Residential Fenestration Performance Analysis Using RESFEN 3.1

Yu Joe Huang
Member ASHRAE

Robin D. Mitchell

Dariush Arasteh, P.E.
Member ASHRAE

Stephen E. Selkowitz
Member ASHRAE

ABSTRACT

This paper describes the development efforts of RESFEN 3.1, a PC-based computer program for calculating the heating and cooling energy performance and cost of residential fenestration systems. The development of RESFEN has been coordinated with ongoing efforts by the National Fenestration Rating Council (NFRC) to develop an energy rating system for windows and skylights so as to maintain maximum consistency between RESFEN and NFRC's planned energy rating system. Unlike previous versions of RESFEN that used regression equations to replicate a large database of computer simulations, Version 3.1 produces results based on actual hour-by-hour simulations. This approach has been facilitated by the exponential increase in the speed of personal computers in recent years. RESFEN 3.1 has the capability of analyzing the energy performance of windows in new residential buildings in 52 North American locations. The user describes the physical, thermal, and optical properties of the windows in each orientation, solar heat gain reductions due to obstructions, overhangs, or shades, and the location of the house. The RESFEN program then models a prototypical house for that location and calculates the energy use of the house using a well-known hourly computer simulation program. The user can vary the HVAC system, foundation type, and utility costs. Results are presented for the annual heating and cooling energy use, energy cost, and peak energy demand of the house and the incremental energy use or peak demand attributable to the windows in each orientation. This paper describes the capabilities of RESFEN 3.1, its usefulness in analyzing the energy performance of residential windows and its developmental effort and gives insight into the structure of the computer program. It also discusses the rationale and benefits of the approach taken in RESFEN in combining a simple-to-use graphical front-end with a detailed hour-by-hour "simulation engine" to produce an energy analysis tool for the general public that is user friendly yet highly accurate.

INTRODUCTION

Today's energy-efficient windows can dramatically lower the heating and cooling costs associated with windows while increasing occupant comfort and minimizing window surface condensation problems. However, consumers are often confused about how to pick the most efficient window for their residence. They are typically given window properties such as U-factors or R-values, solar heat gain coefficients or shading coefficients, and air leakage rates. The relative importance of these properties depends on the specific site and building conditions. These properties are based on steady-state conditions often quite different from the day-to-day climatic variations encountered by a window installed on a house. Knowing the energy and associated cost implications of different windows will help consumers and builders make the best decision for their particular application, whether it is a new home, an addition, or a window replacement.

The RESFEN 3.1 program has been developed at Lawrence Berkeley National Laboratory as a tool to help consumers, designers, and builders pick the most energy-efficient and cost-effective window for a given application. RESFEN 3.1 is scheduled to be completed in October 1998. Throughout its development, starting in late 1996, the authors have worked closely with the Annual Energy Performance (AEP) Committee of the National Fenestration Rating Council (NFRC) to ensure that RESFEN 3.1 would be as consistent as possible with the NFRC 900 Heating and Cooling Rating being developed by the AEP Committee. A preliminary Version 3.0 of RESFEN was completed in December 1997 and distributed to the AEP Committee for review and comments. In January 1998, LBNL proposed a modified set of

Joe Huang, Dariush Arasteh, and **Steve Selkowitz** are staff scientists and **Robin Mitchell** is a research associate in the Building Technologies Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, Calif.

operating conditions and modeling assumptions that could be used for both RESFEN and the NFRC 900 rating and subsequently agreed to do the DOE-2 simulations for the NFRC 900 ratings. From January to June 1998, the authors worked with an AEP Working Group to finalize the simulation methodology for NFRC 900. The DOE-2 simulation database for NFRC 900 was completed and presented to the AEP Working Group in August 1998. At the same time, the authors also incorporated the final NFRC 900 operating assumptions into RESFEN 3.1 and made major modifications to the user front-end.

BACKGROUND

The decision to develop RESFEN 3.1 around hourly DOE-2 simulations, rather than the regression equations used in Version 2.4 and earlier, was predicated on the remarkable increase in the computing power of PCs in recent years. In 1987, an annual DOE-2 simulation of a one-zone house took 40 minutes on a typical PC. By 1992, the same simulation would take 6 minutes on a machine with a 33 megahertz clock speed. By 1993, the simulation time had been reduced to roughly 2 minutes on a machine with a 66 megahertz clock speed. By 1997, the simulation took only 12 seconds on a 200 megahertz computer and even less on faster machines that became available in 1998. On a 200 megahertz PC, even the detailed calculation in RESFEN 3.1 of the incremental energy use of windows requiring a six-zone building model takes less than 30 seconds.

At this level of performance, the advantages for a simulation-based version of RESFEN are overwhelming because of its accuracy and flexibility, as well as ease of development. The previous RESFEN 2.4 program was limited to ten cities and used relatively simple window models based only on U-values and shading coefficients. Even so, the program required a database of thousands of DOE-2 simulations from which the regression equations were developed. If the same approach were used for RESFEN 3.1, the larger number of locations (52) and building conditions would require a database with tens of thousands of DOE-2 runs. In addition, developing and testing the regression equations for the greatly increased diversity of window products would take months of effort. Using a simulation-based approach eliminates the need to generate and analyze a large database and makes adding a new location, changing a modeling assumption, or even replacing the calculation engine no more difficult than adding a weather file, editing the master input file, or swapping the simulation module. The last option is warranted if there is a major upgrade to DOE-2 or if a newer, more accurate simulation program becomes available.

In addition to the rapid increases in computing power in recent years, the availability of powerful software development packages has also made developing graphic user interfaces much easier. The user interface in RESFEN 3.1 was developed using a higher level software package that operates in the common 32-bit PC operating system.

