Vision: a computer program to evaluate the thermal performance of super windows, final report

Ferguson, J. E.; Wright, J. L.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/23001341
Solar Energy Program (Canada), 1984-06

AHE

National Research Council Canada
Conseil national de recherches Canada

SOLAR ENERGY PROGRAM

VISION: A COMPUTER PROGRAM TO EVALUATE THE THERMAL PERFORMANCE OF SUPER WINDOWS

BY

J.E. FERGUSON AND J.L. WRIGHT
SPIDER ENGINEERING ASSOCIATES (WATERLOO) INC.

CONTRACT No. 07SX.31155 - 2 - 2778

PROJECT SCIENTIST: S. BARAKAT

Solar Energy Program

Report No. PASSIVE- 10

JUNE 1984

PRICE: $6.50

Canada

VISION: A COMPUTER PROGRAM TO EVALUATE THE THERMAL PERFORMANCE OF SUPER WINDOWS

Final Report

Prepared by: J.E. Ferguson, P. Eng.
J.L. Wright, P. Eng.

Spider Engineering Associates (Waterloo) Inc.
Waterloo, Ontario

Prepared for: Solar Energy Program
National Research Council
Ottawa, Ontario

OERD REF. No.: 4.2.2

DSS FILE No.: 07SX.31155-2-2778

August, 1983

Updated June, 1984

TABLE OF CONTENTS

	Page
ABSTRACT/RÉSUMÉ	v
SUMMARY	vii
1.0 INTRODUCTION	1
2.0 REFERENCE MANUAL	3
2.1 VISION Overview	3
2.2 Thermal Models and Assumptions	4
2.2.1 Optical Properties of Glazings	4
2.2.2 Optical Properties of Multi-Glazed Window	8
2.2.3 Cosine Polynomial Coefficients	9
2.2.4 Diffuse Optical Properties	11
2.2.5 Incident Solar Radiation	11
2.2.6 Shading	14
2.2.7 Thermal Heat Transfer	14
2.2.7.1 Governing Equations	15
2.2.7.2 Convective Heat Transfer Coefficients	19
2.2.7.3 Solution of the Governing Equations	21
2.2.7.4 Fill Gas Properties	22
2.2.7.5 Slit-Type Honeycomb Heat Transfer	23
2.2.8 Thermal Heat Transfer in Aerogel Windows	25
2.2.8.1 Aerogel Layers	25
2.2.8.2 Governing Equations	26
2.2.8.3 Solution of the Governing Equations	30
2.2.9 Calculation of U-value	31
2.2.10 Calculation of Shading Coefficient	31
2.2.11 Energy Analysis Summary	32
2.2.12 Weather Data	34
2.3 Program Logic	34
2.3.1 Overview	34
2.3.2 Subroutine Logic	34
2.4 Sample Results	36
3.0 USER'S MANUAL	51
3.1 Input Requirements	51
3.1.1 Window Design Data File	51
3.1.2 Weather Data	52
3.2 Output Format	52
3.3 Executing VISION	65
3.4 Computer Requirements	65
3.4.1 Language	65
3.4.2 Hardware	66
3.4.3 Execution Time	66
4.0 REFERENCES	67

TABLE OF CONTENTS (Concluded)

	Page
Appendix A - Glossary of Terms	71

LIST OF TABLES

3.1	Window Input Data	53
3.2	Energy Analysis Input Data	59
3.3	Shading Input Data	60

LIST OF FIGURES

2.1	M-Element Array	8
2.2	Thermal Heat Transfer Analysis Geometry	16
2.3	Thermal Heat Transfer Analysis - Aerogel Windows	27
2.4	Energy Balance within the ith Glazing Element	30
2.5	Overview of Program Logic	35
2.6	Program Logic for TALK	36
2.7	Program Logic for MAIN	37
2.8	Program Logic for WINDOW	38
2.9	Program Logic for READIN	42
2.10	Program Logic for CCOEF	44
2.11	Program Logic for RFILM	45
2.12	Program Logic for SOLMAT	47
2.13	Program Logic for PRINT1	47
2.14	Program Logic for ENANAL	48
2.15	Program Logic for SOLRAD	49
2.16	Program Logic for SHADE	50
2.17	Program Logic for PRINT2	50
3.1	Sample Input Data	61
3.2	Sample Output Data	62
3.3	TALK Exec File	66
3.4	VISION Exec File	66

ABSTRACT

COMPUTER SIMULATION OF SUPER WINDOWS

The objective of this work was to develop a FORTRAN program capable of modelling the combined optical and thermal performance of glazing systems. The program written to meet this goal, called VISION, is capable of modelling conventional, as well as innovative, multi-glazed windows.

The program provides the analyst with two methods to evaluate thermal performance. The first method involves the calculation and comparison of window U-value and shading coefficient. The second method enables the analyst to calculate hourly heat transfer through the window for any period up to one year in length, for as many as eight different window orientations. Window optical performance is characterized primarily using classical optical theory. Convective/conductive/thermal radiation heat transfer between glazings and between the window and the environment are analysed using a rigorous algorithm. A specially modified version of VISION provides the capability of modelling aerogel layers as part of a glazing system. Initial computer runs show VISION to agree well with published values.

RÉSUMÉ

SIMULATION INFORMATISÉE DE SUPER-VITRAGES

L'objectif de ce travail était d'élaborer un programme en FORTRAN capable de modéliser le rendement optique et thermique combinée de vitrages. Le programme écrit à cette fin, nommé VISION, permet la modélisation de fenêtres à multi-vitrages de conception classique et nouvelle.

Le programme fournit à l'analyste deux méthodes d'évaluation du rendement thermique. La première méthode consiste à calculer et à comparer le paramètre U de la fenêtre et le coefficient d'ombre. La seconde méthode permet à l'analyste de calculer le transfert de chaleur horaire à travers la fenêtre pendant une période pouvant aller jusqu'à un an, pour huit orientations différentes des fenêtres. Pour caractériser le rendement optique, on se sert principalement de la théorie optique classique. On se sert d'un algorithme rigoureux pour analyser le transfert de chaleur par convection/conduction/rayonnement thermique entre les vitrages et entre la fenêtre et l'environnement. Les premiers essais sur ordinateur ont montré un bon accord entre les résultats de VISION et les valeurs publiées.

SUMMARY

Recent window designs have incorporated a variety of energy conserving features which cannot be evaluated directly using existing computer programs. Therefore, a new computer program, VISION, has been developed specifically to evaluate and optimize the thermal performance of these super window glazing systems. This report details the thermal models incorporated in the program, and provides instructions regarding its use.

In addition to modelling conventional multi-glazed windows, VISION is also capable of modelling features such as substitute gases, diathermanous glazings, partial vacuums, slit-type convection suppressing films, aerogel layers, thin film optical coatings, and shading.

The program provides the analyst with two methods to evaluate thermal performance. The first method involves the calculation and comparison of window U-value and shading coefficient. The second method enables the analyst to calculate hourly heat transfer through the window for any period up to one year in length, for as many as eight different window orientations.

Window optical performance is characterized primarily using classical optical theory. The unique functional dependence of optical properties on radiation incidence angle is characterized using coefficients for a fifth order polynomial. This approach minimizes execution time requirements for the hourly energy analysis.

Convective/conductive/long wave radiation heat transfer between glazings is analysed using a set of rigorous algorithms.

A comparison of sample thermal performance results for a conventional double glazed window indicates that VISION estimates are in good agreement with published values.

1.0 INTRODUCTION

Windows play an important role in the energy performance of a building. They are responsible for significant conduction heat losses and gains, and virtually all direct solar energy gains. Because of this, recent research efforts have been directed at the development of improved window designs.

To evaluate and optimize the effectiveness of any proposed glazing system, it is necessary to analyse thermal performance. Due to the large number of variables to be considered, and the dynamic nature of solar energy and conduction heat flows, the problem is well suited to computer simulation.

Numerous computer programs exist to calculate overall building thermal performance. Because of their scope, few of these programs perform detailed modelling of windows. Coefficients used to characterize the conduction and solar performance of windows are usually required as input.

Several computer programs have been developed specifically for use in analyzing windows. Mitalas and Arseneault [1] developed a computer program which calculates the solar absorptance and transmittance of single and double panes of common window glass for radiation incidence angles ranging from 0 to 88°. The program also calculates coefficients for a fifth order polynomial, to allow rapid calculation of optical properties given any angle of incidence.

Barakat [2] developed a computer program which calculates total monthly and annual solar heat gains and conduction losses using measured hourly weather data. Up to eight different azimuth angles can be modelled and any number of glazings can be specified, provided they are uncoated and have identical dimensions and optical properties.

Recent energy conserving window designs have incorporated a variety of innovative features, such as heat mirrors, convection suppressive films, and substitute gases, which cannot be directly modelled using the previously identified computer programs. As a result, a new computer program called VISION has been developed to specifically evaluate and optimize the thermal performance of these new 'super windows'. In addition to modelling conventional multi-pane windows, VISION is also capable of modelling features such as:

(i) internal films or glazings which are opaque or partially transparent to long wave radiation

(ii) substitute gases and partial vacuums in the interpane spaces

(iii) convection suppression using slit-type honeycombs

(iv) shading by overhangs, side fins and set back

(v) thin-film optical coatings

(vi) tilted windows

(vii) aerogel layers

This report documents the development and use of VISION. It is divided into two main sections, a Reference Manual and a User's Manual. The Reference Manual describes the thermal models and assumptions incorporated into VISION, and presents the program logic. The User's Manual provides instruction on the use of the program, including input requirements and format, a description of the output, and computer requirements.

2.0 REFERENCE MANUAL

2.1 VISION Overview

VISION was developed for the specific purpose of evaluating the thermal performance of glazing systems. It provides the program user with two methods to achieve this objective.

The first method involves the calculation of the window's U-value and shading coefficient (SC). These are the two most common indices used to characterize the thermal performance of a window.

The U-value represents the total thermal conductance. The product of the U-value and the temperature differential across the window yields the steady state conduction heat transfer through the window (in the absence of solar radiation effects).

The SC is defined as the ratio of the solar heat gain of the window to that of a reference window under identical solar radiation conditions, i.e.,

$$SC = \frac{\text{solar heat gain through window}}{\text{solar heat gain through reference window}}$$

The reference window system is a single pane of double strength (DSA) glass. The total solar heat gains through DSA glass for various latitudes, times, and orientations have been calculated and tabulated (Tables 18 - 24, Chapter 27, ref. 3). The product of the SC and the heat gain for DSA glass yields the total solar heat gain through the window of interest.

These two coefficients, the U-value and SC, can be used as a guide for selecting an optimal window design. For example, if the goal of a designer is to maximize the net heat gains through a window, the U-value should be minimized, and the SC maximized (minimizing conduction losses and maximizing solar gains, respectively). To assist the designer, Harrison and Barakat [4] have recently developed a simple method which utilizes the U-value and SC to quantify the net heat gains or losses through a window. The calculation of these two coefficients also facilitates the analysis of energy consumption in buildings, since the U-value and SC are used by the majority of building energy computer programs to calculate the heat transfer through windows.

