

ADVANCEMENTS IN THERMAL AND OPTICAL SIMULATIONS OF FENESTRATION SYSTEMS: THE DEVELOPMENT OF WINDOW 5

Elizabeth Finlayson

Dariusz Arasteh

Mike Rubin

John Sadlier

Member ASHRAE

Robert Sullivan

Charlie Huizenga

Dragan Curcija

Mark Beall

Member ASHRAE

Member ASHRAE

ABSTRACT

WINDOW is a personal-computer-based computer program used by manufacturers, researchers, and consumers to evaluate the thermal performance properties (U-factors, solar heat gain and shading coefficients, and visible transmittances) of complete windows and other fenestration systems. While *WINDOW* is used by thousands of users in the United States and internationally and is at the foundation of the National Fenestration Rating Council's U-factor and solar heat gain property procedures, improvements to the program are still necessary for it to meet user needs. Version 5, intended for release in late 1995, is being developed to meet these needs for increased accuracy, a flexible and state-of-the-art user interface, and the capabilities to handle more product types.

WINDOW 5 includes the capabilities to define and model the thermal performance of frames/dividers and their associated edge effects. Currently, such an analysis must be performed outside of *WINDOW* and requires simplifications to be made to frame profiles or is based on the use of generic frame and edge correlations. *WINDOW*'s two-dimensional thermal model is composed of four sections: a graphical input, automatic grid generation, an finite-element analysis (FEA) solution, and the display of results. In the graphical input section, users are able to directly import a computer-aided design (CAD) drawing or a scanned image of a window profile, replicate its exact geometry, and assign material types and boundary conditions. The automatic grid generation is transparent

to the user, with the exception of the requirement that complex shapes (i.e., an aluminum extrusion) be broken down into simpler polyshapes. Inclusion of an automatic grid generation makes detailed "true geometry" frame-and-edge heat-transfer analysis accessible to users without extensive knowledge of numerical methods of heat-transfer analysis. After the cross section is meshed it is sent to the FEA engine for solution and the results are returned. A postprocessor allows for the visual display of temperature and heat flux plots. Note that while this two-dimensional heat-transfer tool is being developed specifically for fenestration products, it also can be used to analyze other building envelope components.

WINDOW 5 also will include a built-in version of a national laboratory's program that allows the user to estimate the orientation-dependent annual energy impacts of a given window in a typical residence in various U.S. climates. This program is based on regressions to a database of DOE2.1 runs. Future versions will include a similar feature for commercial buildings.

Other technical additions include an improved angular/spectral model for coated and uncoated glazings, the ability to analyze the optical properties of nonhomogeneous layers, and the ability to model the effects of laminated glazing layers. A door module permits the user to compute the total U-factors of exterior doors based on component U-factors calculated using the two-dimensional FEA module.

INTRODUCTION

WINDOW is a personal-computer (PC) based software program used by fenestration manufacturers, researchers, and consumers to evaluate the thermal performance properties (U-factors, solar heat gain coefficients, and visible transmittances) of complete fenestra-

tion systems. *WINDOW* started out as a simple formula translation (Fortran) code run on a mainframe computer. *WINDOW*4 (LBL 1994), the most recent version, includes the following features:

- analysis of products made from any combination of coated and uncoated glazing layers, gas gaps,

Elizabeth Finlayson, Dariusz Arasteh, Mike Rubin, John Sadlier, and Robert Sullivan are members of the Building Technologies Program at Lawrence Berkeley National Laboratory, Berkeley, Calif. Charlie Huizenga is with the Center for Environmental Design Research at the University of California, Berkeley. Dragan Curcija is with the Department of Mechanical Engineering at the University of Massachusetts, Amherst. Mark Beall is with the Scientific Computation Research Center at Rensselaer Polytechnic Institute, Troy, N.Y.

frames, spacers, and dividers under any environmental conditions and at any tilt;

- specification of the dimensions and thermal properties of separate frame elements (header, sills, jamb, and mullion) in a window;
- determination of U-factors for edge-of-glass, muntin and divided lite (divider), and frame components based on correlations obtained from a two-dimensional finite-element analysis;
- importation of U-factors for frame components, dividers, and edge-of-glass obtained from a two-dimensional finite-difference analysis (EE 1992);
- calculation of optical properties using a multiband (wavelength-by-wavelength) spectral model; and
- export of energy performance properties to the Department of Energy (DOE) 2.1E (Birdsall et al. 1990) building energy analysis program.

Version 5 of the WINDOW program, currently under development, offers users a graphical interface and three new technical capabilities. These new technical capabilities, the focus of this paper, are first being released as stand-alone programs before being merged with WINDOW4's capabilities (Finlayson et al. 1993) and released as WINDOW5. The new programs are: a two-dimensional heat-transfer tool for modeling frame and edge effects (THERM), an annual energy tool for modeling the impacts of windows in typical homes throughout the U.S. (RESFEN), and an optical properties tool for modeling glazings with glue-on films based on the properties of the substrate and the film (LAMINATE). THERM, RESFEN, and LAMINATE are discussed in detail in the following sections.