USER INPUT/OUTPUT SCREENS

The user interface in RESFEN 3.1 consists of a single screen for inputs and several tabs for outputs (see Figure 1). The menu and toolbar across the top provide standard functions such as opening, saving, and printing files, and a button with a lightning bolt to start the computer simulations. General

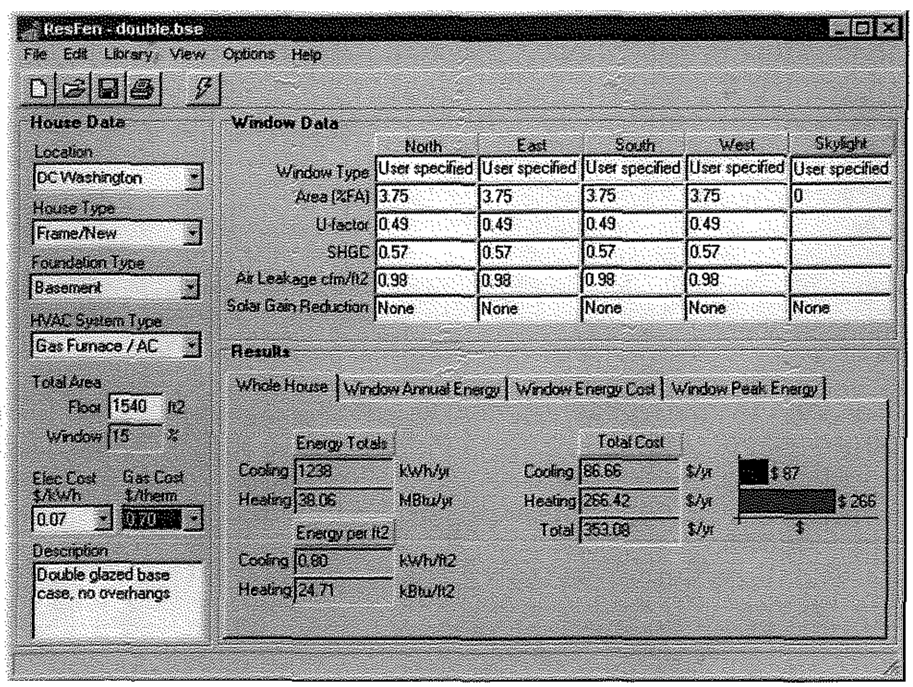

Figure 1 *RESFEN 3.1 User Screen with Whole House Annual energy tab displayed.*

information on the size and location of the house, utility costs, and the house, foundation, and space-conditioning system types are entered in the House Data section on the left. The user can select from 52 locations in the U.S. and Canada, house floor areas from 1000 ft^2 to 3000 ft^2, one to three foundation types (slab, basement, or crawl space) depending on location, and either a furnace with an air-conditioner or an electric heat pump system. Since the locations and house model are not intrinsically fixed as in a database program, these can be expanded or modified with minor difficulty for future applications. For example, the authors have already developed a prototype web-based version of RESFEN that they will eventually expand to include more than 200 North American, and possibly some other, locations.

More detailed information on the size, thermal/optical properties, and shading conditions of the windows in each orientation are entered in the Window Data section in the top center of the screen (see top center of Figure 1). Users can select between two methods for simulating window performance—either the simpler U-factor and Solar Heat Gain Coefficient (SHGC) method or the more detailed WINDOW 4.1 method—and nine possible shading combinations, including typical, none, interior shades, overhang, obstructions from adjoining buildings, internal shades and overhangs, overhangs and obstructions, internal shades and obstructions, and all (see center of Figure 2).

One of the primary goals for developing RESFEN 3.1 is to provide more accurate calculations of the energy performance of newer glazing products. If the user selects the "Window 4 Lib" option under "Window Type" in the Window Data section, RESFEN 3.1 will search for the specified library file from the WINDOW 4.1 program and display its contents (see Figure 3). Once a custom window type has been selected from the library file, RESFEN 3.1 makes a DOE-2.1E simulation modeling the window with the angular optical properties and U-factors from the corresponding ASCII library file. This procedure is explained fully later in this paper.

The Results section in the lower part of the screen has four tabs labeled "Whole House," "Window Annual Energy," "Window Energy Cost," and "Window Peak Energy." Each tab presents the respective simulation outputs. The Whole House tab presents the total heating and cooling energy use and cost for the entire house (see bottom of Figure 1). The other three tabs present the incremental impact of the windows by orientation to the annual energy use, cost, or peak demand of the house. These are shown first in tabular form as total energies or normalized per square foot of window area (see bottom of Figure 2). They can also be viewed as bar charts (see Figure 4).

For record keeping and to facilitate comparison of different window options, RESFEN 3.1 has a simple database management system that permits users to review the summary

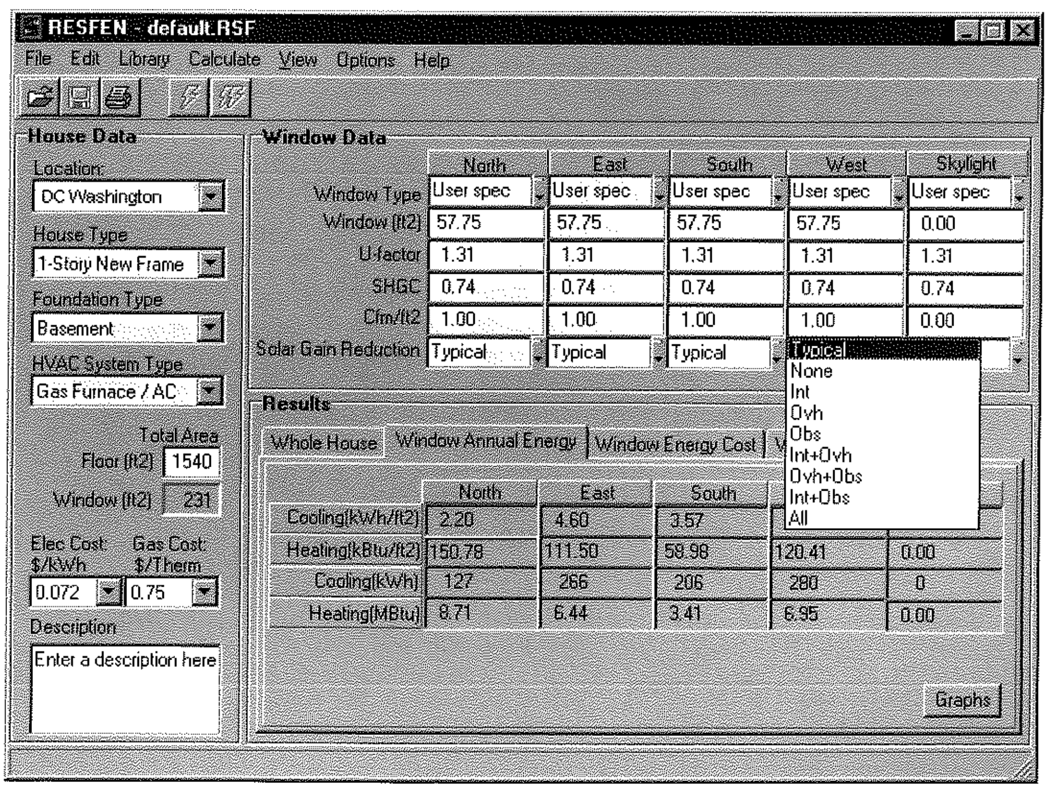

Figure 2 *RESFEN 3.1 User Screen with Solar Gain Reduction pulldown list and Window Annual Energy tab displayed.*