The use of U-values and SC's represents a valuable technique for the optimization and selection of window designs. However, both factors are sensitive to environmental conditions. The surface and inter-pane heat transfer coefficients are functions of the temperature differentials. The

SC is sensitive to the solar incidence angle. Since U-values and SC's are generally calculated for an average or design set of environmental conditions, they represent only estimates of the actual weather-dependent values.

To overcome the approximate nature of the U-value and SC approach, VISION allows the analyst to select a more rigorous method to evaluate thermal performance. This second method involves the calculation of the hourly heat transfer through the window for any period up to one year in length. As many as eight different window orientations (i.e., azimuth/tilt combinations) may be specified. Window location is limited only by the availability of compatible hourly weather tapes. Output consists of monthly and annual summaries of solar gains, conduction losses, and net heat gains.

2.2 Thermal Models and Assumptions

The primary requirement of VISION is to calculate the heat transfer through windows for different environmental conditions. These heat flows can be divided into two components: heat flow due to direct transmission of incident solar radiation and heat flow due to the existence of a temperature differential across the window.

The following sections describe the models used in calculating these heat flows, as well as the assumptions used to calculate the U-value and shading coefficient.

2.2.1 Optical Properties of Glazings

The optical properties of uncoated glazings or films are calculated using classical optical theory (see ref. 5, for example). It should be noted that following general practice [6] the analysis is based on the assumption that the optical properties are sufficiently constant over the solar spectrum to allow the use of band-averaged optical properties.

When a beam of radiant energy strikes an interface between air and a transparent material, some of the energy is reflected. The ratio of the reflected beam to the incident beam is given by Fresnel's formula,[1]

$$(1.1) \qquad RM = \frac{\tan^2 (THETA - THETAP)}{\tan^2 (THETA + THETAP)}$$

$$(1.2) \qquad RE = \frac{\sin^2 (THETA - THETAP)}{\sin^2 (THETA + THETAP)}$$

[1] The reader is referred to Appendix A for a complete Glossary of Terms.

where RM and RE are the interface reflectivities for the magnetic and electric polarization components of incident radiation, respectively.

The angle of refraction, THETAP, is related to the incidence angle, THETA, through Snell's Law.

$$\text{(1.3)} \qquad \sin(\text{THETA}) = \text{RINDX} * \sin(\text{THETAP})$$

For a normal incidence angle,

$$\text{(1.4)} \qquad \text{THETA} = \text{THETAP}$$

and

$$\text{(1.5)} \qquad \text{RM} = \text{RE} = \frac{(\text{RINDX} - 1)^2}{(\text{RINDX} + 1)^2}$$

The fraction of radiation absorbed in a single pass through the glazing material is

$$\text{(1.6)} \qquad A' = 1 - \exp\left[\frac{-\text{KL}}{\cos(\text{THETAP})}\right]$$

The total absorptivity ALFA, reflectivity RHO, and transmissivity TAU of the single pane or film can be calculated using Stokes' equations, which account for multiple reflections within the glazing.

$$\text{(1.7)} \qquad \text{ALFA} = \frac{(1 - A) * (1 - R) * (1 + R * A)}{1 - R^2A^2}$$

$$\text{(1.8)} \qquad \text{TAU} = \frac{(1 - R)^2 * A}{1 - R^2A^2}$$

$$\text{(1.9)} \qquad \text{RHO} = 1 - \text{TAU} - \text{ALFA}$$

where

$$\text{(1.10)} \qquad A = 1 - A'$$

Since incident radiation is randomly polarized, ALFA, TAU, and RHO are calculated using interface reflectivity R for both electric and magnetic polarization (i.e., RE and RM), and averaged [5].

$$\text{(1.11)} \qquad \text{ALFA} = \frac{\text{ALFAM} + \text{ALFAE}}{2}$$

(1.12) $$TAU' = \frac{TAUM + TAUE}{2}$$

(1.13) $$RHO = \frac{RHOM + RHOE}{2}$$

Equations (1.1) to (1.13) yield estimates of optical performance for a single uncoated glazing. Due to symmetry, the upward facing (i.e., outer) and downward facing (i.e., inner) surfaces have identical absorptivity and reflectivity. However, the equations do not apply to a glazing with a thin-film coating. Such a glazing usually has a thin film applied to one side, which eliminates optical symmetry. More importantly, the thin film introduces two additional interfaces: an air-film interface and film-substrate interface. Snell's Law can be applied to these interfaces. However, film thickness can be (and in fact is usually designed to be) of the same order as the wavelength of the incoming radiation. The assumption of parallel sidedness inherent in Stokes' equations ((1.7) to (1.9)) breaks down due to the large fluctuations in thickness with respect to wavelength in a piece of commercial glass [7].

Estimates of the optical performance of thin film glazings are calculated in one of two ways. If measured values of transmittance and reflectance are available for a range of incidence angles, curve-fit coefficients are calculated for fifth order polynomials, equivalent to the method suggested by Stephenson [8]. Using the incident angle as the dependent variable, the specific optical property, say transmissivity, can be calculated for any incidence angle using an equation of the form:

(1.14) $$TAU\ (\theta) = \sum_{i=0}^{5} CFTFT_i * \cos^i (\theta)$$

The procedure used to calculate the coefficients was adapted directly from a computer program written by Mitalas and Arseneault [1].

If measured optical properties are available for only normal incidence angles, directional performance is estimated using the normal optical properties and a weighting factor. The weighting factor is the ratio of the directional performance of the substrate used for the thin-film (i.e., the glazing on which the thin film is deposited) and the normal performance of the substrate. In other words, as a best estimate the directional performance of the thin-film coating is assumed to be proportional to the directional performance of the substrate alone. For example, given the normal transmissivity, TUAN, of the thin-film/substrate system, the directional transmissivity is estimated as:

(1.15) $$\text{TAU}(\theta) = \text{TAUN} * \frac{\text{TAUS}(\theta)}{\text{TAUSN}}$$

A similar relation is used for ALFA (θ). RHO is calculated by subtracting TAU and ALFA from unity.

In most cases, the space between glazings is considered to be completely transparent to short wave radiation. However, if a convection-suppressing film (i.e., honeycomb) is present, it is treated as an additional optical element, since it reduces interpane solar transmittance.

Honeycomb transmittance is calculated using the correlation developed by Hollands et al. [9],

(1.16) $$\text{TAU} = 0.5 + 0.5 * [\text{RHOHC}^{\text{NEXP}} * (\text{NEXP} + 1 - \text{RAT}) + \text{RHOHC}^{\text{NEXP} + 1} * (\text{RAT} - \text{NEXP})]$$

where

(1.17) $$\text{RHOHC} = \text{RPHI} + \frac{(1 - \text{RPHI})^2 * \text{AHC}}{(1 - \text{RPHI} * \text{AHC})}$$

(1.18) $$\text{RPHI} = 0.5 * \left[\frac{\sin^2(\text{PHI} - \text{PHIP})}{\sin^2(\text{PHI} + \text{PHIP})} + \frac{\tan^2(\text{PHI} - \text{PHIP})}{\tan^2(\text{PHI} + \text{PHIP})}\right]$$

(1.19) $$\text{PHI} = 90° - \text{PROFIL},$$ PROFIL = projected incidence angle

(1.20) $$\text{PHIP} = \frac{\sin(\text{PHI})}{\text{RINDX}}$$

(1.21) $$\text{AHC} = \exp\left\{\frac{-\text{RINDX} * \text{KL}}{[\text{RINDX}^2 - \sin^2(\text{PHI})]^{1/2}}\right\}$$

(1.22) $$\text{RAT} = \text{ASPRAT} * \tan(\text{PROFIL})$$

NEXP = truncated value of RAT

All honeycomb film properties were based on 0.0127 mm (0.0005 in.) thick teflon film, and a normal specular reflectivity of 0.981 [10].

The absorptivity of the honeycomb film is assumed to be zero, following Shewen and Hollands [10]. Therefore the reflectivity is simply

(1.23) $$\text{RHO} = 1 - \text{TAU}$$

2.2.2 Optical Properties of Multi-Glazed Windows

The previous section described the methods used to calculate the optical properties of a single glazing. Edwards's embedding technique [11] is used to calculate the total optical performance of a multi-glazed system.

Referring to Figure 2.1, a window with M - 1 glazings together with the interior form an M-element array, Edwards shows that the total reflectance of the first i elements of the array can be related to the total reflectance of the first i - 1 elements and the reflectivity and transmissivity of the ith element by

$$\text{REFL}_i = \text{RHOU}_i + \frac{\text{TAU}_i^{\,2} * \text{REFL}_{i-1}}{1 - \text{RHOD}_i\ \text{REFL}_{i-1}} \tag{2.1}$$

where

REFL_i = total reflectance of an i-element array

RHOU_i = reflectivity of the upward facing (i.e., outer) surface of element i

RHOD_i = reflectivity of the downward facing (i.e., inner) surface element i

TAU_i = transmissivity of element i

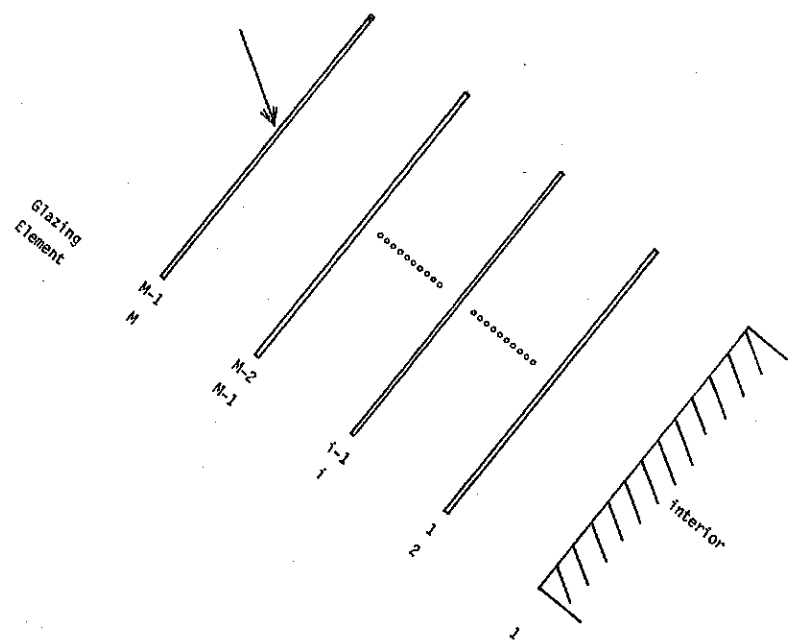

Figure 2.1. M-Element array

The fraction of incoming radiation on an M-element array which is absorbed by the ith element is calculated as

(2.2) $$ABSOR_{i,M} = (ALFAU_i + ALFAD_i * REFL_{i-1} * TRANS_i) * (\prod_{j=i+1}^{M} TRANS_j)$$

where

$ALFAU_i$ = absorptivity of upward facing surface of element i

$ALFAD_i$ = absorptivity of downward facing surface of element i

(2.3) $TRANS_i$ = ratio of the radiation flux flowing downward **from** element i to the radiation flux flowing downward **onto** element i

$$= \frac{TAU_i}{1 - RHOD_i * REFL_{i-1}}$$

It should be noted that $ABSOR_{1,M}$ represents the fraction of incoming radiation incident on the window which is transmitted to the interior and absorbed. It is sometimes referred to as the effective transmittance-absorptance product, or effective $\tau\alpha$.