THERM

THERM was developed to allow for the seamless modeling of two-dimensional heat transfer within WINDOW. It models frame, edge-of-glass, divider, and divider-edge heat-transfer effects in a manner consistent with previous research in this area (EE 1990). THERM builds on previous efforts in this field by offering a graphical interface that supports a variety of tools to make model creation efficient and accurate and by using a finite-element solver capable of handling geometries made up of any number of polygons (thereby virtually duplicating the exact geometry of any cross section). While these features may not be critical to solving problems when material properties are defined using the effective conductance approach (Carpenter and McGowan 1993), they will serve as the foundation for future improvements (direct modeling of radiation and convection) and they permit the modeling of products other than windows (skylights, greenhouse windows, doors, and walls). THERM's user input features and near-exact modeling features also reduce the possibilities for simulator error or improper judgment decisions

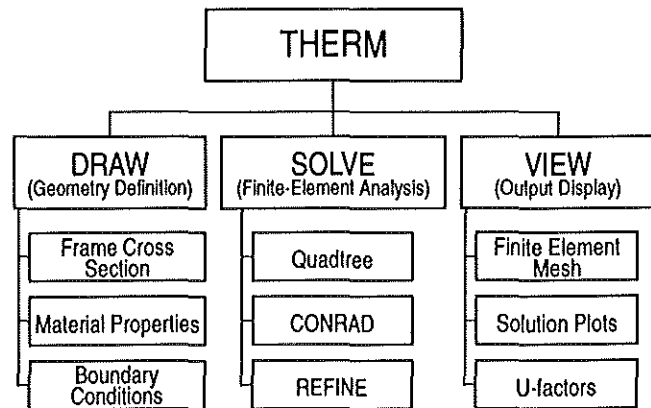


Figure 1 Schematic of the THERM program.

when a cross section (physical, on paper, or on a CAD drawing) is converted to input for a two-dimensional heat-transfer tool.

THERM is composed of three fully integrated sections: geometry definition (DRAW), finite-element analysis (SOLVE), and output displayer (VIEW). The SOLVE section is further composed of three subsections: automatic mesh generation (FINITE QUADTREE), finite-element solution (CONRAD), and mesh adaptation (REFINE). A schematic is shown in Figure 1.

THERM's standard graphical interface format makes it easy to master. This interface has several useful features:

- a combination of mouse and cursor operations simplifies the operation of the program and the creation of cross-section geometries;
- the copy, cut, paste, select all, and delete features make editing easy;
- a toolbar with buttons gives easy access to frequently used commands;
- a windowing feature allows multiple projects to be worked concurrently and keeps track of all open projects; and
- a context-sensitive help feature, including a help menu and a status bar, provides information about selected features.

The DRAW Feature

THERM's graphical interface supports a powerful drawing tool, DRAW. DRAW allows a user to create a cross section, from multishaped polygons, for analysis using any combination of three methods: drawing with straight-line geometry, snapping to the vertices of a CAD file shown as an underlay, and tracing over a bitmap. When drawing a cross section using straight-line geometry, a user can draw either with rectangles or with irregularly shaped polygons. Curves can be approximated by subdividing an arc into straight-line segments. Defining the vertices of the polygons that form a cross

section is the most important step. The vertices can be defined in two ways:

- The mouse input method uses clicks to locate the vertices of the polygon; the screen gives a running record of the distance between vertices.
- The step method uses keyboard input to move the cursor a specified vertical or horizontal distance.

After a polygon is created, the vertices can be moved to modify the shape. Points can be added to existing polygons to refine the drawing. Polygons can be copied or cut and pasted, or they can be moved. Figure 2(a) shows a sample wall cross section drawn using a combination of the CAD file underlay and the straight-line geometry methods.

DRAW has been developed to take advantage of CAD programs used throughout the building industry. Many companies have computer-generated drawings of their products. DXF is the common CAD file format supported by THERM. THERM recognizes the vertices in a DXF file; a selected DXF file vertex becomes a vertex in a THERM polygon. This feature allows a user to create complicated geometries quickly and accurately. THERM also contains an auto-convert feature. The auto-convert feature makes a best guess at interpreting the

DXF file. This feature can handle drawings that conform to THERM design guidelines. Other drawings need some refinement, but a majority of the effort otherwise required to create a cross section in DRAW is eliminated.

The third method for importing a geometry into THERM is by using a bitmap underlay. Bitmaps can be created by scanning in drawings of parts. Unlike the DXF file, THERM cannot distinguish a vertex from any other point in a Bitmap. Bitmaps form an underlay that the user traces over. A rescale feature in THERM allows the traced geometry to be corrected so that the actual dimensions of the cross section are represented.

Creating a geometrical representation of a cross section in THERM is the first step before performing a finite-element heat-transfer analysis. After the cross section has been defined, material thermal properties must be specified and the external boundary conditions must be defined. Material properties are specified for selected polygons. There are two different classes of materials—solids and cavities. Solids have a specified thermal conductivity and solar absorptance. The cavity model is used for cavities commonly found in aluminum and vinyl window frames. THERM determines the maximum width and height of the cavity and then calculates a Nusselt number based on this bounding rectangle