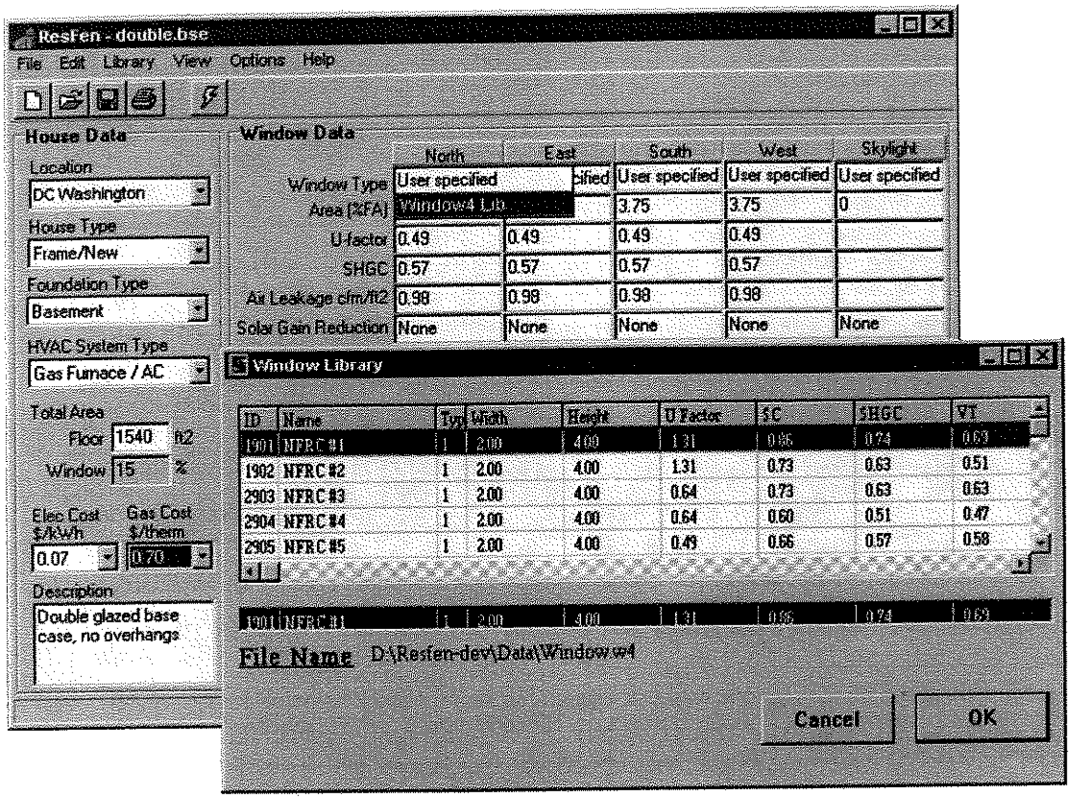

Figure 3 RESFEN 3.1 User Screen with custom Window library opened.

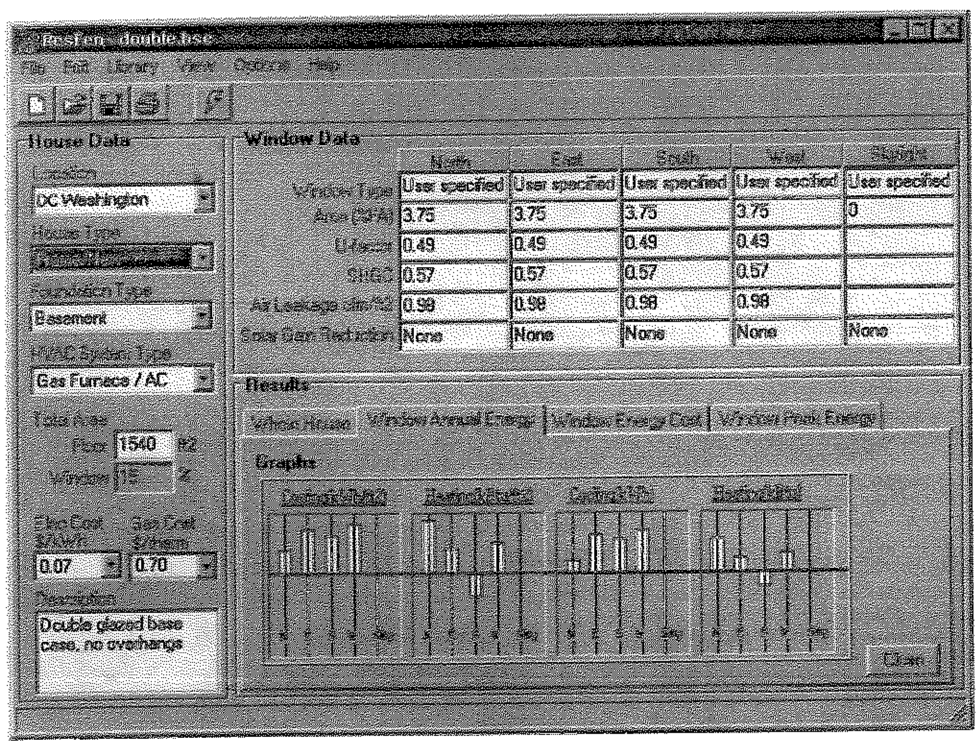

Figure 4 RESFEN 3.1 User Screen with graph option of Window Annual Energy tab opened.