2.2.3 Cosine Polynomial Coefficients

As demonstrated by the previous relations, the optical performance of a window is a function of the solar incidence angle. The incidence angle varies continually over a day throughout the year, and also depends on the window orientation. The optical properties are required to calculate the U-value and SC, as well as the hourly heat gains for the energy analysis. To avoid repeating the time-consuming optical calculations required to estimate the absorptance of each array element, $ABSOR_{i,M}$, and total reflectance, $REFL_M$, for each sunlit hour of the year,[1] fifth order polynomials equivalent to those described previously in section 2.2.1 are utilized. Values of absorptance for each element and total reflectance are calculated for incidence angles ranging from 0 to 89° in 1° increments. Treating these values as the dependent variables, and the cosine of the incidence angle as the independent variables, six coefficients are calculated for a fifth order polynomial for each property. These coefficients enable quick calculation of the transmittance, reflectance, and absorptance for any angle of incidence. For example, the reflectance of a window for an incidence angle θ is calculated as

---

[1] Assuming an average of 8 sunlit hours per day, optical calculations would be repeated as many as:

8 hours × 365 days × 8 window orientations = 23360 times/year

$$(3.1) \qquad \text{REFL}(\theta) = \sum_{i=0}^{5} \text{COEFR}_i * \cos^i(\theta)$$

As will be explained further in Section 2.2.4, these coefficients also greatly facilitate the calculation of optical properties for diffuse radiation.

For a given window design which does not incorporate a honeycomb, optical performance is strictly a function of incidence angle, and accuracy is limited by the fit of the polynomial. Curve-fit errors are very small. For example, the relative differences between the actual and the polynomial-estimated values for the effective $\tau\alpha$ of a conventional double glazed window are less than 0.3% for incidence angles ranging from 0 to 85°. The relative errors for incidence angles between 86 and 90°, which range from 1 to 10%, are not considered significant due to the small absolute values of the optical properties for these extreme angles. Similar results were obtained for a triple glazed window with a single thin film coating.

The use of a honeycomb introduces a second area of approximation. As previously described in Section 2.2.1, the optical performance of a honeycomb window is dependent not only on the incidence angle, but on the projected incidence angle as well. The optical properties used to calculate the polynomial coefficients are estimated assuming a projected angle of incidence of 30°.[1] The relative errors caused by this approximation were considered acceptable in light of the considerable modelling simplifications. For example, the optical properties for a recommended [10] double glazed honeycomb window system (65 mm inter-pane spacing, 10 mm slit spacing, 0.0127 mm teflon film) were calculated over a range of incidence angles and projected incidence angles. The relative differences between the actual and polynomial-estimated values of $\tau\alpha$ were less than 5% for projected incidence angles ranging from 0 to 60°.

---

[1] The projected angle of incidence is defined as the angle between the normal to a surface, and the projection of the sun's rays on a vertical plane normal to the same surface. A value of 30° was considered to be representative of an average value over a heating season. The actual projected incidence angle is a function of the latitude, time of day and time of year. Assuming a heating season extending from October 15 to April 15, a south facing vertical window located at 45° north latitude will experience a daily range of projected incidence angle from 0° (i.e., sunset or sunrise) to 36° (Oct. 15), 0-22° (Dec. 15) and 0-55° (Apr. 15).

It should be noted that no consideration has been given to non-vertical windows since, as will be explained further in Section 2.2.7.5, the thermal heat transfer algorithm for honeycomb windows is restricted to vertical windows only.

2.2.4 *Diffuse Optical Properties*

Incident solar radiation is comprised of two components: beam (or direct) radiation and diffuse radiation. Beam radiation is intercepted by a surface with negligible direction change from the sun. Diffuse radiation is radiation which has been scattered, either by the atmosphere, or following reflection from other surfaces such as the ground. Diffuse radiation does not have a unique direction, and is generally assumed to be of equal intensity in all directions.

The optical properties described in the previous sections all relate to the beam properties, and hence are functions of the angle of incidence. Since diffuse radiation has equal intensity in all directions, calculation of the diffuse optical properties requires the integration of the beam properties over a hemisphere. (Properties derived in this manner are sometimes referred to as hemispherical-diffuse values.) For example, the reflectance of a window to diffuse radiation can be calculated as:

$$(4.1) \qquad REFL_{diff} = \int_{\theta=0}^{\pi/2} REFL\ (\theta) * \sin 2\theta \, d\theta$$

Fortunately, use of the cosine coefficients greatly simplifies this calculation. As Stephenson [8] points out, diffuse reflectance can be calculated as:

$$(4.2) \qquad \int_{\theta=0}^{\pi/2} REFL\ (\theta) * \sin 2\theta \, d\theta = 2 * \sum_{i=0}^{5} \frac{COEFR_i}{i + 2}$$

Similar equations are used for diffuse absorptance at each window array element.

2.2.5 *Incident Solar Radiation*

The data read from the weather tapes for the hourly energy analysis contain hourly measurements of total radiation (beam plus diffuse) incident on a horizontal surface, integrated over a period of an hour ending at time IH. To calculate solar heat gains through a window, it is necessary to estimate the beam and diffuse radiation incident on the window.

Assuming that a non-zero level of radiation has been measured for the hour, the first step in calculating incident radiation is to calculate the solar position angles which are independent of the window orientation. These include:

Solar declination (calculated once per day)

(5.1) $$DECL = 23.45 * \sin \left[\frac{(284 + DAY)}{365} * 360\right], \text{ deg}$$

Hour angle ½ hour before/after sunset/sunrise (calculated once per day)

(5.2) $$SSRMAX = \cos^{-1} [-\tan (DECL) * \tan (LAT)] - 0.1309, \text{ rad}$$

Hour angle

(5.3) $$HRANG = (12 - HCOR) * 15, \text{ deg}$$

(5.4) $$HCOR = IH - 0.5$$ (adjusts hour to mid-point of measurement period)

Zenith angle

(5.5) $$THETAZ = \cos^{-1} [\cos (LAT) * \cos (DECL) * \cos (HRANG) + \sin (LAT) * \sin (DECL)]$$

The minimum allowable THETAZ corresponds to ½ hour before sunset (or after sunrise). If the hour angle falls outside this boundary, SSRMAX is used as the hour angle.

If the zenith angle is less than zero, the sun is below the horizon and all radiation is diffuse. If the sun is above the horizon, the correlation of Orgill and Hollands [12] is used to calculate the beam/diffuse split of radiation from the sky.

If $XKT \geq 0.75$

(5.6a) $$HHD = HHT * 0.1769$$

If $0.35 \leq XKT < 0.75$

(5.6b) $$HHD = HHT * (1.55699 - 1.840127 * XKT)$$

If $XKT < 0.35$

(5.6c) $$HHD = HHT * (1 - 0.248857 * XKT)$$

and

(5.7) $HHB = HHT - HHD$

where

HHT = horizontal total radiation

HHD = horizontal diffuse radiation

HHB = horizontal beam radiation

(5.8) $XKT = HHT/HHEX$

(5.9) $HHEX = SOLCON * ECC * \cos (THETAZ)$

SOLCON = extra terrestrial radiation (solar constant)
= 1353 W/m^2

(5.10) ECC = earth orbit eccentricity

$= 1 + 0.033 * \cos (2\pi * DAY/365)$

To calculate the incident radiation on a window of arbitrary slope and azimuth angle, it is first necessary to calculate the solar incidence angle, defined as:

(5.11)
$$\begin{aligned} THETA = \cos^{-1} [&\sin (DECL) * \sin (LAT) * \cos (SLOPE) \\ &- \sin (DECL) * \cos (LAT) * \sin (SLOPE) * \cos (AZMTH) \\ &+ \cos (DECL) * \cos (SLOPE) * \cos (HRANG) * \cos (LAT) \\ &+ \cos (DECL) * \sin (LAT) * \sin (SLOPE) * \cos (AZMTH) * \\ &\quad \cos (HRANG) \\ &+ \cos (DECL) * \sin (SLOPE) * \sin (AZMTH) * \sin (HRANG)] \end{aligned}$$

The ratio of the beam horizontal radiation and beam incident radiation is calculated as:

(5.12)
$$RB = \frac{\cos (THETA)}{\cos (THETAZ)}$$

A negative incidence angle indicates that the sun is 'behind' the window and hence only diffuse radiation strikes it. In this case, RB is equated to zero.

The incident beam radiation (in the absence of shading) is

(5.13) $HTB = RB * HHB$

Diffuse incident radiation comes from two sources: ground-reflected radiation and sky-reflected radiation. The ratio of incident diffuse to total horizontal diffuse radiation, assuming a hemispherical diffuse sky radiation model, is simply the window-sky view factor.

$$(5.14) \qquad RD = \frac{1 + \cos(SLOPE)}{2}$$

The ratio of the incident reflected radiation to the total (beam plus diffuse) horizontal radiation is simply the product of the window/ground view factor and the ground reflectivity.

$$(5.15) \qquad RR = \left[\frac{1 - \cos(SLOPE)}{2}\right] * RHOG$$

The total incident diffuse radiation is

$$(5.16) \qquad HTD = RD * HHD + RR * HHT$$

2.2.6 Shading

The presence of an overhang or side fins can shade the window from direct beam radiation. To estimate the fraction of window area which is shaded by these features, a detailed computer program developed recently by Bekooy [13] was acquired and adapted for use in VISION.

The method allows the calculation of the fraction area shaded for windows tilted from 0 to 180°. In addition to modelling overhangs and side-fins, the model also accounts for rectangular projections suspended from the end of an overhang.

Once the fraction area shaded, FSHADE, has been calculated, the incident beam radiation is estimated using a modified form of equation (5.13).

$$(6.1) \qquad HTB = HHB * RB * (1 - FSHADE)$$

It is assumed that the shading features do not affect sky or ground-reflected diffuse radiation.

2.2.7 Thermal Heat Transfer

Conduction, convection, and long-wave radiation heat transfer between each element of the window environment array (henceforth called 'thermal' heat transfer) is modelled using a detailed algorithm developed by Hollands and Wright [14, 15, 16]. This algorithm was originally used to model thermal heat transfer through an air layer containing a number of parallel films or glazings, and bounded by a pair of parallel opaque plates.

The algorithm has been extended for use in VISION to include:

- heat transfer between the environment and the outer and inner glazings
- recently developed correlations for convective heat transfer across vertical and inclined air layers
- the capability to model slit-type honeycomb convection suppression materials
- the capability to model substitute gases (argon, krypton, argon/Freon, and argon/SF_6 mixtures) as well as air in the interstitial spaces

The resulting algorithm is capable of modelling heat transfer in a window which contains an arbitrary number of parallel glazings or film elements, each of which (including the inner and outer glazings) can be partially transparent to long wave thermal radiation. The governing equations are sufficiently general to permit each glazing to have asymmetric radiative properties and to account for the absorption of solar energy in each of the individual glazings.

2.2.7.1 Governing Equations

Heat flow through a window system comprised of parallel glazings or films can be quantified using a relatively straightforward analysis of coupled heat transfer.