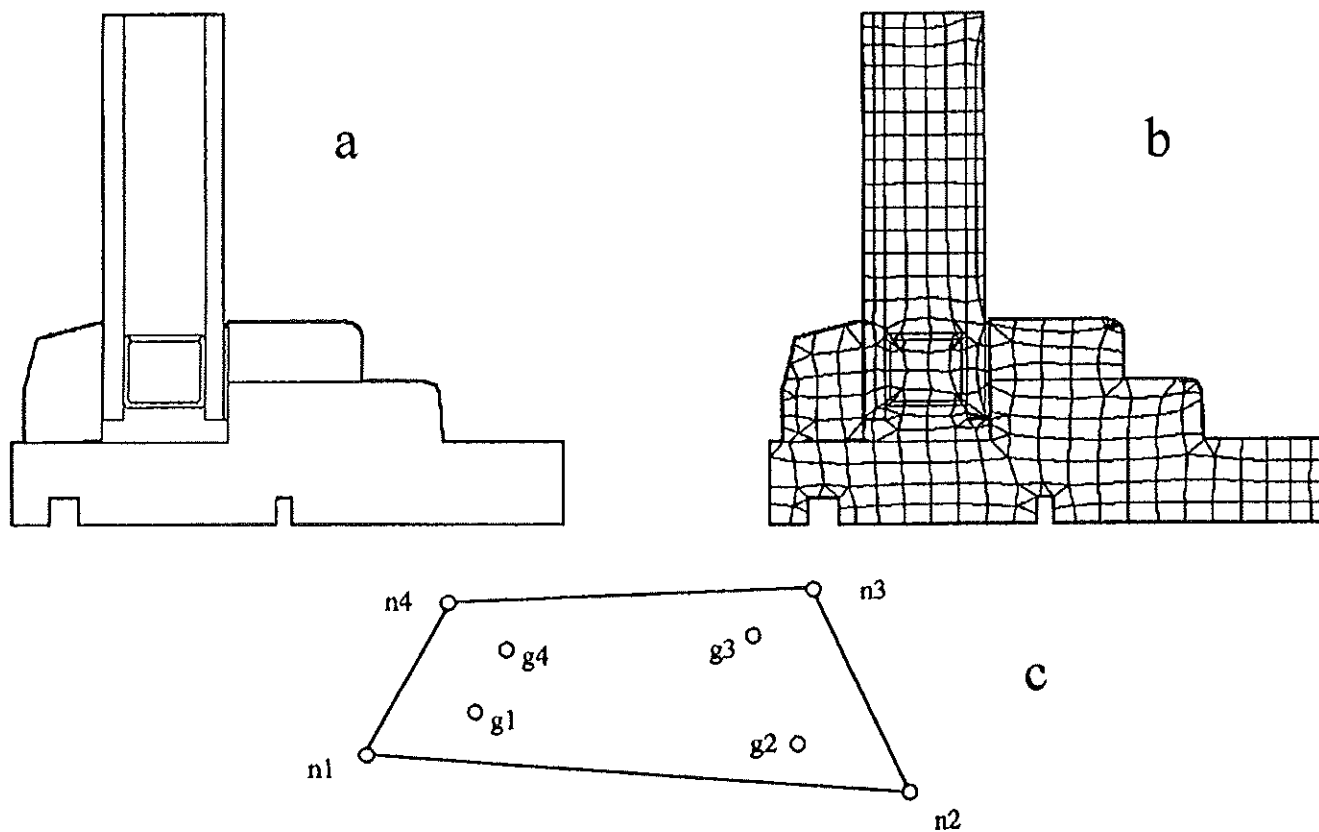


Figure 2 *a* Window cross section created in DRAW using a DXF file underlay and straight-line geometry drawing; *b* mesh generated by Modified Quadress method; *c* quadrilateral finite element: nodes are labeled counter-clockwise: n1, n2, n3, n4; corresponding Gaussian Integration points are labeled g1, g2, g3, g4.

with characteristic length being the dimension parallel to the heat flow. WINDOW uses standard correlations to calculate the Nusselt number (Rohsenow et al. 1985).

Insulated glazing units can be selected from the WINDOW4 glazing-system library. The gas gap in an insulated glazing unit is treated as a solid with an effective conductivity that accounts for conduction, convection, and radiation. THERM displays a graphical representation of a glazing system with all material properties defined. The size and thermal properties of a spacer model are included in the glazing system representation.

With the geometry specified and the material properties selected for the glazing system, the final task is to define the external boundary conditions. THERM begins by drawing a boundary around the outside of the completed cross section. The program then checks for voids or overlaps and will not proceed with calculations if any exist. The default boundary condition applied is adiabatic (zero heat flux in the direction perpendicular to the boundary). Nonadiabatic boundaries are defined by selecting their end points and specifying the appropriate boundary condition from a library or with a user-defined value. A convective/linearized radiative boundary condition for the glazing system is imported from WINDOW4. After the boundary condition has been defined for all the exposed surfaces in the cross section, the user can tag selected surfaces. Values are returned for the U-factor and heat-transfer per unit of projected area for each tagged surface.

The SOLVE Feature

After the geometry, material properties, and boundary conditions have been specified in DRAW, the SOLVE feature meshes the cross section, performs the heat-transfer analysis, runs an error estimation, refines the mesh if necessary, and finally returns the converged solution. This section describes each of these functions in detail.

THERM currently is a two-dimensional conduction heat-transfer analysis tool based on the finite-element method. Finite-element and finite-difference methods are widely used to solve equations in heat-transfer analysis. Finite-difference methods solve a global approximation of the energy equation. Finite-element methods minimize the global error resulting from localized approximate solutions to the energy equation. In the finite-difference method, rectangles are formed by the orthogonal intersection of grid lines. In the finite-element method, each element is unique, and each face of the element can have a different slope. An example of a finite-element mesh is shown in Figure 2. Although there are finite-difference methods that handle complex geometries using the superposition of multiple grids, the finite-element method in its basic form can model the complicated geometries that are found in fenestration

products and other building elements. The potential disadvantage in using a finite-element method is the complexity of the mesh required in comparison to the much simpler grid used in the finite-difference method. Manual creation of a finite-element mesh requires an advanced understanding of numerical methods. However, during the past 20 years, powerful algorithms have been developed that automatically generate finite-element meshes (George 1991). THERM uses one such algorithm, FINITE QUADTREE (Baehmann et al. 1987). FINITE QUADTREE generates a well-conditioned finite-element mesh, requiring only a definition of the geometry under consideration.