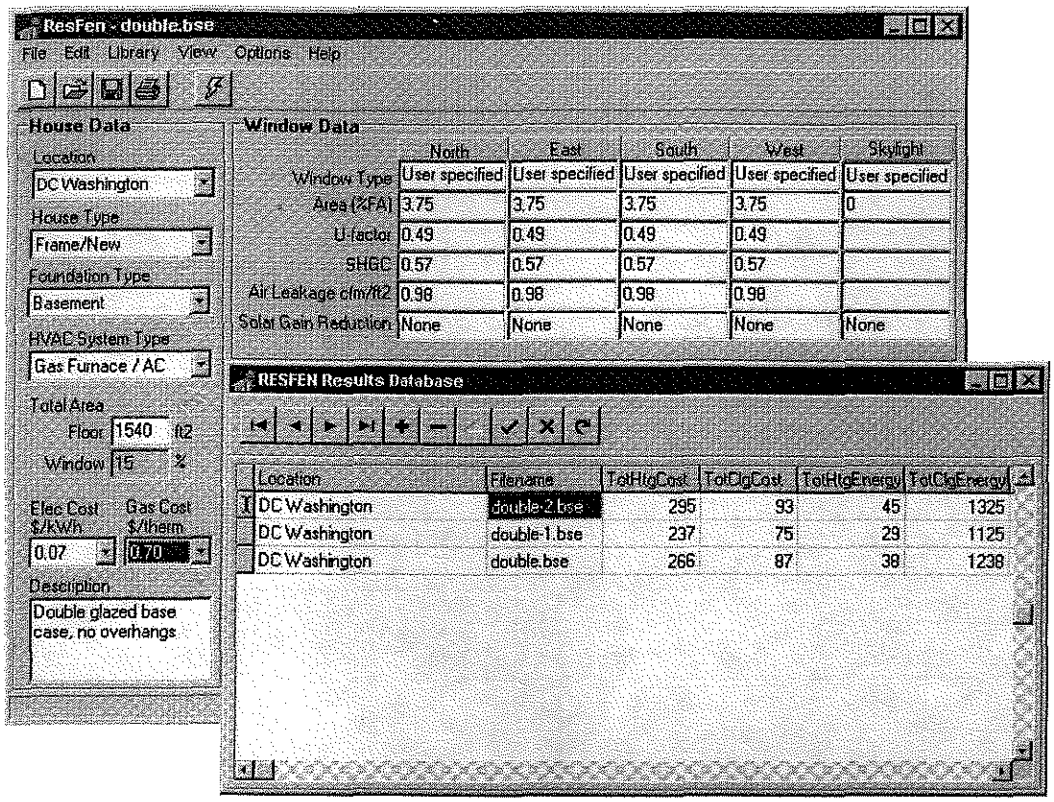

Figure 5 *RESFEN 3.1 Results database window.*

results from previous calculations and to export them as text files to common spreadsheet programs for further analysis (see Figure 5).

CALCULATION METHOD

RESFEN 3.1 uses as its "simulation engine" a customized version of the DOE-2.1E program compiled for a common 32-bit PC operating system. DOE-2 is a dynamic hourly building energy simulation program developed and maintained at LBNL that is well known to and widely used by engineers and energy researchers in North America and abroad (LBL 1980; Winkelmann et al. 1993). A few changes have been made to the DOE-2 program so that it can be used only inside the RESFEN program. However, the fundamental algorithms have not been altered, so RESFEN 3.1 gives results identical to those calculated by standard versions of DOE-2.1E. Based on the user-selected inputs, RESFEN 3.1 generates an input file in standard DOE-2 Building Description Language (BDL) and then runs an input processor module akin to DOEBDL. This is followed by a simulation module akin to DOESIM, which is linked with the appropriate weather file. After the DOE-2 run has been completed, a Fortran post-processor program extracts from the output file the annual heating and cooling use, costs, and peak demands of the house and how much of that energy use can be attributed to the windows alone. These are then passed back to the user interface for display on the main RESFEN 3.1 screen. Figure 6 is a flow chart showing how the user inputs, template and weather files, DOE-2 DLL programs and accompanying library files, and output post-processor program are linked within the program.

MODELING ASSUMPTIONS

House Configuration

The overall intention of the modeling strategy in RESFEN 3.1 is to represent average conditions of new and existing residential construction in different parts of the country. Table 1 summarizes the operating assumptions used in the computer simulations. We spent substantial effort working with the AEP Working Group to define these assumptions and in some cases utilize or develop new models for foundation heat flows (Winkelmann 1998) and part-load curves for residential furnaces and air-conditioners (Henderson et al. 1999). Table 2 shows the assumed shell conditions for both new and existing houses. For new houses, these are based on the prescriptive requirements of the current *Model Energy Code* (CABO 1993); for existing houses, these are based on a previous LBNL study of residential house characteristics (Ritschard et al. 1992). Table 2 also indicates the default and alternative foundation types in each location. The former is the most common foundation type in each location; the latter are other foundation types found in more than 10% of the houses according to a National Association of Home Builders' survey (Labs et al. 1988). RESFEN 3.1 allows users to override the

