.2ºC (0.36ºF).

Infiltration Calculations

Significant differences were found between the steady-state load calculated by BLAST and that of the analytical solution in the first infiltration test (Infiltration-1), where a fixed infiltration rate is specified. It appears this deviation comes from an error in the air density calculation used by BLAST. The air density is calculated in the program using standard ideal gas laws for air, in which it is necessary to employ a gas constant. Examination of the BLAST source code revealed that a value of 0.003235 was being used for the inverse of the gas constant for air. This implies a value for the gas constant of 309.1 J/kg·K (0.0789 Btu/lb·ºF). This number should be much closer to a value of 287 J/kg·K (0.0686 Btu/lb·ºF), which would apply at room temperature. The source code also shows that the value of specific heat of air used by BLAST is 1004 J/kg·K (234.0 Btu/lb·ºF). Using the BLAST air density and specific heat, hand calculation of the zone load result for this case confirms the value output by the program, which is 5810 W (19,823 Btu/h). The analytical solution is 6304.7 W (21510 Btu/h).

Vertical Shading

Comparison of the BLAST results for the solar shading test case (SolRadShade) with the analytical solution initially showed poor results. It was found out that there appears to be an error in the BLAST user manual regarding the syntax used to specify a vertical wing. Under "Wings and Overhangs" in the BLAST user manual, the following input syntax is given for a vertical wing:

"WITH WINGS(usn1, usn2)"

where "usn1" is supposed to be the depth and "usn2" the height of the vertical wing. The correct shading effect was only found with the arguments (or the definitions) reversed,

"WITH WINGS(usn2, usn1)"

The resulting zone loads, when using the syntax as it appears in the BLAST manual, are shown in Figure 9 for a vertical wing on the right side of a south-facing window. In this case, only a very small shading effect is observed. This might be expected with a wing that is only 0.6 m (1.97 ft) high at the bottom of the 3 × 3 m (9.84 × 9.84 ft) window. Using the alternative syntax—reversing the arguments—can be seen to give results that agree well with the analytical solution.

Dependence on Weather Data Period

It was noted that the BLAST results for the external solar radiation test ExtSolRad show good agreement with the analytical solution while specifying the weather tape for only a single day (August 21) in BLAST input file. However, devi-

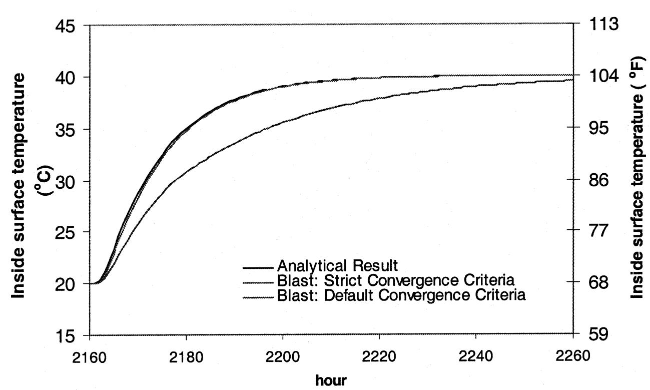

Figure 8 *Inside surface temperature response for test TCI using different convergence criteria.*

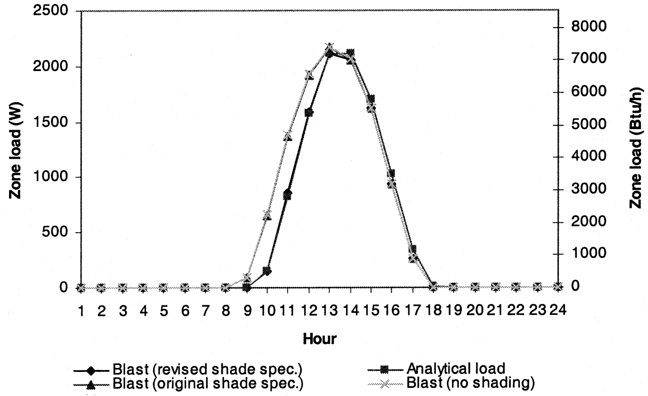

Figure 9 *Comparison of zone loads with alternative shade specifications: right-side wing on a south-facing window.*

ation does occur when a weather tape period of more than one week is specified. The reason for this has not been determined.

Weather Data Processing

In order to complete the tests involving solar irradiation, it was necessary to modify the weather data processor (WIFE) used by BLAST. Without modification, the weather data processor "fixes" the "error" of having no diffuse radiation in the weather file. Diffuse irradiation is set to zero in the test weather files so that loads are only induced by direct irradiation. It is acknowledged that this would be a problem for most users and may be an issue with other test programs.

CONCLUSIONS AND RECOMMENDATIONS

An analytical verification test suite for building fabric models of whole building energy simulation programs has been developed. The test suite consists of a series of sixteen tests covering convection, conduction, solar irradiation, long-wave radiation, and infiltration phenomena, as well as ground-coupled floors. The test suite consists of standardized documentation for each test case that includes results for one or more sets of test parameters along with the derivation of the analytical solution. In addition, a source code used to implement the analytical solutions and a user interface that drives this code have been developed as part of the ASHRAE 1052-RP project.