The physical layout of the system, the independent variables, and some of the nomenclature incorporated in the solution are presented in Figure 2.2. The index i is used to indicate location in the multi-layer array. The i = 1 layer is the indoor environment, and the i = N layer is the outdoor environment. The independent variables are as follows:

TAS_i = the thickness of the various gas layers, m

N = number of array elements (N = number of glazings + 2)

S = window tilt from horizontal

$TEMP_1$ = indoor temperature, K

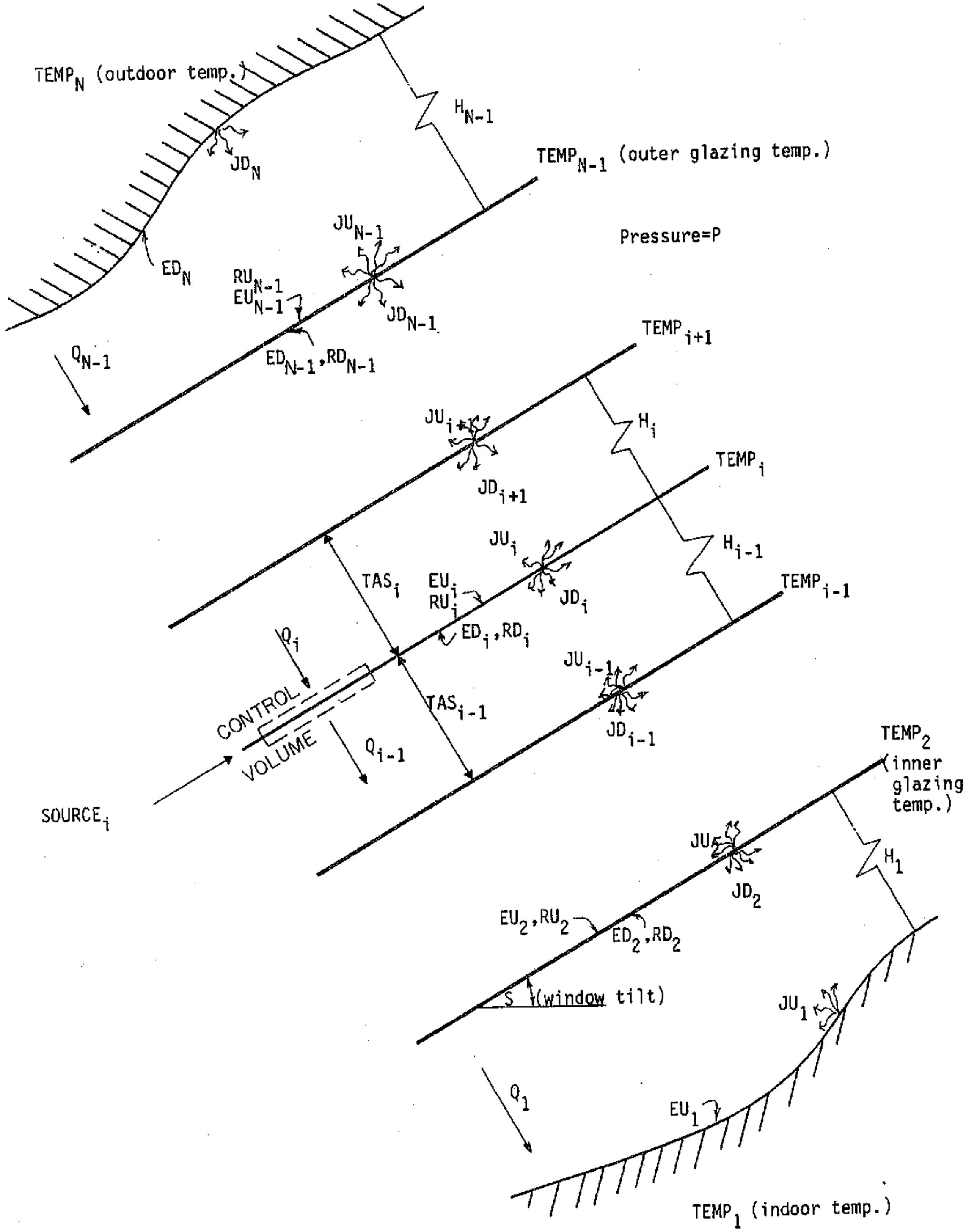

Figure 2.2. Thermal heat transfer analysis geometry

$TEMP_N$ = outdoor temperature, K

EU_i = hemispherical long wave emissivity of the upward facing (i.e., outer) surface of element i

ED_i = hemispherical long wave emissivity of the downward facing (i.e., inner) surface of element i

RU_i = hemispherical long wave reflectivity of the upward facing surface of element i

RD_i = hemispherical long wave reflectivity of the downward facing surface of element i

P = pressure of gas in interstitial space, kPa

$SOURCE_i$ = source term used to represent the solar radiation absorbed by glazing i, W/m^2

The variables JU_i and JD_i are the radiosities, representing radiation travelling from the ith surface upward (i.e., in the outdoor direction) or downward (i.e., in the indoor direction), respectively. The variable Q_i is the total long wave radiation plus conductive-convective heat transfer rate downward across the ith gas layer.

Based on the assumptions that the thermal resistance of the glazings can be neglected, and that each element included in the window array possesses grey optical properties in the long wave (i.e., 3 to 50 μm) radiation region, it is possible to write a set of 3N - 4 linear equations which can be solved to yield the temperature of each glazing, as well as the heat transfer at each layer. These equations consist of 2N - 2 radiosity equations [17] and N - 2 energy balance equations corresponding to the N - 2 glazings.

Referring to the control volume shown in Figure 2.2, an energy balance applied at the ith glazing yields:

(7.1) $$Q_i + SOURCE_i = Q_{i-1}$$

where

(7.2) $$-Q_i = JU_i - JD_{i+1} + \hat{H}_i * (EB_i - EB_{i+1})$$

(7.3) $$JU_i = EU_i * EB_i + RU_i * JD_{i+1} + (1 - EU_i - RU_i) * JU_{i-1}$$

(7.4) $JD_i = ED_i * EB_i + RD_i * JU_{i-1} + (1 - ED_i - RD_i) * JD_{i+1}$

(7.5) $\hat{H}_i = H_i * (TEMP_i - TEMP_{i+1})/(EB_i - EB_{i+1})$

(7.6) $EB_i = \sigma * TEMP_i^4$

The parameter H_i, which appears in equation (7.5), is the standard conductive-convective heat transfer coefficient (henceforth referred to simply as the 'convective' heat transfer coefficient) between the ith and (i+1)th glazings.

To model the indoor and outdoor surroundings as the 1st and Nth elements of the multi-layer array, equations (7.3) and (7.4) were modified slightly. The inner and outer glazings are modelled as small surfaces in large enclosures [18]. Therefore, it is assumed that the amount of radiation leaving the inner and outer glazings which is reflected back to the windows from the surroundings is negligible. Treating the room as a black cavity,

(7.7) $JU_1 = EB_1$

Similarly, the radiosity of the outdoor environment is expressed as

(7.8) $JD_N = ED_N * EB_N$

where

(7.9) $ED_N = F_{sky} * F_c * E_{sky} + (1 - F_{sky} * F_c)$

(7.10) F_{sky} = window to sky shape factor

$= [1 + \cos(S)]/2$

F_c = fraction of sky which is clear

(7.11) E_{sky} = clear sky emittance [6]

$$= \frac{R_{sky}}{\sigma * TEMP_N^4}$$

(7.12) R_{sky} = long wave sky radiation falling on a horizontal surface [19]

$= 5.31 \times 10^{-13} * TEMP_N^6$, W/m^2

2.2.7.2 Convective Heat Transfer Coefficients

Convective heat transfer coefficients for air (or gas) layers are generally related to the dimensionless Nusselt number

$$(7.13) \qquad Nu = \frac{H_i * TAS_i}{k}$$

where

k = thermal conductivity of the gas

VISION calculates Nusselt numbers for each inter-pane space using correlations developed by El Sherbiny et al. [20] for windows where tilt angles range from 60 to 90°, correlations by Hollands et al. [21] for tilt angles ranging from 0 to 60°, and a power law from Arnold et al. [22] for tilt angles from 90 to 180°. The correlations are based on experimental measurements of heat transfer across inclined air layers, which were made for typical ranges of Rayleigh number RA, and the aspect ratio A, where

$$(7.14) \qquad A = \frac{HGHT}{TAS}$$

The Nusselt number correlations are:

<u>Vertical layer</u>

$$(7.15) \qquad Nu = [Nu_1, Nu_2, Nu_3]_{max}$$

where

$$(7.16) \qquad Nu_1 = 0.0605 * RA^{1/3}$$

$$(7.17) \qquad Nu_2 = \left\{1 + [0.104 * RA^{0.293}/(1 + (6310/RA)^{1.36})]^3\right\}^{1/3}$$

$$(7.18) \qquad Nu_3 = 0.242 * (RA/A)^{0.272}$$

<u>Layers inclined at S = 60°</u>

$$(7.19) \qquad Nu = [Nu_1, Nu_2]_{max}$$

where

$$(7.20) \qquad Nu_1 = \left\{1 + [0.0936 * RA^{0.314}/(1 + G)]^7\right\}^{1/7}$$

(7.21) $$Nu_2 = (0.104 + 0.175/A) * RA^{0.283}$$

(7.22) $$G = 0.5/[1 + (RA/3160)^{20.6}]^{0.1}$$

Layers inclined from 60 to 90°

For layers inclined at angles between 60 and 90°, a straight line interpolation between the results of equations (7.15) and (7.19) is used. These equations are valid in the ranges of

$$10^2 \leqslant RA \leqslant 2 \times 10^7 \qquad \text{and} \qquad 5 \leqslant A \leqslant 110$$

Layers inclined at 0 to 60°

(7.23) $$Nu = 1 + 1.44 * \left(1 - \frac{1708}{RA \cos (S)}\right)^{\bullet} * \left(\frac{1 - [1708 * \sin^{1.6} (1.8 * S)]}{RA \cos (S)}\right) + \left(\left[\frac{RA \cos (S)}{5830}\right]^{1/3} - 1\right)^{\bullet}$$

where

(7.24) $$(x)^{\bullet} = (1/2)(x + |x|)$$

Equation (7.23) is valid in the ranges of

$$RA \leqslant 10^5 \qquad \text{and} \qquad A \geqslant 20$$

Layers inclined from 90 to 180°

Gas layers contained in downward facing windows which are bounded by a warm inner glazing and cool outer glazing are modelled using the following scaling law [22]:

(7.25) $$Nu = 1 + (Nu_v - 1) \sin (S)$$

where

Nu_v = Nusselt number for the vertical layer, given by equation (7.15)

Gas layers contained in upward facing windows which are heated from above are treated in a similar manner. Gas layers in downward facing windows which are heated from below are modelled using equations (7.15) through (7.24).