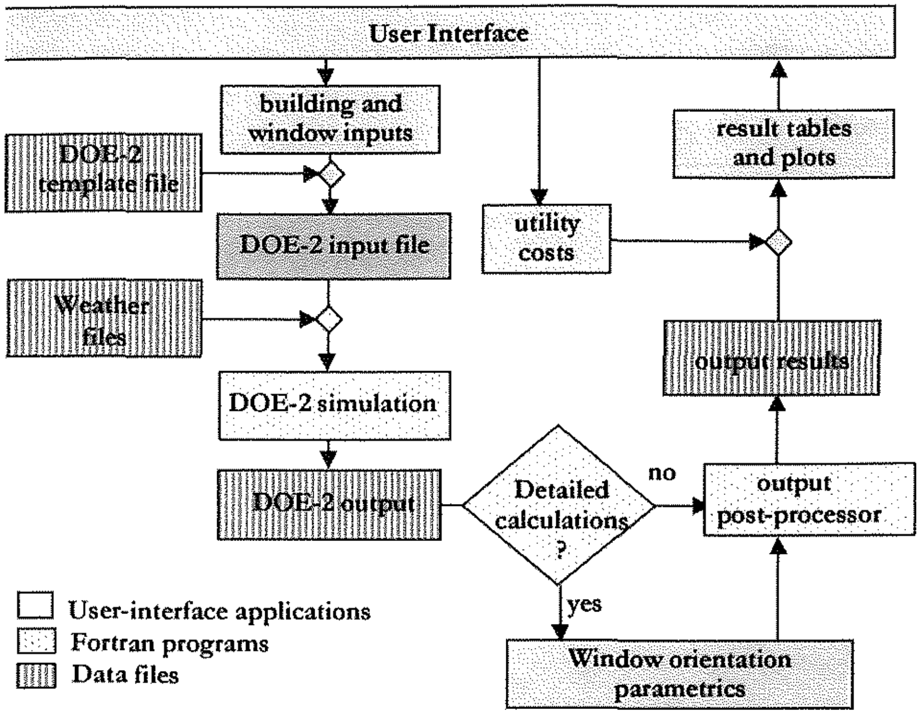

Figure 6 *Schematic Flow Chart of RESFEN 3.1.*

TABLE 1
NFRC 900 Assumptions Comparison

Parameter	RESFEN 3.1 New Construction	RESFEN 3.1 Existing Construction
Floor Area (ft^2 and dimensions)	1540[a] 415 × 41.5× 8	Same
Foundation	Vary the foundation based on location See Table 2	Same
Insulation	See Table 2. (Council of American Building Officials 1993)	See Table 2 (Ritschard et al. 1992)
Infiltration (leakage-area)	ELA=0.77 ft^2 or 0.58 ACH (Air-changes/hour)	ELA=1.0 ft^2 or 0.70 ACH
Structural Mass (lb/ft^2)	3.5lb/ft^2 in accordance with the Model Energy Code and NFRC	Same
Internal Mass Furniture (lb/ft^2)	8.0 lbs/ft^2 in accordance with the Model Energy Code	Same
Window Area (% Floor Area)	15%	Same
Window Type	Variable	Same
Window Distribution	Equal	Same
Solar Gain Reduction	Four effects included:[b] • 1′overhang on all 4 orientations; • a 67% transmitting same-height obstruction 20′ away intended to represent adjacent building; • Interior shades (Seasonal SHGC multiplier, summer value = 0.80, winter value = 0.90); • To account for other sources of solar heat gain reduction (insect screens, trees, dirt, building, and window self shading), the SHGC multiplier was further reduced by 0.01. This result in a final winter SHGC multiplier of 0.8 and a final summer SHGC multiplier of 0.7.	Same
HVAC System	Furnace and A/C, Heat Pump	Same

TABLE 1 (Continued)
NFRC 900 Assumptions Comparison

Parameter	RESFEN 3.1 New Construction	RESFEN 3.1 Existing Construction
HVAC System Sizing	For each climate, system sizes are fixed for all window options. Fixed sizes are based on the use of DOE-2 autosizing for a house with the representative window for that specific climate. Autosizing multiplier of 1.3 used.[c]	Same
HVAC Efficiency	AFUE = 0.78, A/C SEER = SEER 10.0	AFUE=0.70, A/C SEER-8.0
Duct Losses	Heating: 10% (fixed), Cooling: 10% (fixed)	Same
Part-Load Performance	New part-load curves for DOE2 (Henerson 1998)	Same
Thermostat Settings	Heating: 70°F; Cooling: 78°F Basement: Heating 62°F; Cooling 85°F	Same
Night Heating Setback	65°F (11 p.m. - 6 a.m.)[d]	Same
Internal Loads (kBtu/day)	56 Sensible 12.2 Latent	Same
Natural Ventilation	Enthalpic-Sherman-Grimsrud (78°F / 72°F based on 4 days history)[e]	Same
Weather Data	TMY2[f]	Same
Number of Locations	48 US cities, 4 Canadian cities	Same
Calculation Tool	DOE-2.1E	Same

[a] The NFRC 900 model assumes a house measuring 28' × 55' or 1540ft^2. Because the windows in the house are equally split between the four cardinal directions, the total perimeter length of this house is also equally split among the four orientations, resulting in 41.5 perimeter feet on each side of the house. While such an "average" house may be physically impossible to build, it is useful as a computer abstraction for estimating house energy performance under average solar conditions.

[b] These assumptions are intended to represent the average solar heat gain reduction for a large sample of houses. A 1 ft overhang is assumed on all four orientations in order to represent the average of a 2 ft overhang and no overhang. A 67% transmitting obstruction 20 ft away on all 4 orientations represents the average of obstructions 20 ft away from 1/3 of the total windows and no obstructions in front of the remaining 2/3 of the windows. An interior shade is assumed to have a Solar Heat Gain Coefficient multiplier of 0.7 and is assumed to be deployed 1/3 of the time in the winter and 2/3 of the time in the summer, leading to the SHGC multiplier of 0.9 in the winter and 0.8 in the summer. To account for the solar heat gain reducing effects from other sources such as screens, trees, dirt, and self-shading of the building, the SHGC multiplier was further reduced by 0.1 throughout the year; this amounts to a 12.5% decrease in the summer and an 11.1% decrease in the winter. The final SHGC multipliers (0.8 in the winter and 0.7 in the summer) thus reflect the combined effects of shading devices and other sources.

[c] For each climate, DOE-2's auto-sizing feature was used with the window most likely to be installed in new construction. Table 2 shows the required prescriptive U-factors for windows for the 52 climates. For climates where the U-value requirement is greater than or equal to 1.0, NFRC Window Type 1 (aluminum frame with single glazing) was used. For all climates where the U-factor requirement is between 0.65 and 1.0, NFRC Window Type 14 (aluminum frame with double glazing) was used. For climates with U-value requirements at or below 0.6, as well as in the four Canadian climates,NRFC Window Type 5 (vinyl frame with double glazing) was used for the sizing calculations.

[d] A moderate setback of 65°F was used in recognition that some but not all houses may use night setbacks. Recent studies of residential indoor conditions have shown that nighttime temperatures are significantly lower than those during the day in the heating season ("Occupancy Patterns and Energy Consumption in New California Houses," Berkeley Solar Group for the California Energy Commission, 1990).

[e] NFRC 900-1998 uses a feature in DOE-2 that allows the ventilation temperature to switch between a higher heating (or winter) and a lower cooling (or summer) temperature based on the cooling load over the previous four days.