FINITE QUADTREE The first step in a finite-element analysis is the definition of a mesh. This mesh is made up of a finite number of nonoverlapping subregions, known as *elements*, that cover the whole region under analysis. An example of a finite-element mesh is shown in Figure 2. The manual creation of a well-conditioned finite-element mesh requires a sophisticated knowledge of the solution method. This labor-intensive component of the finite-element analysis is accomplished for the user in THERM by the automatic meshing algorithm FINITE QUADTREE. The FINITE QUADTREE mesh generator is based on a spatial decomposition procedure that represents the domain of an object as a set of nonoverlapping squares, referred to as *quadrants*, that are stored in a hierarchic tree. The object to be meshed is placed in a square universe that entirely encloses it. The square represents the "parent" quadrant; it is subdivided into four "daughter" quadrants (Baehmann et al. 1987). The remainder of the tree is then defined in a recursive manner by subdividing the boundary and interior quadrants until all quadrants are at the level dictated by the geometry of the object and the mesh control parameter. After the quadtree has been defined, all terminal quadrants are checked to ensure that only one tree-level difference exists between them and their neighbors so that there is not a large size difference between adjacent finite elements in the final mesh. The final step in the algorithm is to convert the quadtree into a combination of well-shaped quadrilaterals and triangles. For analytical purposes, all elements are treated as quadrilaterals. A triangle is defined as a quadrilateral element in which two of the nodes are coincident.

Figure 2 shows an example of the elements used in THERM. The meshing algorithm in THERM creates an initial mesh based solely on the geometry of the cross section and a mesh parameter. The mesh parameter governs the maximum element size and is the only parameter in the mesh generation procedure that the user can specify. The mesh is defined, so that every element is made up of a single material; thus, thermal conductivity is constant across the element. This mesh is then sent to the finite-element solver, CONRAD.

CONRAD CONRAD, the finite-element module in THERM, is a derivative of the public-domain computer program TOPAZ2D (Shapiro 1986, 1993). Many excellent reference books describe the finite-element method in detail (Zienkiewicz and Taylor 1989; Pepper and Heinrich 1992). A brief overview of the solution method used in CONRAD is presented here. A complete discussion of the solution method is given in Curcija et al. (1995). CONRAD is designed to solve the steady-state, two-dimensional energy equation on an arbitrarily shaped domain:

$$k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + q_g = 0. \quad (1)$$

For this equation to be solved, the thermal conductivity, k , and boundary conditions must be known. By the time the cross section has been meshed, the thermal conductivity of each element is a known constant. The boundary conditions also are defined in DRAW; expressed as equations, the boundary conditions take the following forms:

$$\begin{aligned} q &= 0 && \text{adiabatic boundary condition} \\ q &= \bar{q} && \text{known heat flux, } \bar{q}, \text{ boundary condition} \\ q &= h(\theta - \theta_\infty) && \text{convective/linearized radiative boundary condition,} \end{aligned}$$

with the magnitude of the heat flux vector normal to the boundary, q , given by Fourier's law:

$$q = -k \left(\frac{\partial \theta}{\partial x} n_x + \frac{\partial \theta}{\partial y} n_y \right). \quad (2)$$

CONRAD uses the finite-element analysis based on the method of weighted residuals. The method of weighted residuals seeks to solve an equation of the form:

$$\iint_{\Omega} W \mathcal{R} dx dy = 0. \quad (3)$$

The residual function, \mathcal{R} , results when an approximation for the actual temperature field is substituted into Equation 1. The residual function is zero for the exact temperature field. The weighted residual method does not seek to force the residual function to zero everywhere in the domain; instead, the residual function is multiplied by a weighting factor, W , forcing the integral of the weighted expression to zero and minimizing the error of the approximate solution. This is done by first integrating Equation 3 by parts and substituting in the boundary conditions:

$$\begin{aligned} k \iint_{\Omega} \left(\frac{\partial W}{\partial x} \frac{\partial \theta}{\partial x} + \frac{\partial W}{\partial y} \frac{\partial \theta}{\partial y} - W q_g \right) dx dy \\ + \int_{\Gamma_h} W h (\theta - \theta_\infty) d\Gamma_h - \int_{\Gamma_q} W \bar{q} d\Gamma_q = 0. \end{aligned} \quad (4)$$

Equation 4 is the "weak" form of the energy equation because it contains only first derivatives. It is as an

exact expression for determining the temperature field as Equation 1. The Galerkin form of the weighted residual method, used in CONRAD, uses algebraic shape functions— N_i for the weighting function, $W = N_i$, and, to approximate the temperature field, $T = N_i \theta_i$. Equation 4 is set up for each element generated by FINITE QUADTREE. The integration over each element is approximated by a numerical integration using second-order Gaussian quadrature, with integration points shown in Figure 2. The local systems of equations are combined into a global matrix, and a solution is obtained for the unknown nodal temperatures and heat fluxes using a direct method. U-factors are obtained from heat flow on the boundary, which is calculated by integrating the boundary heat flux. After the solution has been obtained on the initial mesh, it is sent to the error estimator, REFINE, to check for convergence.