The indoor convective film coefficient H_1 is calculated as:

(7.26a) $H_1 = 4.0054502\ W/m^2K$ $S = 0°$

(7.26b) $H_1 = 3.8353502\ W/m^2K$ $S = 45°$

(7.26c) $H_1 = 3.0415502\ W/m^2K$ $S = 90°$

(7.26d) $H_1 = 2.2477496\ W/m^2K$ $S = 135°$

(7.26e) $H_1 = 0.9436496\ W/m^2K$ $S = 180°$

These values were calculated using a correlation of ASHRAE data developed by Konrad and Larsen [23]. The ASHRAE heat transfer coefficients account for radiative as well as conductive and convective heat transfer components. The previously noted radiosity relations account for radiative heat transfer separately. To eliminate the radiative component from the ASHRAE data, the values presented in equation (7.26) were calculated assuming a window emissivity of zero.

Coefficients for tilt angles other than those indicated are calculated using linear interpolation.

The outdoor heat transfer coefficient is calculated using a correlation developed by Lokmanhekim [24]. If the window is facing a windward direction,

(7.27) $H_{N-1} = 8.07 * V^{0.605},\ W/m^2$ $V \leq 2\ m/s$

(7.28) $H_{N-1} = 12.27\ W/m^2$ $V > 2\ m/s$

If the window is facing a leeward direction

(7.29) $H_{N-1} = 18.64 * (0.3 + 0.05 * V)^{0.605},\ W/m^2$

2.2.7.3 Solution of the Governing Equations

The convective heat transfer coefficients H_i are required to calculate the heat transfer between each element in the window system. However, as identified in the previous section, these coefficients are temperature dependent, and therefore are a function of the heat transfer. For this reason, an iterative procedure is used to solve the governing equations listed in Section 2.2.7.1. The equations are used to develop a matrix of coefficients. The matrix is solved using a double precision, elimination-type solver for each iteration, and a new set of black emissive powers and radiosities for each window element are calculated. Glazing temperatures can then be determined from these values. If the relative differences between these temperatures and the temperatures calculated in the previous iteration are less than a preset tolerance[1], the current estimates are used as the final temperature, and the heat transfer at each element, Q_i, is calculated.

2.2.7.4 Fill Gas Properties

The thermal conductivity k, viscosity VISC, and specific heat at constant pressure CP for all three fill gases (i.e., air, argon, and krypton) are calculated using linear interpolation over the temperature range from 240 to 300 K. The properties were assumed to be independent of pressure in the pressure range of interest ($P \leq 101$ kPa (1 atm) but not rarefied). This is a reasonable assumption since a deviation from 101 kPa by one order of magnitude was found to affect at most the fourth significant digit of any particular property.

Property data for air and argon (at P = 101 kPa) were obtained directly from NBS literature [25]. Similar data for krypton were not readily available. Therefore, property data for krypton were developed using argon data and the theory of corresponding states [26]. The resulting data were found to agree favourably with available measured values [27, 28, 29].

The correlation equations for air, argon and krypton follow:

Air

(7.30) $$k = (0.0953286 + 0.0033086\ TM)\ 2.414 \times 10^{-2},\ \text{W/m K}$$

(7.31) $$VISC = 0.0035165 + 0.0000498\ TM,\ \text{g/m s}$$

(7.32) $$CP = (3.4898964 + 0.0000511\ TM)\ 0.287041 \times 28.97,\ \text{J/g mol K}$$

Argon

(7.33) $$k = (0.151607 + 0.0031036\ TM)\ 1.634 \times 10^{-2},\ \text{W/m K}$$

(7.34) $$VISC = 0.003618 + 0.0000644\ TM,\ \text{g/m s}$$

(7.35) $$CP = (2.525325 - 0.0000661\ TM)\ 0.208152 \times 39.948,\ \text{J/g mol K}$$

---

[1] A tolerance of 1×10^{-4} usually results in sufficient accuracy.

Krypton

(7.36) $k = (0.855136 + 0.0286275\ TM)\ 1.0 \times 10^{-3}$, W/m K

(7.37) $VISC = 0.00234 + 0.0000783\ TM$, g/m s

(7.38) $CP = 0.2497 \times 83.8$ J/g mol K

where TM is the mean gas layer temperature in K.

The conductivity, viscosity, and specific heat of gas mixtures which are modelled by VISION are calculated as a function of the corresponding properties of the individual constituents. The method by which these calculations are made can be found in ref. 30.

In order to estimate the properties of the argon/Freon and argon/SF_6 mixtures the following correlation were used:

Freon

(7.39) $k = -0.0023603 + 3.9526 \times 10^{-5}\ TM$, W/m K

(7.40) $VISC = -0.007614 + 7.428 \times 10^{-5}\ TM$, g/m s

(7.41) $CP = (0.249 + 0.001169\ TM)\ 120.91$, J/g mol K

SF_6

(7.42) $k = 0.013$ W/m K

(7.43) $VISC = 7.214 \times 10^{-4} + 4.928 \times 10^{-5}\ TM$, g/m s

(7.44) $CP = (0.4186)(146.1)$ J/g mol K

It should also be noted that the Rayleigh number at each gas space is calculated assuming that the compressiblity factor of the fill gas is:

(7.45) $Z = 1$

and the thermal expansion coefficient of the fill gas is:

(7.46) $BETA = 1/TM$, K^{-1}

2.2.7.5 Slit-Type Honeycomb Heat Transfer

The algorithm used to model thermal heat transfer through a slit-type honeycomb system is based on correlations developed by Shewen and Hollands [10].

The convective and radiative heat transfer mechanisms are considered to act in parallel. For this reason, two heat transfer coefficients are calculated: a radiative heat transfer coefficient HR, and a convective heat transfer coefficient. This latter coefficient is calculated using the standard Nusselt number relation (equation (7.13)).

The radiative and convective/conductive equations are as follows:

(7.47) $$HR = aD^{b} \, (ASPRAT)^{cD^{b}} + e - 0.025/TAS, \; W/m^{2}\,K$$

where

D = spacing between honeycomb slits, m

(7.48) ASPRAT = elevation aspect ratio of the honeycomb slits

$= TAS_i/D$

a,b,c,d,e — are correlation parameters which depend on the emissivities of the boundary glazings and the honeycomb material. These will generally be determined experimentally.[1]

and

(7.49) $$Nu = 1 + \left\{ \left[\gamma_1 * \frac{(RA)^2}{ASPRAT^4}\right]^m + \left[\gamma_2 * RA^{0.2} * A^{0.4}\right]^m \right\}^{1/m}$$

where

$m = -0.386$

The values of γ_1 and γ_2 must also be determined experimentally.[1]

It should be noted that equations (7.41) and (7.43) are restricted to modelling slit-type honeycombs which are:

(i) contained between two glazings which are opaque with respect to long wave radiation

(ii) placed in a **vertical** window

---

1 Values for various glazing types are presented in Section 3.1.1.

2.2.8 Thermal Heat Transfer in Aerogel Windows

2.2.8.1 Aerogel Layers

One material which is of interest in the research of super windows (and which is currently being developed for use in glazing systems) is a transparent insulating material called aerogel. Aerogel is made by drying a colloidal gel of silica to produce a porous material which can be as much as 97% void by volume [31]. As a result of this structure, aerogel is very light and has optical, thermal, and structural properties which make it desirable for use in super windows.

As a result of its very large void fraction, aerogel has an effective index of refraction which is very close to unity. Its reflectivity in air is negligeably low. The solar transmission characteristics of aerogel are such that a layer of aerogel used in a glazing system could be no thicker than about 20 mm [31].

The thermal conductivity of aerogel is remarkably low (about 27% less than that of air [31]). This desirable feature is a result of the typical pore size of aerogel, which is less than that of the mean free path of air at atmospheric pressure. In addition, aerogel is effectively opaque in the infrared wavelength region. This property enables the aerogel layer to operate as an effective infrared radiation shield in order to reduce thermal heat transfer.

Typically, the use of aerogel in glazing systems is envisioned as an insulating layer which is sandwiched and supported between two panes of glass. The analysis which is presented here, and which is incorporated in a special version of VISION, is set up in a general enough manner that an aerogel layer may be analysed as part of an arbitrary multi-layer glazing array. Conduction, convection, and long-wave radiation heat transfer between each element of the glazing array are modelled using a detailed algorithm. The characteristics of this algorithm include the capability to model:

(1) heat transfer between the environment and the outer and inner glazings

(2) heat transfer between a number of opaque window elements, each of arbitrary thickness and thermal conductivity

(3) recently developed correlations for convective heat transfer across vertical and inclined gas layers

(4) substitute gases (argon, krypton, plus argon/Freon and argon/SF_6 mixtures), as well as air in the interstitial spaces

(5) absorption of solar radiation in each of the individial glazings

(6) asymmetric radiative properties of the various glazings

2.2.8.2 Governing Equations

Heat flows through a glazing system comprised of opaque, parallel glazings or films, while accounting for the thermal resistance of each glazing, can be quantified using a relatively straightforward analysis of coupled heat transfer.

The physical layout of the system, the independent variables, and some of the nomenclature incorporated in the solution are presented in Figure 2.3. The index i is used to indicate location in the multi-layer array. The i = 1 layer is the indoor environment and the i = N layer is the outdoor environment. The independent variables are as follows:

TAS_i = thickness of the various gas layers, m

N = number of array elements (N = number of glazings + 2)

S = window tilt from horizontal

TU_1 = indoor temperature, K

TD_N = outdoor temperature, K

TU_i = temperature of upper (outdoor facing) surface of ith glazing, K

TD_i = temperature of downward (indoor facing) surface of ith glazing, K

EU_i = hemispherical long-wave emissivity of downward (i.e., inward) facing surface of element i

ED_i = hemispherical long-wave emissivity of upward (i.e., outward) facing surface of element i