[f] There are 239 TMY2 locations with average weather data compiled from 30 years of historical weather data ("TMY2 User's Manual, National Renewable Energy Laboratory," Golden, Colo., 1995), but only 55 WYEC2 locations ("WYEC2 User's Manual, American Society of Heating, Refrigerating, and Air-Conditioning Engineers," Atlanta, Ga., 1997). The two weather data sets are of comparable reliability, but to maintain internal consistency and draw upon a larger data set, the decision was made to use only TMY2 weather tapes.

TABLE 2
Foundation Type and Envelope Insulation Default R-Values

ST	City	Foundation Types		New Construction R-Values			Existing Construction R-Values		
		Default	Alternate	Ceiling	Wall	Floor	Ceiling	Wall	Floor
AK	Anchorage	Bsmt	—	38	19	30	22	7	0
AL	Birmingham	Slab	Crawl, Bsmt	38	14	6	19	7	0
AZ	Phoenix	Slab	—	30	11	0	11	7	0
CA	Fresno	Slab	Crawl, Bsmt	38	14	6	11	7	0
CA	Los Angeles	Slab	Crawl, Bsmt	26	11	0	11	7	0
CA	Red Bluff	Slab	Crawl, Bsmt	38	14	6	11	7	0
CA	San Diego	Slab	Crawl, Bsmt	30	11	0	11	7	0
CA	San Francisco	Slab	Crawl, Bsmt	38	14	6	11	7	0
CO	Denver	Bsmt	Crawl	38	19	11	11	7	0
DC	Washington	Bsmt	—	38	19	9	11	7	0
FL	Jacksonville	Slab	—	30	11	0	11	7	0
FL	Miami	Slab	—	19	11	0	11	7	0
GA	Atlanta	Slab	Bsmt, Crawl	38	19	2	11	7	0
HI	Honolulu	Slab	—	19	11	0	11	7	0
ID	Boise	Bsmt	Crawl	38	19	9	19	7	0
IL	Chicago	Bsmt	—	38	19	14	19	7	0
LA	Lake Charles	Slab	—	26	11	0	19	7	0
MA	Boston	Bsmt	—	38	19	11	22	7	0
ME	Portland	Bsmt	—	38	19	15	22	7	0
MN	Minneapolis	Bsmt	—	38	19	15	22	7	0
MO	Kansas City	Bsmt	—	38	19	8	22	7	0
MT	Great Falls	Bsmt	—	38	19	15	19	7	0
NC	Raleigh	Crawl	Slab, Bsmt	38	19	13	11	7	0
ND	Bismarck	Bsmt	—	38	19	28	22	7	0
NE	Omaha	Bsmt	—	38	19	11	22	7	0
NM	Albuquerque	Slab	—	38	19	3	11	7	0
NV	Las Vegas	Slab	Crawl	30	14	0	11	7	0
NV	Reno	Slab	Crawl	38	19	4	11	7	0
NY	Buffalo	Bsmt	—	38	19	14	19	7	0
NY	New York City	Bsmt	Slab	38	19	8	11	7	0
OH	Dayton	Bsmt	Slab, Crawl	38	19	9	19	7	0
OK	Oklahoma city	Slab	—	38	19	2	19	7	0
OR	Medford	Crawl	Bsmt	38	19	19	19	7	0
OR	Portland	Crawl	Bsmt	38	19	19	19	7	0
PA	Philadelphia	Bsmt	—	38	19	9	11	7	0
PA	Pittsburgh	Bsmt	—	38	19	9	19	7	0
SC	Charleston	Crawl	Slab	30	14	11	11	7	0

TABLE 2 (Continued)
Foundation Type and Envelope Insulation Default R-Values

ST	City	Foundation Types		New Construction R-Values			Existing Construction R-Values		
		Default	Alternate	Ceiling	Wall	Floor	Ceiling	Wall	Floor
TN	Memphis	Crawl	Bsmt, Slab	38	19	13	19	7	0
TN	Nashville	Crawl	Bsmt, Slab	38	19	19	19	7	0
TX	Brownsville	Slab	—	19	13	0	19	7	0
TX	El Paso	Slab	—	38	14	6	19	7	0
TX	Fort Worth	Slab	—	30	14	0	19	7	0
TX	San Antonio	Slab	—	26	11	0	19	7	0
UT	Salt Lake City	Bsmt	—	38	19	9	11	7	0
VT	Burlington	Bsmt	—	38	19	15	22	7	0
WA	Seattle	Bsmt	Crawl	38	19	9	19	7	0
WI	Madison	Bsmt	—	38	19	15	22	7	0
WY	Cheyenne	Bsmt	—	38	19	15	11	7	0
AB	Edmonton	Bsmt	—	38	19	15	22	7	0
NS	Halifax	Bsmt	—	38	19	15	22	7	0
PQ	Montreal	Bsmt	—	38	19	15	22	7	0
ON	Toronto	Bsmt	—	38	19	15	22	7	0

default foundation by an alternate foundation type should they so chose.

Building Locations and Weather Data

At present, RESFEN 3.1 covers 52 North American locations, 48 in the United States and 4 in Canada (see Table 2). This list is based primarily on a list of 45 cities defined by the lead author in a previous LBNL project to define representative U.S. climates for simulating residential building energy use (Huang et al. 1987). An additional three U.S. cities and the Canadian locations were added at the request of the AEP Working Group. For consistency, we used the revised Typical Meteorological Year (TMY2) weather tapes from the National Renewable Energy Laboratory for all 48 of the U.S. cities (NREL 1995). Since TMY2 weather files were not available for Canadian sites, we used ASHRAE's revised Weather Year for Energy Calculations (WYEC2) weather tapes for three of the Canadian locations (Edmonton, Montreal, and Toronto) and a Canadian TMY weather tape for Halifax (ASHRAE 1997).

Window Properties

In contrast to the limited number of options allowed for the house description, RESFEN 3.1 provides much more detail for modeling the windows in each of the four cardinal orientations (north, south, east, and west). There are three ways to model the window: (1) user-defined U-factor (U-value) and solar heat gain coefficient (SHGC), (2) WINDOW 4.1 defined U-factor and SHGC, or (3) WINDOW 4.1 defined custom window library file. The first option is the simplest and requires the user to input the U-factor and SHGC as shown on an NFRC label attached to the window (see Figure 7 for sample) or listed in the product literature from the window manufacturer. The second option allows use of the WINDOW 4.1 program, also developed by LBNL, to calculate the thermal and solar characteristics of a window product based on its construction (number of panes, gap size, frame type, etc.) and glass optical properties (Arasteh et al. 1994).