REFINE REFINE, the error estimator, follows the method presented by Zienkiewicz and Zhu (1992a, 1992b). Although a detailed description of this method is beyond the scope of this paper, a conceptual overview is included. Recall that the finite-element method solves the "weak" form of the energy equation (Equation 4). Some points in the element have a higher order of convergence than others; these are called superconvergent points. For quadrilateral elements used in CONRAD, the superconvergent points coincide with the Gaussian integration points (Figure 2). The first step in error estimation is to use this knowledge of the finite-element solution to make a good guess at a better solution at all the nodal points. To accomplish this, a least-squares method is used to fit a smooth function to the values of the gradient at the superconvergent points in a patch of elements around the node. The patch of elements around a node is defined as all the elements sharing that node. A better solution for the vector field of heat fluxes, q_r , at the nodal points is recovered from this smooth function. The shape functions from the original problem are then used to interpolate the nodal solutions to obtain values for the recovered solutions throughout each element. Using the recovered fluxes, q_r , and the original fluxes, q , the contribution to the global error for each element is calculated as:

$$\|e\| = \left(\int_{\Omega} (q_r - q)^T (q_r - q) d\Omega \right)^{1/2}. \quad (5)$$

The global error is determined by summing the elemental errors for all the elements in the mesh. If the global error is above a specified value, then the error estimator signals the mesh generator, and the mesh is refined in areas where there is high error. The refined mesh is sent back to CONRAD, and a new solution is obtained. This process continues until the global error is less than the predetermined convergence value. The user can then

view the converged results with THERM's postprocessing feature, VIEW.

The VIEW Feature

The converged results from the finite-element analysis can be viewed in THERM. VIEW displays a mesh plot of the finite-element mesh, in addition to four result formats. The results can be displayed as:

- isotherms,
- color-flooded isotherms,
- heat-flux vector plot, and
- color-flooded lines of constant flux.

The color-flooded isotherms use the same color map as the laboratory's infrared imaging system. THERM also reports the U-factors of those boundaries that were tagged in the original definition of the problem. Figure 3 shows results for a sample window cross section that has been analyzed using THERM. Figure 4 shows results

for a sample wall cross section that has been analyzed using THERM.

RESFEN

The evaluation of window thermal properties (i.e., U-factors and solar heat gain coefficients) that takes place in the current WINDOW program is an essential step in evaluating window thermal performance. However, important questions are left unanswered:

- What is the effect of a given window in a specific application?
- How much energy and money could be saved by using one window instead of another in a specific application?

Answers to such questions typically are obtained from a building energy simulation program. There are many such programs operating at differing levels of complexity and accuracy. Common to all these programs is the need to define the entire building before answers to

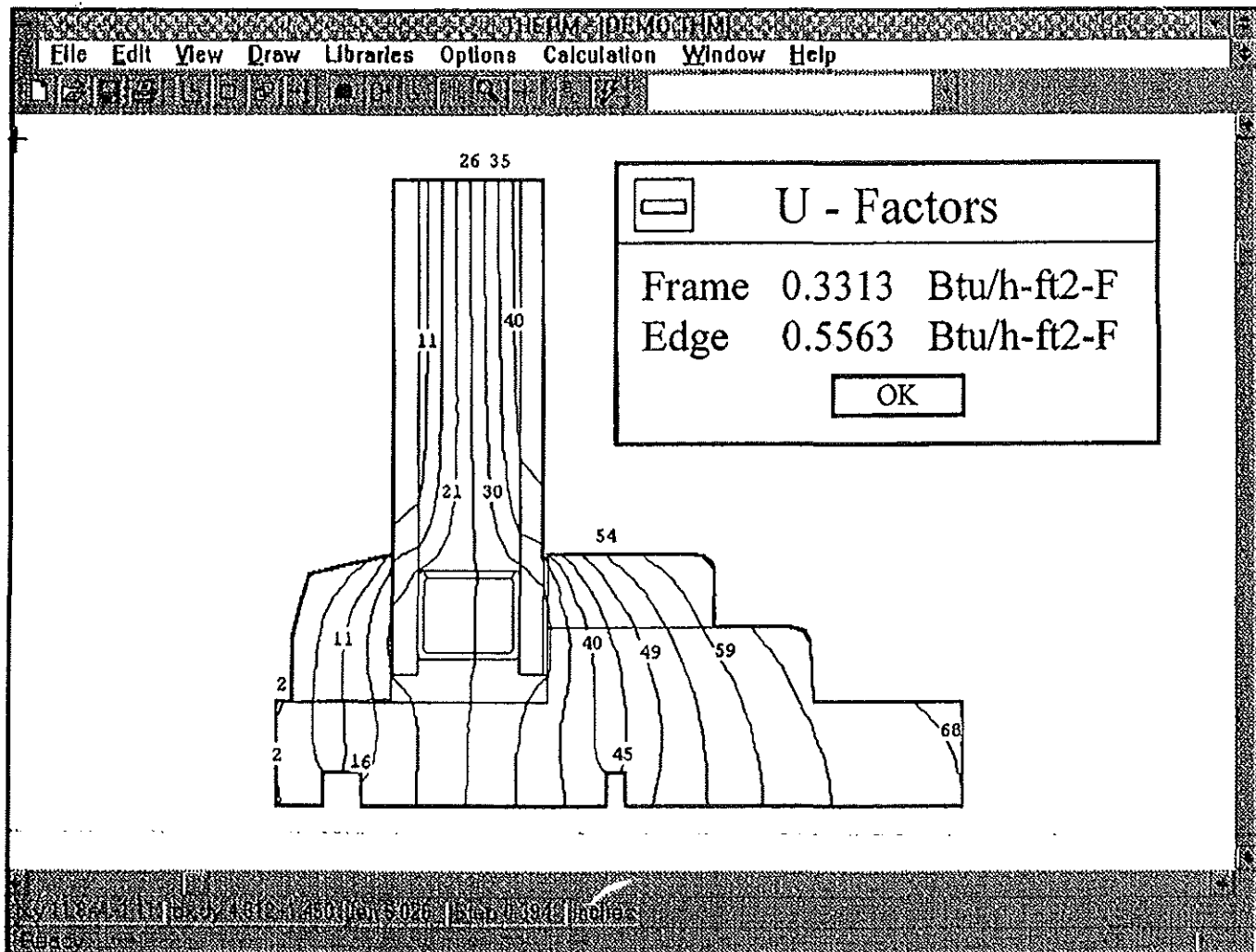


Figure 3 Sample output for simple window cross section including isotherms and frame and edge U-factors.