KG_i = thermal conductivity of ith glazing, W/m K

LG_i = thickness of ith glazing, m

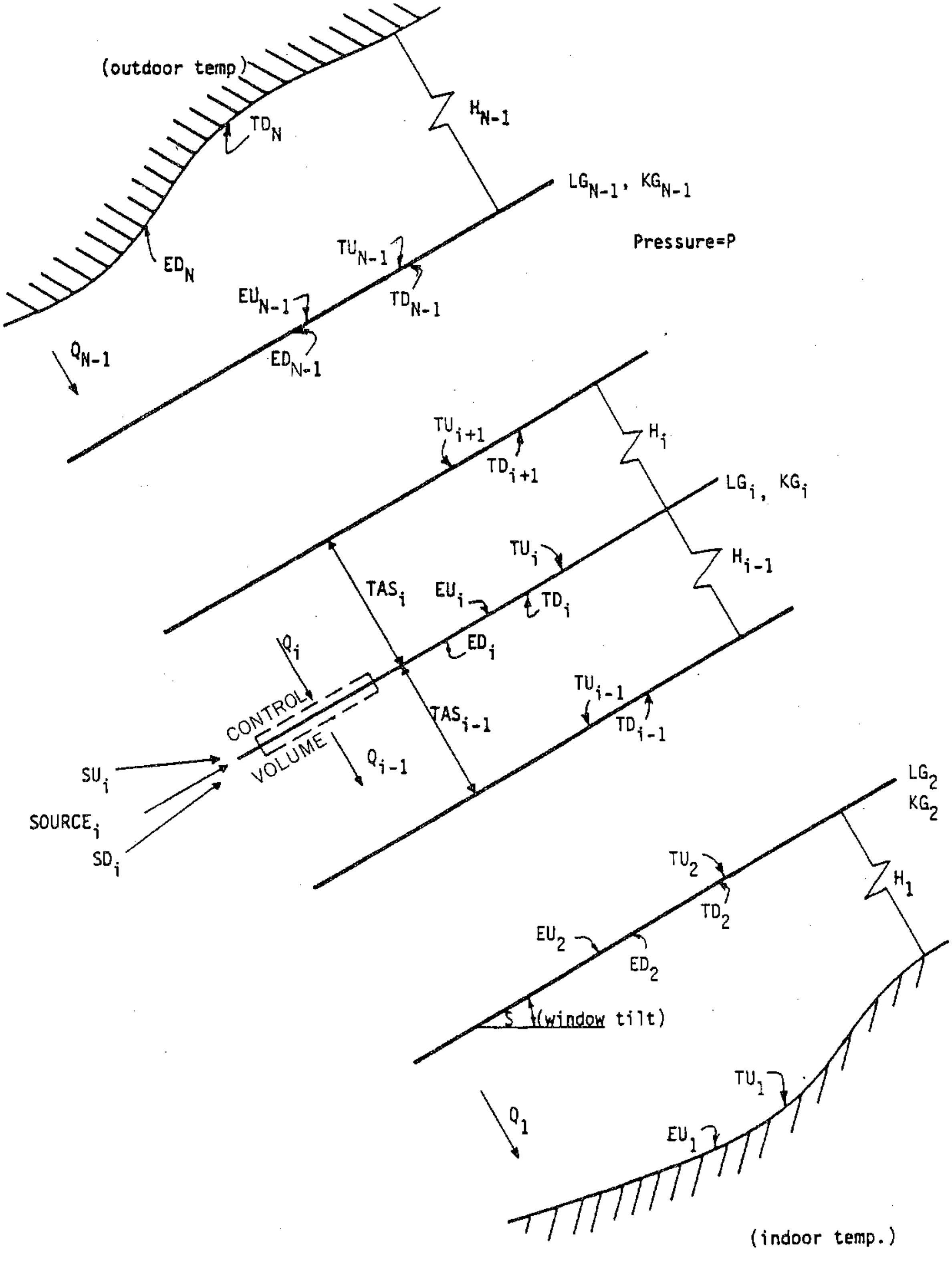

Figure 2.3. Thermal heat transfer analysis - aerogel windows

SU_i = rate at which solar energy is absorbed at upward surface of ith glazing, W/m^2

SD_i = rate at which solar energy is absorbed at downward surface of ith glazing, W/m^2

$SOURCE_i$ = rate at which solar energy is absorbed in the material of the ith glazing, W/m^2

H_i = heat transfer coefficient between ith and (i+1)th glazings including convection, conduction, radiation, $W/m^2\ K$

Q_i = heat transfer rate between (i+1)th and ith glazings

P = pressure of interstitial fill gas

The variable Q_i is the total long-wave radiation plus conductive-convective heat transfer rate downward across the ith gas layer.

Based on the assumption that each element in the window array possesses grey optical properties in the long-wave (i.e., 3 to 50 µm) radiation band, it is possible to write a set of 2N - 4 linear equations which can be solved to yield the temperatures of each glazing, as well as the heat transfer rate at each layer. These equations describe two energy balances each of which can be applied at each of the N - 2 glazings.

With reference to the control volume shown in Figure 2.3, an energy balance applied to the ith glazing yields:

(8.1) $$Q_i + SOURCE_i + SD_i + SU_i = Q_{i-1}$$

where

(8.2) $$Q_i = H_i * (T_{i+1} - T_i)$$

(8.3) $$H_i = H_{C,i} + H_{R,i}$$

(8.4) $$H_{R,i} = \left[\frac{\sigma}{(1/EU_i) + (1/ED_{i+1}) - 1}\right] * \left[\frac{TU_i^4 - TD_{i+1}^4}{(TU_i - TD_{i+1})}\right]$$

The parameter $H_{C,i}$ which appears in equation (8.3) is the conductive-convective heat transfer coefficient between the ith and (i+1)th glazings. $H_{C,i}$ is calculated in the manner shown in Section 2.2.7.2. $H_{R,i}$ is the corresponding radiative heat transfer coefficient.

The indoor facing glazing is treated as a small surface in a large enclosure. Hence, Q_1 is given as:

$$(8.5) \qquad Q_1 = H_{C,1}(TD_2 - TU_1) - \sigma TU_1^4 + ED_2\sigma TD_2^4 + \sigma TU_1^4(1 - ED_2)$$

The heat transfer rate from the outdoor environment to the outer glazing is given as:

$$(8.6) \qquad Q_{N-1} = H_{C,N-1}(TD_N - TU_{N-1}) - \sigma EU_{N-1}TU_{N-1}^4 - \sigma ED_N T_N^4 (1 - EU_{N-1}) + \sigma ED_N T_N^4$$

$H_{C,N-1}$, $H_{C,1}$ and ED_N are calculated according to the methods presented in Sections 2.2.7.1 and 2.2.7.2.

To account for the thermal resistance of a glazing element plus the effects of absorbed solar radiation at that glazing element, it is necessary to apply an energy balance at each elemental layer of that glazing. Once this energy balance has been applied it can be shown that the temperature drop across the ith glazing is given by:

$$(8.7) \qquad TD_i - TU_i = \frac{LG_i}{2KG_i}\,[2(SD_i - Q_{i-1}) + SOURCE_i]$$

The variables which appear in equation 8.7 are shown in Figure 2.4.

It is of interest to note that the effect of three separate source terms (SD_i, SU_i, and $SOURCE_i$) appear in Figure 2.4 and are accounted for in equations 8.1 and 8.7. The quantities SD_i and SU_i represent the rate at which solar energy is absorbed at the downward and upward facing surfaces of the glazing element, respectively. The parameter $SOURCE_i$ represents the rate at which solar energy is absorbed within the material of the glazing element. This absorption denoted by $SOURCE_i$ is assumed to be distributed uniformly throughout the thickness of the glazing element.

In the case in which the ith glazing element consists of a single homogeneous material there can be no solar energy absorption at the glazing/gas interface. That is to say, radiation which encounters an interface is either transmitted through or reflected from the interface, but not absorbed at the interface. Therefore, the source terms SU_i and SD_i must be equal to zero. Solar radiation which is absorbed within the glazing will appear in the $SOURCE_i$ term. However, it is useful to consider a glazing element which consists of an insulating core of material such as aerogel which is sandwiched between two relatively thin layers of glass. In this case the sandwiched glazing element can be represented as one

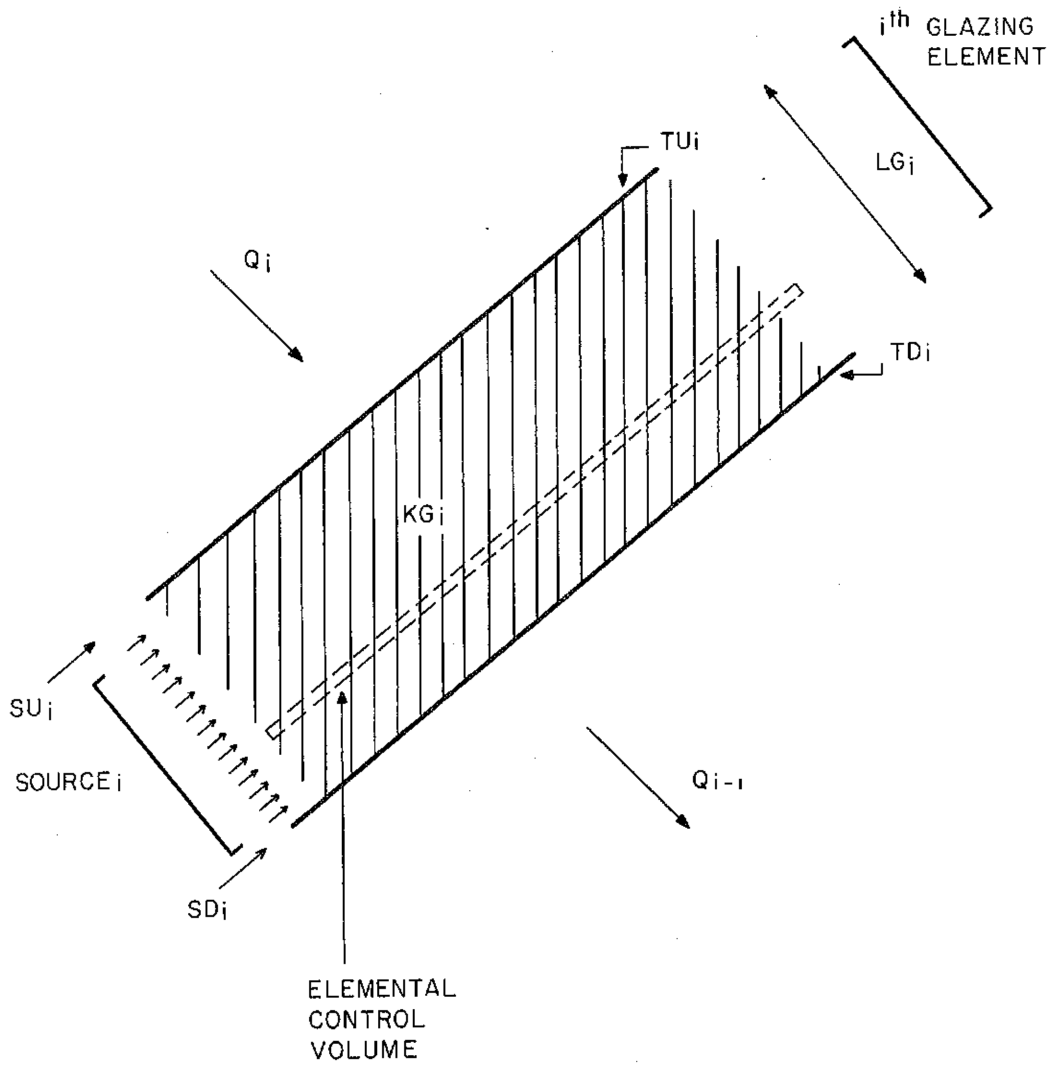

Figure 2.4. Energy balance within the ith glazing element

element in which the solar radiation absorbed in the glass casings appears as SU_i and SD_i source terms while the solar energy absorbed in the aerogel appears as the $SOURCE_i$ term.

2.2.8.3 Solution of the Governing Equations

The heat transfer coefficients, H_i, which are required to calculate the heat transfer between the various elements of the window array, are temperature dependent and are therefore a function of the various heat transfer rates. For this reason, an iterative procedure is used to solve the governing equation. Equations (8.1) and (8.7) are applied at each glazing element and used to set up a matrix of coefficients. This matrix is solved using an elimination type solver and a new set of glazing element temperatures is calculated. Following this a new set of heat transfer coefficients is calculated and a new matrix is set up and solved. Once the solution of glazing temperatures has converged to a preset tolerence, the iteration is terminated and the heat transfer rates, Q_i, are calculated.

2.2.9 Calculation of U-Value

The U-value is used to estimate heat transfer through windows in the absence of solar radiation. Since thermal heat transfer characteristics are dependent on environmental conditions such as temperature and wind speed, the U-value is a function of the assumed weather conditions.