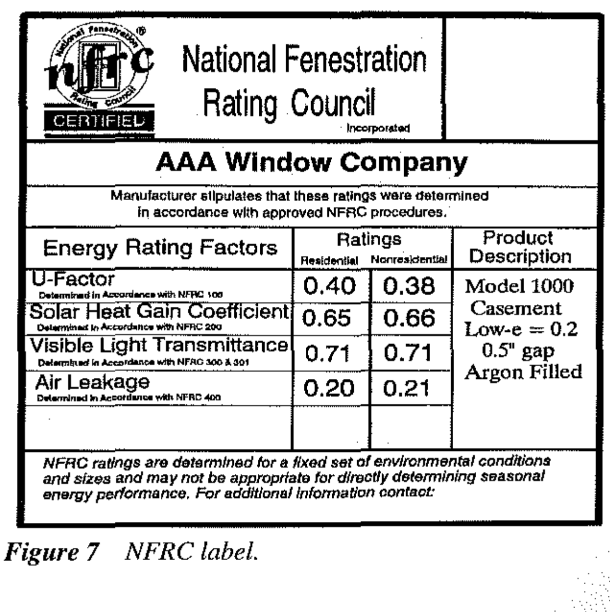

Figure 7 *NFRC label.*

With either of the above two options, the DOE-2 engine in RESFEN models the window using the defined U-factor and SHGC but assumes the window has the same angular optical properties as single-pane clear glass. The third option utilizes DOE-2's ability to read a WINDOW 4.1 window file with information on the edge-of-glass effects, frame conductance, and, most importantly, the angular properties of the glazing system (Winklemann et al. 1993). For a multi-pane window system, the results using Option 3 may differ substantially from using Options 1 or 2.

In the RESFEN 3.1 input screen, the user has a choice of "User specified" or "Window 4 Lib" (see Figure 4). "User specified" corresponds to Option 1, where the user inputs the U-factor and SHGC in the space below. If the user selects "Window 4 Lib," RESFEN 3.1 will search for the specified WINDOW 4.1 binary file containing the U-factors and SHGCs calculated by WINDOW 4.1. If RESFEN 3.1 does not find a corresponding WINDOW 4.1 ASCII file needed by DOE-2, or if the user specifies "User specified" after the U-factor and SHGC have been read in from the WINDOW 4.1 binary file, RESFEN 3.1 will complete the simulation using the WINDOW 4.1 U-factor and SHGC, corresponding to Option 2. If RESFEN 3.1 does find the corresponding WINDOW 4.1 ASCII file needed by DOE-2, it will simulate the window using the additional information in the ASCII file, corresponding to Option 3. Figure 8 clarifies these options in a simple flow chart.

RESULTS

The outputs from the DOE-2 simulations are displayed in tabular form and plotted as bar charts in the Results section of the main RESFEN screen. The first tab, titled "Whole House," shows the total heating and cooling energy use of the house, which is taken directly from the DOE-2 output and needs no further explanation (see bottom of Figure 1).

The other three tabs show the change in energy use, cost, or peak demand due to the windows in each orientation.[1] These results are obtained from parametric DOE-2 simulations. To extract the incremental effect of the windows in each orientation, RESFEN 3.1 does four DOE-2 simulations in which the user-defined windows in one orientation are omitted without changing the exterior wall area (technically, this is achieved by replacing the window with a fictitious substance that transmits neither heat flow nor solar heat gain). The resultant energy use of the house is subtracted from the house energy use calculated previously to derive the net energy impact from the windows in that orientation. Since the energy use of the windows is derived relative to a neutral adiabatic surface, RESFEN 3.1 avoids the difficulties in previous versions where the window energy use was compared to a predetermined "windowless wall." This change is especially necessary

1. RESFEN simulates all the windows in each orientation as a single window with a multiplier. Despite this simplification, the paper will refer to the windows in each orientation as plural.

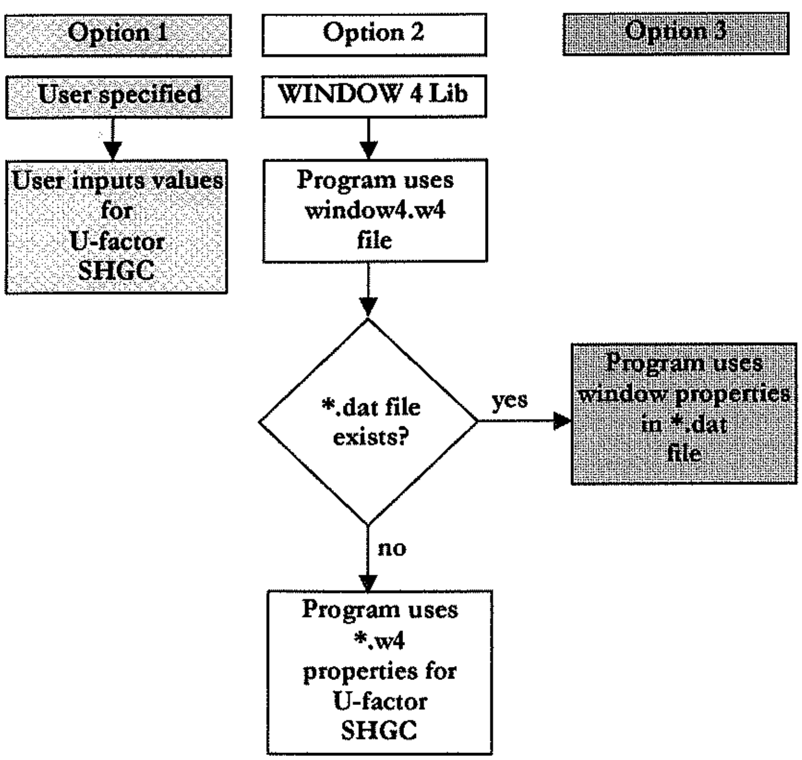

Figure 8 *Window Modeling Options in RESFEN 3.1.*

in RESFEN 3.1 since the modeled wall conditions are location-specific.