In the development of the test suite, effort has been made to ensure that the documentation is clear, that the analytical solutions are correct, and that the software is usable by real testers. This has been aided by both in-house and "blind" third party testing of the documentation and software.

The value of developing and using a tool such as this test suite has been shown through testing of an established building energy analysis program. Although the program in question has been in the public domain for more than twenty years, problems in the program's documentation and models were diagnosed by using these analytical tests. The test suite has also been found useful in the development of the new EnergyPlus program through the third party testing carried out during this project. It is intended that this test suite will become a useful tool for the development and diagnosis of problems with building energy simulation programs of the future.

REFERENCES

Allen, E., D. Bloomfield, N. Bowman, K. Lomas, J. Allen, J. Whittle, and A. Irving. 1985. Analytical and empirical validation of dynamic thermal building models. Proceedings of Building Energy Simulation Conference. Seattle, Wash.

ASHRAE. 2001. *ANSI/ASHRAE Standard 140-2001, Standard method of test for the evaluation of building energy analysis computer programs*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Bland, B.H. 1992. Conduction in dynamic thermal models: Analytical tests for validation. *Building Services Engineering Research and Technology* 13(4): 197-208.

BLAST. 1995. *BLAST users' manual*. Champaign, Ill.: United States Army Construction Engineering Research Laboratory.

Bloomfield, D., R. Brewer, B. Stringer, I. Cooper, and S. Lera. 1988. IEA Task 8, the UK Experience: Improving the design of low energy passive solar houses. *Building Research & Practice, the Journal of CIB,* no. 6.

Blottner, F.G., 1990. *Accurate Navier-Stokes results for the hypersonic flow over a spherical nosetip*. *AIAA Journal of Spacecraft and Rockets* 27(2): 113-122.

Boehm, B.W. 1981. *Software engineering economics*. Prentice-Hall.

BRE. 1988. Final report of BRE/SERC collaboration, An investigation into analytical and empirical validation techniques for dynamic thermal models of buildings. Building Research Establishment, U.K.

Davies, M.G. 1993. Heat loss from a solid floor: A new formula. *Building Sevices Engineering Research Technology* 14(2): 71-75.

Delsante A.E., A.N. Stokes, P.J. Walsh. 1983. Application of Fourier transforms to periodic heat flow into the ground under a building. *International Journal of Heat Mass Transfer* 26(1): 121-132.

Duffie J.A., and W.A. Beckman 1991. *Solar engineering of thermal processes*. New York: Wiley.

Holmes, M.J., and A. Wilson. 1996. Revised sections A5, A8, A9 of the CIBSE guide: Second draft. London: Ove Arup and Partners, p. 148.

Incropera, F.P., and D.P, DeWitt. 1990. *Introduction to Heat Transfer*, 2nd ed. New York: John Wiley.

Judkoff, R., D. Wortman, B. O'Doherty, and J. Burch. 1983. *A methodology for validating building energy analysis* *simulations.* SERI/TR-254-1508. Golden, Colo.: Solar Energy Research Institute (now NREL).

Judkoff, R., and J. Neymark. 1995. *Building energy simulation test (BESTEST) and diagnostic method.* NREL/TP-472-6231. Golden, Colo.: National Renewable Energy Laboratory.

Pipes, L.A. 1957. Matrix analysis of heat transfer problems. *Journal of the Franklin Institute* 263(3): 195-206.

Rees, S.J., J.D. Spitler, and P. Haves. 1998. Quantitative comparison of North America and U.K. cooling load calculation procedures—Results. *ASHRAE Transactions* 104(2): 47-57. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Rees, S.J., J.D. Spitler, R. Dougherty, and D. Xiao. 2002. Transient conduction analytical solutions for testing of building energy simulation programs. Submitted to *ASHRAE Transactions.*

Rodriguez E.A., and S. Alvarez 1991. Solar shading analytical tests (I). IEA21RN136.

Spitler, J.D., and S.J. Rees. 1998. Quantitative comparison of North America and U.K. cooling load calculation procedures—Methodology. *ASHRAE Transactions* 104(2): 36-46. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Spitler, J.D., S.J. Rees, and D. Xiao. 2001. *Development of an analytical verification test suite for whole building energy simulation programs—Building fabric (1052-RP): Final Report*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Stefanizzi, P., A. Wilson, and A. Pinney, 1988. The internal longwave radiation exchange in thermal models. *BRE/SERC report: An investigation into analytical and empirical validation techniques for dynamic thermal models of buildings*, Vol. 2.

USNO. 2001. U.S. Naval Observatory: Astronomical Applications Department, Sun or Moon Altitude/Azimuth Table for One Day, http://aa.usno.navy.mil/data/docs/AltAz.html.

Walton G.N. 1981. *Passive solar extension of the building loads analysis and system thermodynamics (BLAST) program*, Technical Report. Champaign, Ill.: United States Army Construction Engineering Research Laboratory.

Yazdanian, M., and J.H. Klems. 1994. Measurement of the exterior convective film coefficient for windows in low-rise buildings. *ASHRAE Transactions* 100(1): 1087-1096. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.