ASHRAE [3] uses a standard set of conditions to estimate summer and winter design U-values. However, it is pointed out that these design conditions "are more severe than a fenestration would be exposed to on a continual basis, and the U-values should not be used in an annual energy analysis."

For this reason, three U-values are calculated by VISION, corresponding to winter and summer design conditions, and an 'average' condition. The winter and summer conditions correspond to ASHRAE design values. Winter conditions assume an indoor temperature of 21°C, an outdoor temperature of -18°C, and a wind speed of 24 km/h. The corresponding summer conditions are 24°C, 32°C, and 12 km/h, respectively. The average conditions were assumed to be 21°C, 0°C, and 10 km/h, respectively. They were selected with the intent of producing a U-value that would be suitable for use in an annual energy analysis.

VISION also requires specification of the fraction cloud cover to calculate the radiosity of the outdoor environment. Cloud cover was assumed to be 50% for all three conditions.

The U-value is calculated by equating incident radiation (beam and diffuse) to zero and solving for the heat transfer resulting from the temperature differential. The U-value is then simply the ratio of the heat transfer inward through the window (which must be equal to the heat transfer from the inner glazing to the interior) and the outdoor-indoor temperature difference.

$$(9.1) \qquad UVAL = \frac{Q_1}{TEMP_N - TEMP_1}$$

2.2.10 Calculation of Shading Coefficient

The shading coefficient SC is defined as the ratio of the window's solar heat gain for a specific set of environmental conditions to the solar heat gain for a reference window under identical conditions.

Like the U-value, the SC is a function of environmental conditions. The conditions used in VISION were selected to match as closely as possible those used by ASHRAE [3]. VISION assumptions include:

- west-facing vertical orientation
- 4 p.m. solar time
- 43° north latitude
- August 21
- direct normal radiation of 741 W/m^2 [3] [1] resulting in beam radiation of 628.2 W/m^2 and diffuse radiation of 84.3 W/m^2 [12] [2]
- indoor and outdoor temperature of 21°C

Under these conditions, the total solar gain of the reference window (single glazed double strength glass) as calculated by VISION is 612.3 W/m^2. The SC for a window is therefore calculated as

$$SC = \frac{QSOLT}{612.3} \qquad (10.1)$$

where

QSOLT = total solar gain through the window

QSOLT is comprised of two components: the direct solar gains, and the solar energy absorbed by each glazing which passes through to the interior by thermal heat transfer. The direct solar gains are calculated as the sum of direct beam and diffuse components.

$$QSOL_{dir} = HTB * ABSOR_{1,M} + HTD * COEFTD \qquad (10.2)$$

Since no temperature differential exists, all of the energy flowing from the inner glazing to the interior by thermal heat transfer must be due to absorbed solar radiation. Therefore,

$$QSOLT = QSOL_{dir} + Q_1 \qquad (10.3)$$

2.2.11 Energy Analysis Summary

The hourly energy analysis uses the previously described models to perform detailed hourly energy calculations. Output from this analysis includes monthly and annual summaries of the following:

---

[1] Based on interpolation of values for 40° and 48° north latitude. Tables 23 and 29, Chapter 27, ref. 3.

[2] Using the Orgill-Hollands correlation [12], assuming clear sky and ground reflectivity of 0.2.

- degree days
- total incident (beam plus diffuse) radiation for each window orientation
- total solar gains, conduction losses, and net heat gains for each window orientation

Degree days are calculated using an 18°C temperature base, and account for only those days which fall within the period the user designates as the heating season.

The total incident radiation is calculated simply as:

(11.1) $RADTN = HTB + HTD$

As mentioned in the discussion of the SC calculation, total solar gains are comprised of direct and absorbed/redirected gains. Equation (10.2) is used to calculate direct solar gains. The calculation of absorbed/redirected gains differs slightly from the SC calculation due to the existance of non-zero temperature difference. The thermal heat transfer analysis accounts for both solar and temperature differential effects. It therefore becomes necessary to isolate the solar component. This is achieved using the ratio of thermal resistances. Having determined the temperature of each glazing, and the heat tranferred between glazings, the interstitial thermal resistance of space i is calculated as

(11.2) $$RES_i = \frac{TEMP_{i+1} - TEMP_i}{Q_i}$$

Treating the incident radiation which is absorbed on the ith glazing as a source term, the amount of absorbed energy which flows inward is:

(11.3) $$QSOLLW_i = SOURCE_i * \frac{RESOUT_i}{RESTOT}$$

where

$SOURCE_i$ = amount of radiation absorbed by the ith glazing, W/m^2

$RESOUT_i$ = thermal resistance from the ith glazing to the exterior, $K\ m^2/W$

RESTOT = total thermal resistance of window (interior to exterior, $K\ m^2/W$

The inward heat flow due to temperature difference is therefore the total inward thermal heat transfer, Q_1, minus the inward flowing solar component.

(11.4) $$QCOND = Q_1 - \sum_{i=2}^{M} QSOLLW_i$$

The net inward heat flow is simply the sum of the inward temperature and solar-induced heat flows.

(11.5) $$QNET = QSOL_{dir} + \sum_{i=2}^{M} QSOLLW_i + QCOND$$

2.2.12 Weather Data

The hourly energy analysis uses hourly measured weather data read from weather tapes. The National Research Council is currently planning to develop comprehensive weather tapes for a variety of Canadian locations. Pending the development of these tapes, VISION has been adapted to use weather tapes produced for the solar simulation program WATSUN [32]. These tapes contain hourly data for total horizontal radiation and ambient temperature. As mentioned previously, VISION requires data for wind speed and direction, and fraction cloud cover. Lacking any measured hourly data, default values of 3 m/s, 90°, and 50% are used for wind speed, wind direction, and fraction cloud cover, respectively.

2.3 Program Logic

2.3.1 Overview

VISION is comprised of a total of ten subroutines and nine function routines which are controlled by a main program. A front-end program, which can be used to create an input file, has also been written. Figure 2.5 presents the sub-routine and function routine names, and illustrates their interaction.

VISION can be divided into two main sections. The first section, controlled by the subroutine WINDOW, is responsible for calculating the U-values and SC, as well as the coefficients for the fifth order optical property polynomials. The second section, controlled by the subroutine ENANAL, is responsible for the hourly energy analysis. The MAIN program is used to call these two major groups.

2.3.2 Subroutine Logic

Figures 2.6 to 2.17 present flow charts of the logic for the front-end TALK, the main program MAIN, and the ten subroutines WINDOW, READIN, CCOEF, RFILM, SOLMAT, PRINT1, ENANAL, SOLRAD, SHADE, and PRINT2.