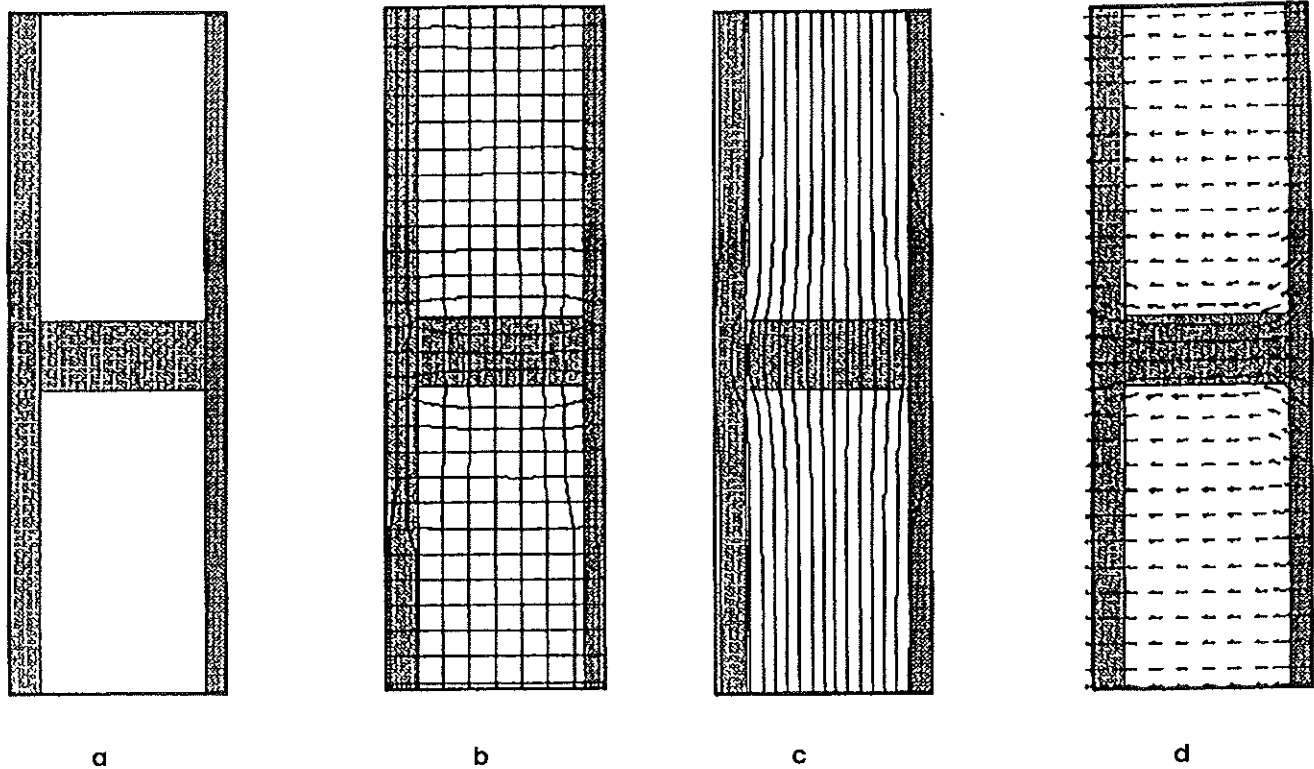


Figure 4 Sample analysis of a simple wall system; a geometric representation; b finite-element mesh, c isotherms; d heat flux vectors.

RESIDENTIAL FENESTRATION PERFORMANCE ANALYSIS TOOL							
File Edit House Window View Help							
House Data		Window Data					
Run ID: DEFAULT		Window Type Shading Type		Window 4 Library...			
Units: IP		Area (%FA)		South	West	Total	
Location: Atlanta, GA		Height (ft)		Awning	Casement	4.00 (61.6 ft ²)	
Electric Cost: \$.08/kWh		Width (ft)		Double Slider			
Gas Cost: \$.50/therm		U-Factor		Double Hung			
House: Type: Ranch Floor: Slab Wall: Frame HVAC: Ac & Gf		SC		Fixed			
Calculate		CFM/Lft		Single Slider			
Quit		Shading Type		Single Hung	None		
Output Data - Energy Compared to: windowless wall							
Cooling (kWh/ft ²)		2.1	3.7	3.5	4.3	3.4	
Heating (kBtu/ft ²)		-2.1	-11.9	-22.4	-7.0	-10.8	
Cooling (kWh)		33.1	56.8	53.3	66.5	209.6	
Heating (kBtu)		-33.1	-182.9	-344.2	-107.8	-667.9	
Total (kBtu)		79.7	11.1	-162.4	119.2	47.6	
Cooling (kWh/ft ²) Heating (kBtu/ft ²) Cooling (kWh) Heating (kBtu) Total (kBtu)							
N E S W Tot		N E S W Tot		N E S W Tot		N E S W Tot	

Figure 5 Screen image showing the input/output user interface of RESFEN. The pull-down menu for the selection of window type is presented.

specific window questions can be obtained. This modeling can be time consuming.