The "Window Annual Energy," "Window Energy Cost," and "Window Peak Energy" can be viewed in tabular form, both normalized per square foot of window and then as totals (see Figure 2). Using the "Graphs" button, the same data are presented as bar charts to provide a quick graphical overview of the relative performance of the windows by orientation. The bars are always scaled to the highest value, making visual comparisons between heating and cooling energies, or different locations, potentially misleading. The exception is for "Window Energy Cost," where the heating and cooling costs are plotted using the same scale.

Positive numbers indicate how much the windows have increased the heating or cooling energy use of the house. Negative numbers may appear for the window heating energy. These indicate that the windows on balance provide more solar gain than conductive heat loss and thus help to lower the building's heating energy use. In the sample calculation for double-pane windows in Washington, shown in Figure 2, the cooling results are similar for the east, south, and west orientations (4.1 to 4.8 kWh/ft^2) but are noticeably lower for the north orientation (2.3 kWh/ft^2). The heating results vary greatly by orientation from 54.2 kBtu/ft^2 for the north to −18.9 kBtu/ft^2 for the south orientation.

Table 3 shows how the different options available in RESFEN 3.1 for modeling the windows will affect their calculated energy performance. We modeled a single-pane clear window and a selective low-E double-pane window in two locations using Option 2 (WINDOW 4.1 calculated U-factor and SHGF) and Option 3 (WINDOW 4.1 custom DOE-2.1E library). For the single-pane window, the window heating energy use calculated by either option is within 12% while the cooling energy use is basically the same for both locations. However, for the selective low-E double-pane window, the results calculated by the two options are quite different, especially for heating. Option 3 showed slightly less cooling and much less heating energy use (a factor of 10 less in Washington and a factor of 4 less in Madison) than Option 2, due to more detailed modeling of the optical and thermal properties of the complex glazing systems.

CONCLUSIONS

The authors have developed a simplified computer program in collaboration with members of the fenestration industry that allows the general public to accurately estimate in a few seconds the energy performance of windows in typical residential applications in more than 50 North American climates. This program uses a graphical input interface that is understandable and attractive to nonspecialists but relies on a sophisticated hourly simulation program to compute window energy performance. Recent improvements in the computing power of personal computers and the availability of software for developing graphical user interfaces have made such an approach practical and relatively easy to implement. Such a computer solution also retains a high level of flexibility in that the building locations, modeling assumptions, and prototypical building descriptions can all be changed without affecting the fundamental structure of the program.

TABLE 3
Comparison of Window Energy Use Calculated by RESFEN 3.1 Using Option 2 and Option 3

	Washington, D.C.				Madison, Wisc.			
	Option 2		Option 3		Option 2		Option 3	
	HE (MBtu)	CE (kWh)	HE (MBtu)	CE (kWh)	HE (MBtu)	CE (kWh)	HE (MBtu)	CE (kWh)
Single-Pane Clear (U=1.30, SHGF=0.74)								
Whole House	65.59	1246	65.57	1291	104.11	680	104.63	702
North Windows	8.33	134	7.50	136	12.21	82	11.11	88
East Windows	5.88	283	5.12	285	9.36	182	8.34	185
South Windows	2.57	214	1.97	217	5.81	157	4.97	154
West Windows	6.37	301	5.66	297	10.03	204	9.05	204
Total Windows	23.15	932	20.25	935	37.41	625	33.47	631
Low-E Double-Pane with Argon (U=0.29, SHGF=0.30)								
Whole House	42.83	686	42.65	701	67.92	307	67.71	311
North Windows	2.17	57	1.03	52	3.21	32	1.57	30
East Windows	1.20	114	0.20	103	2.08	68	0.60	63
South Windows	−0.23	86	1.06	75	0.55	55	−0.76	46
West Windows	1.27	122	0.26	109	2.22	77	0.71	71
Total Windows	4.41	379	0.43	339	8.06	232	2.12	210

REFERENCES

ASHRAE. 1997. *WYEC2 User's Manual.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Arasteh, D.K., E.U. Finlayson, and C. Huizenga. 1994. WINDOW 4.1: A PC program for analyzing window thermal performance in accordance with standard NFRC procedures. LBL Report 35298, Lawrence Berkeley National Laboratory, Berkeley, Calif.

CABO. 1993. *Model Energy Code.* Falls Church, Va.: Council of American Building Officials.

Henderson, H., Y.J. Huang, and D. Parker. 1999. Residential equipment part-load curves for use in DOE-2. LBNL-42145, Lawrence Berkeley National Laboratory, Berkeley, Calif.

Huang, Y.J., R. Ritschard, I. Turiel, S. Byrne, D. Wilson, C. Hsui, J. Bull, R. Sullivan, L. Chang, and P. Albrand. 1987. Methodology and assumptions for evaluating heating and cooling energy requirements in new single-family residential buildings. Technical support document for the PEAR microcomputer program. LBL-19128, Lawrence Berkeley Laboratory, Berkeley, Calif.

Labs, K., J. Carmody, R. Sterling, L. Shen, Y.J. Huang, and D. Parker. 1988. *Building Foundation Design Handbook.* ORNL/Sub/86-72143/1, Oak Ridge National Laboratory, Oak Ridge, Tenn.

LBL and Los Alamos Scientific Laboratory. 1980. *DOE-2 Reference Manual,* Parts 1 and 2. Berkeley, Calif.: Lawrence Berkeley Laboratory.

NREL. 1995. *TMY2 User's Manual.* Golden, Colo.: National Renewable Energy Laboratory.

Ritschard, R.L., J.W. Hanford, and A.O. Sezgen. 1992. Single-family heating and cooling requirements: Assumptions, methods, and summary results. GRI-91/0236, Gas Research Institute, Chicago, Ill.

Winkelmann, F.C., B.E. Birdsall, W.F. Buhl, K.L. Ellington, A.E. Erdem, J.J. Hirsch, and S. Gates. 1993. DOE-2 Supplement, Version 2.1E, pp. 2-98 through 2-117. LBL-34947, Lawrence Berkeley National Laboratory (Window Library), Berkeley, Calif.

Winkelmann, F.C. 1998. "Underground surfaces: How to get better underground surface heat transfer calculations in DOE-2.1E." In *Building Energy Simulation User News*, Vol. 19, No. 1. Lawrence Berkeley National Laboratory, Berkeley, Calif.