Research at a national laboratory showed that for many common residential buildings, specific building parameters (i.e., wall insulation levels and occupancy patterns) do not significantly affect energy use and cost differences between window glazing options in residential buildings (Sullivan and Selkowitz 1985, 1987). Thus, a standard residential building can be defined and the effects of window variations studied if we simulate the performance of this building by varying only window-related parameters. This capability has been built into the RESFEN computer program (Sullivan et al. 1992), which makes use of a regression database determined from thousands of DOE2 runs. Figure 5 shows a sample RESFEN screen and the run parameters that a user must provide.

RESFEN can currently import window products directly from the WINDOW4 window library. However, the two programs are not completely coupled; a user cannot easily iterate back and forth between them to quickly estimate the energy impacts of different window products. WINDOW5 will include RESFEN's algorithms and an appropriate interface that will allow users to quickly compare the annual energy impacts of residential windows. Future versions of the program will address the effects of different window products in commercial buildings.

LAMINATE

Applied window films are used widely in the retrofit of existing windows. Consumers want to obtain the optical properties of specific combinations of window film and glass. Compiling a database of all possible combinations of these properties would require a prohibitively large number of measurements. LAMINATE eliminates the need for these measurements by calculating the properties of a window film and glass combination based solely on the measured properties of the individual components. This allows users to obtain many combinations of products from various manufacturers with a relatively small database of glazings and films.

The calculation method requires the user to know the spectral transmittance and reflectance at normal incidence for both the film and the glass. These properties are contained in a standard WINDOW spectral data file. The calculation is performed at each defined wavelength to simplify the notation; reference to spectral dependence is omitted.

LAMINATE assumes an uncoated glass substrate (subscript *s*); therefore, only two independent measured quantities are required: the transmittance (T_s) and the reflectance (R_s). From these measured values we obtain α_s , the internal absorption of the glass-substrate material; τ_s , the transmissivity of the air-to-glass interface;

and ρ_s , the reflectivity of the air-to-glass interface (Furler 1991):

$$\rho_s = \frac{(T_s^2 - R_s^2 + 2R_s + 1) - \sqrt{(T_s^2 - R_s^2 + 2R_s + 1)^2 - 4(2 - R_s)R_s}}{2(2 - R_s)} \quad (6)$$

and, because no absorption occurs at the interface,

$$\tau_s = 1 - \rho_s \quad (7)$$

and

$$\alpha_s = \frac{R_s - r_s}{r_s T_s} \quad (8)$$

For most applied films (subscript *f*), reflectances of front and back surfaces are not equal; thus, three separate measured quantities are needed: the transmittance (T_f), the reflectance from the outward-facing adhesive side (R_f), and the reflectance from the inward-facing side R'_f . The measured film properties— T_f , R_f , and R'_f —are used to determine the transmissivity, τ , and reflectivities of the outward-facing side, ρ_c , and the inward-facing side, ρ'_c , of the coating (subscript *c*). Experimental analysis has shown (Furler et al. 1995) that the index-matching and low absorptance properties of adhesives commonly used to apply the film to glass have a negligible effect on the optical properties of the combined unit. These properties essentially are equal for different adhesives. Therefore, the values for the adhesive (subscript *a*) are fixed in the model and based on averages of measurements.

$$T_f = \frac{\alpha_a \tau_a \tau_c}{1 - \alpha_a^2 \rho'_a \rho'_c} \quad (9)$$

$$R_f = \rho_a + \frac{\alpha_a^2 \tau_a^2 \rho'_c}{1 - \alpha_a^2 \rho'_a \rho'_c} \quad (10)$$

$$R'_f = \rho_c + \frac{\alpha_a^2 \tau_c^2 \rho'_a}{1 - \alpha_a^2 \rho'_a \rho'_c} \quad (11)$$

There are only three unknowns in these equations: the transmittance and reflectance from each side of the coating, τ_c , ρ_c , and ρ'_c . Solving for the unknowns from Equations 9 through 11 gives

$$\rho'_c = \frac{R_f - \rho_a}{\alpha_a^2 (\tau_a^2 + R_f \rho'_a)} \quad (12)$$

$$\tau_c = \frac{T_f (1 - \alpha_a^2 \rho'_a \rho'_c)}{\alpha_a \tau_a} \quad (13)$$

$$\rho_c = R'_f - \frac{\alpha_a^2 \tau_c^2 \rho'_a}{1 - \alpha_a^2 \rho'_a \rho'_c} \quad (14)$$

The properties of the substrate with the applied film are then determined from known quantities:

$$T = \frac{\alpha_a \alpha_s \tau_s \tau_c}{1 - \alpha_a^2 \alpha_s^2 \rho_s' \rho_c'} \quad (15)$$

$$R = \rho_s + \frac{\alpha_a^2 \alpha_s^2 \tau_c^2 \rho_s'}{1 - \alpha_a^2 \alpha_s^2 \rho_s' \rho_c'} \quad (16)$$

$$R' = \rho_s + \frac{\alpha_a^2 \alpha_s^2 \tau_c^2 \rho_s'}{1 - \alpha_a^2 \alpha_s^2 \rho_s' \rho_c'} \quad (17)$$

The results from LAMINATE are spectral data files fully compatible with the WINDOW glass library. WINDOW calculates average optical properties for the visible and solar spectra. Errors in average properties from data generated by LAMINATE vs. measurements the actual applied film and glass combination are well within the specified measurement tolerances of 1 percentage point in transmittance and 2 percentage points for reflectance. Typical errors are 0.5 percentage point or less.

CONCLUSION

WINDOW5 is a flexible platform this is being developed to accommodate innovations in energy simulations. WINDOW5 incorporates the widely used WINDOW4 algorithms. The first portion of WINDOW5 to be released is the stand-alone program THERM. THERM is a two-dimensional finite-element analysis tool, which includes design, meshing, analysis, and output. The interface used to develop THERM gradually will expand to incorporate all the features currently found in WINDOW4, as well as RESFEN and LAMINATE and other features still in the planning stage. Although in the past a national laboratory has concentrated on developing analysis tools designed specifically for windows, WINDOW5 is a tool flexible enough to be used for other building components such as walls.

ACKNOWLEDGMENTS

This work was supported by the assistant secretary for Conservation and Renewable Energy, Office of Building Technologies, Building Systems, and Materials Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. The authors would like to thank their colleagues, in particular, Reto Furler and Peter English for their contribution to the work presented in this paper.

NOMENCLATURE

h	= surface heat-transfer coefficient
k	= thermal conductivity
n_x, n_y	= vector components of the outward facing normal to the boundary
q_g	= internal energy source

\bar{q}	= known heat flux on the boundary
q	= nodal flux vector used in error estimation
x, y	= spatial coordinates
N	= shape functions
\mathfrak{R}	= residual function
R	= reflectance (measured quantity)
T	= transmittance (measured quantity)
W	= weighting function
Γ	= boundary surface
Ω	= element or problem domain.
α	= absorptivity
∞	= unknown temperature field
ρ	= reflectivity
τ	= transmissivity

Subscripts

a	= adhesive
c	= coating
r	= recovered
s	= substrate
∞	= ambient conditions

Superscripts

$'$	= inward-flowing surface property
T	= transpose

REFERENCES

- Baehmann, P.L., S.L. Wittchen, M.S. Shephard, K.R. Grice, and M.A. Yerry. 1987. Robust, geometrically based, automatic two-dimensional mesh generation. *International Journal for Numerical Methods in Engineering*. 24: 1043 - 1078.
- Birdsall, B., W.F. Buhl, K.L. Ellington, A.E. Erdem, and F.C. Winkelmann. 1990. Overview of the DOE-2 building energy analysis program. Version 2.1D. LBL Report 19735, Rev. 1. Berkeley, Calif.: Lawrence Berkeley Laboratory.
- Carpenter, S., and A. McGowen. 1993. Effect of framing systems on the thermal performance of windows. *ASHRAE Transactions Symposia* CH-93-7-1. Atlanta, Ga.: American Society of Heating, Refrigerating and Air-conditioning Engineers.
- Curcija, D., J.P. Power, and W.P. Goss. 1995. CONRAD: A finite element method based computer program module for analyzing 2-D conductive and radiative heat transfer in fenestration systems. Draft report. Amherst: University of Massachusetts.
- EE. 1990. Development of a procedure for calculating total window U-value and SHGC. DSS File No. 23216-9-9117. Ottawa, Ont.: Efficiency and Alternative Energy Technology Branch, Mines and Resources. Enermodal Engineering Ltd.
- EE. 1992. FRAME, A computer program to evaluate the thermal performance of window frame systems. Version 3.0. Enermodal Engineering Ltd.
- Finlayson, E.U., D.K. Arasteh, C. Huizenga, M.D. Rubin, and M.S. Reilly. 1993. WINDOW 4.0: Documentation of calculation procedures. LBL Report 33943. Berkeley, Calif.: Lawrence Berkeley Laboratory.
- Furler, R. 1991. Angular dependence of optical properties of homogeneous glasses. *ASHRAE Transactions* 97(2).
- Furler, R., M. Rubin, and J. Sadlier. 1995. Synthesis of the optical properties of applied films on glass. Draft paper.

- George, P. L. 1991. *Automatic mesh generation*. New York: Masson, John Wiley & Sons.
- Lawrence Berkeley Laboratory. 1994. WINDOW 4.1: Program description, A.P.C. program for analyzing the thermal performance of fenestration products. LBL-35298. Berkeley, Calif.: Lawrence Berkeley Laboratory.
- Pepper, P.W., and J.C. Heinrich. 1992. *The finite element method basic concepts and applications*. Washington, D.C.: Hemisphere Publishing Corp.
- Rohsenow, W.M., J.P. Hartnett, and E.N. Ganic. 1985. *Handbook of heat transfer fundamentals*, 2d ed. New York: McGraw Hill.
- Shapiro, A.B. 1986. TOPAZ2D—A two-dimensional finite element code for heat transfer analysis, electrostatic, and magnetostatic problems. UCID-20824. Berkeley, CA: Lawrence Livermore National Laboratory.
- Shapiro, A.B. 1993. TOPAZ2D computer program, rev. 9/9/93. Lawrence Livermore National Laboratory.
- Sullivan, R., and S. Selkowitz. 1985. Window performance analysis in a single-family residence. *ASHRAE Transactions* 91(1).
- Sullivan, R., and S. Selkowitz. 1987. Residential heating and cooling energy cost implications associated with window type. *ASHRAE Transactions* 93(1): 1553-1566.
- Sullivan, R., B. Chin, D. Arasteh, S. Selkowitz. 1992. RESFEN: A residential fenestration performance design tool. *ASHRAE Transactions* 98(1).
- Zienkiewicz, O.C., and R.L. Taylor. 1989. *The finite element method*, 4th ed. vol. 1. Maidenhead, U.K.: McGraw-Hill.
- Zienkiewicz, O.C., and J.Z. Zhu. 1992a. The superconvergent patch recovery and a posteriori error estimates. Part 1: The recovery technique. *International Journal for Numerical Methods in Engineering* 33: 1331-1364.
- Zienkiewicz, O.C., and J.Z. Zhu. 1992b. The superconvergent patch recovery and a posteriori error estimates. Part 2: The error estimates and adaptivity. *International Journal for Numerical Methods in Engineering* 33: 1365-1382.