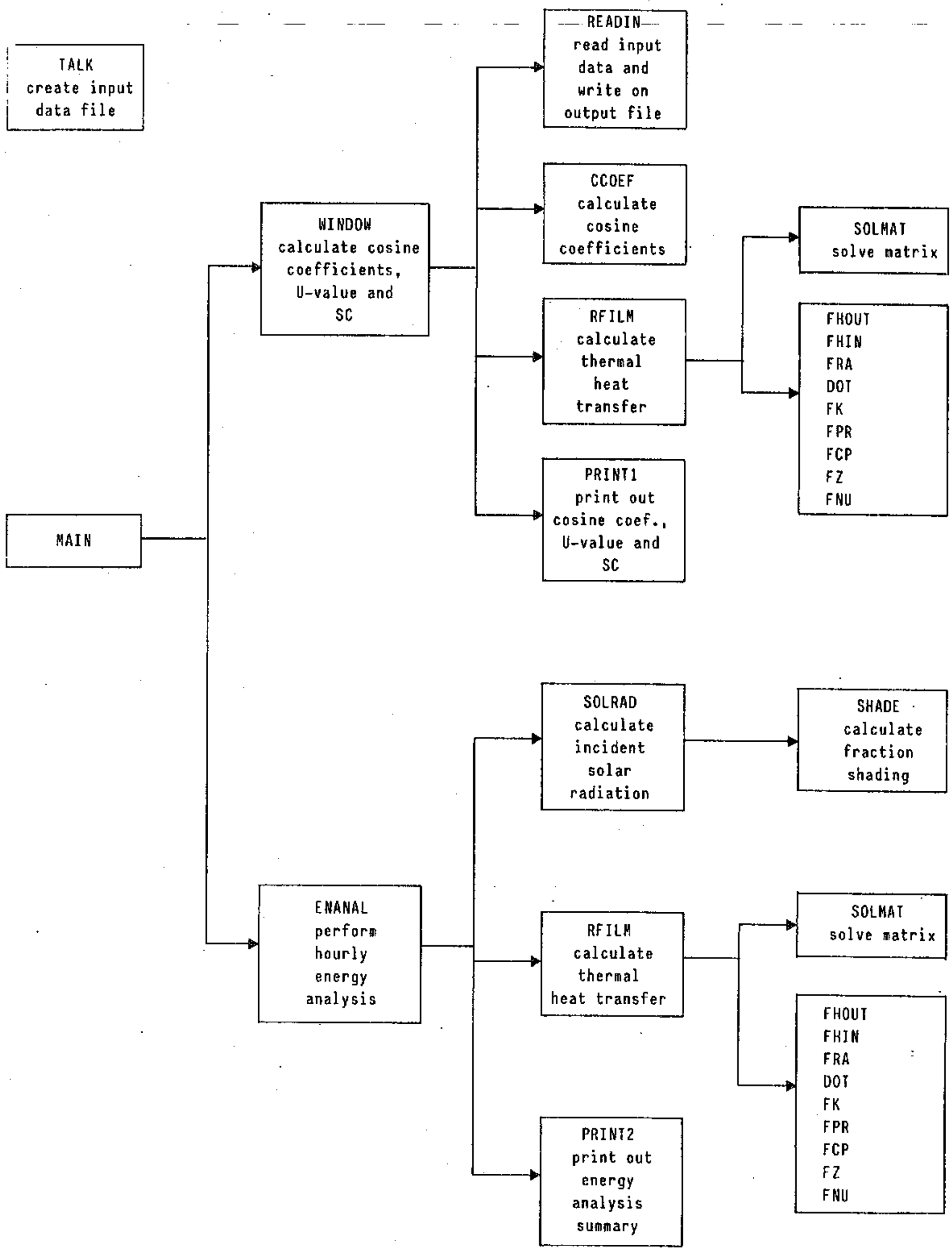

Figure 2.5. Overview of program logic

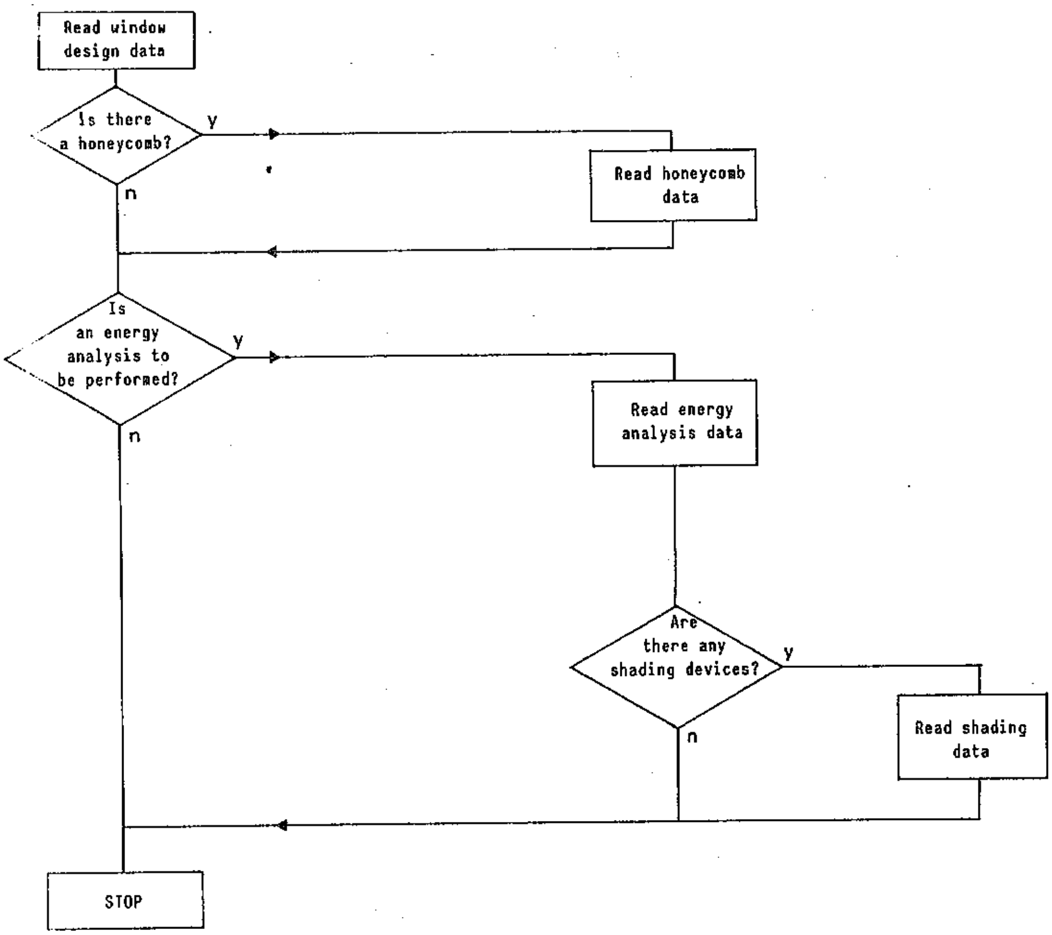

Figure 2.6. Program for logic TALK

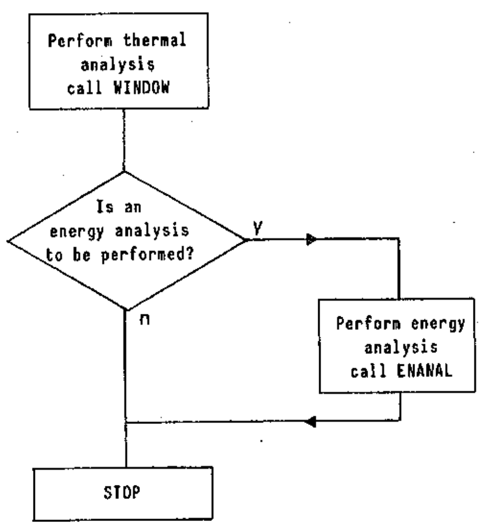

Figure 2.7. Program for logic MAIN

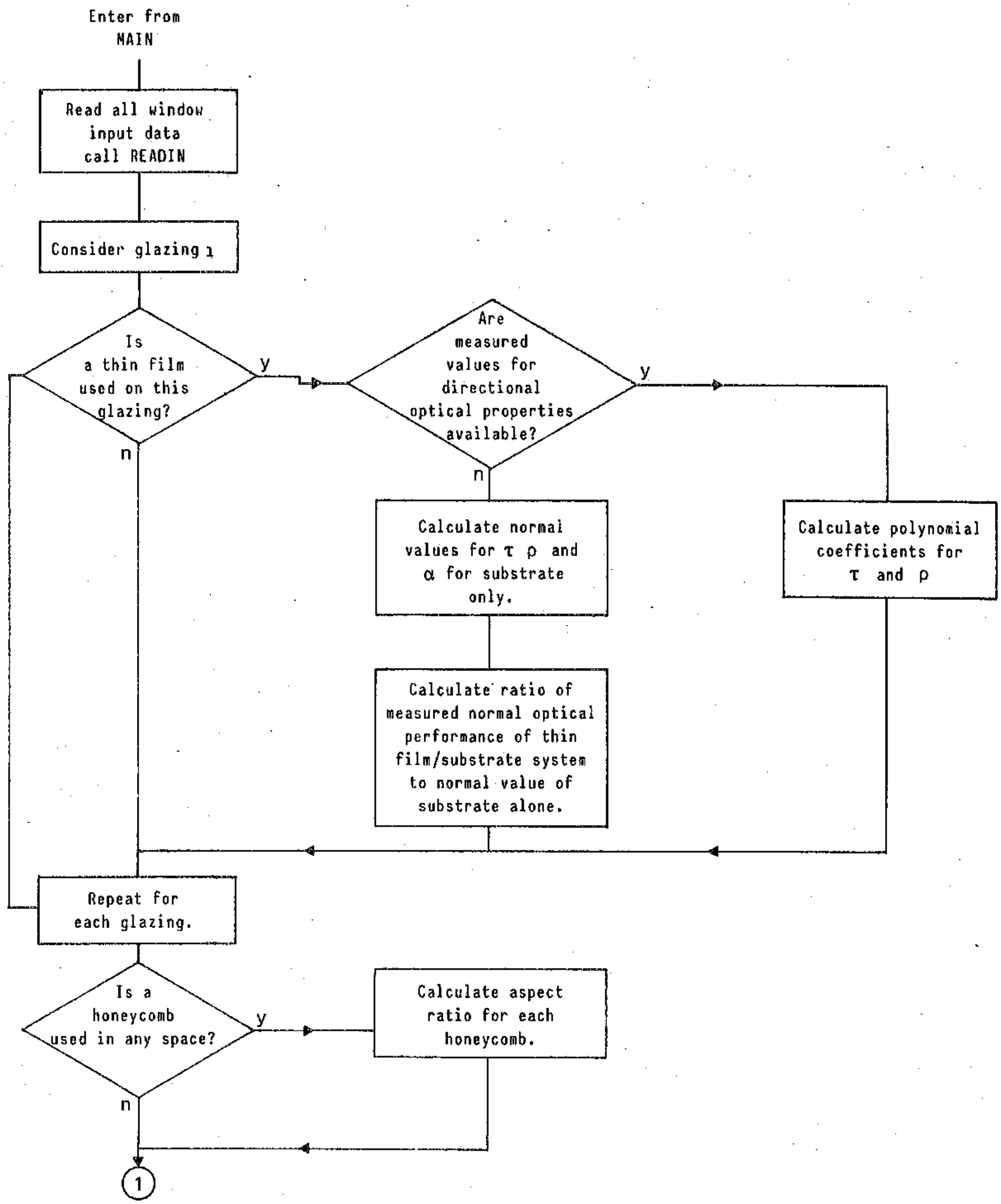

Figure 2.8. Program logic for WINDOW

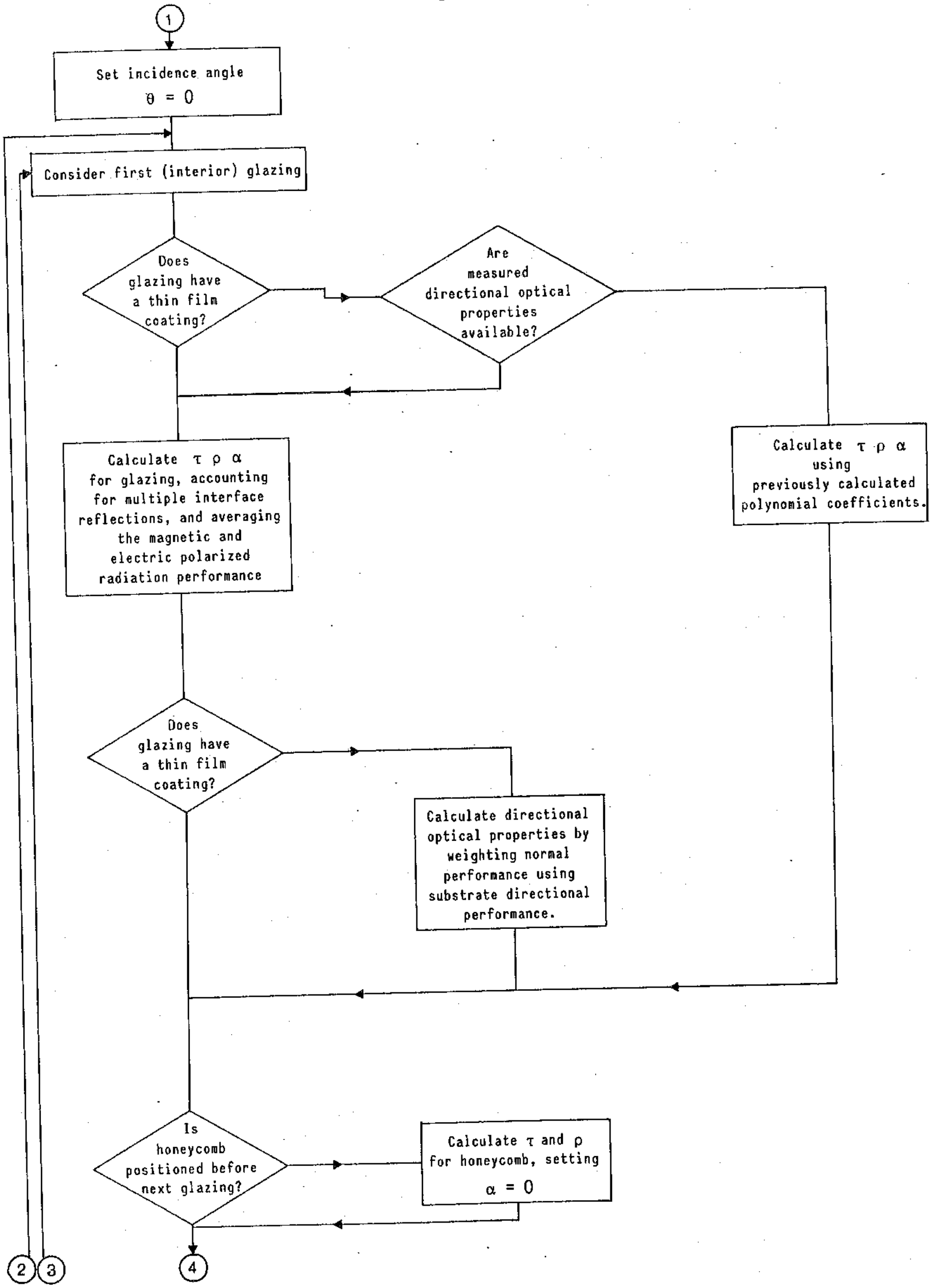

Figure 2.8 (Continued)

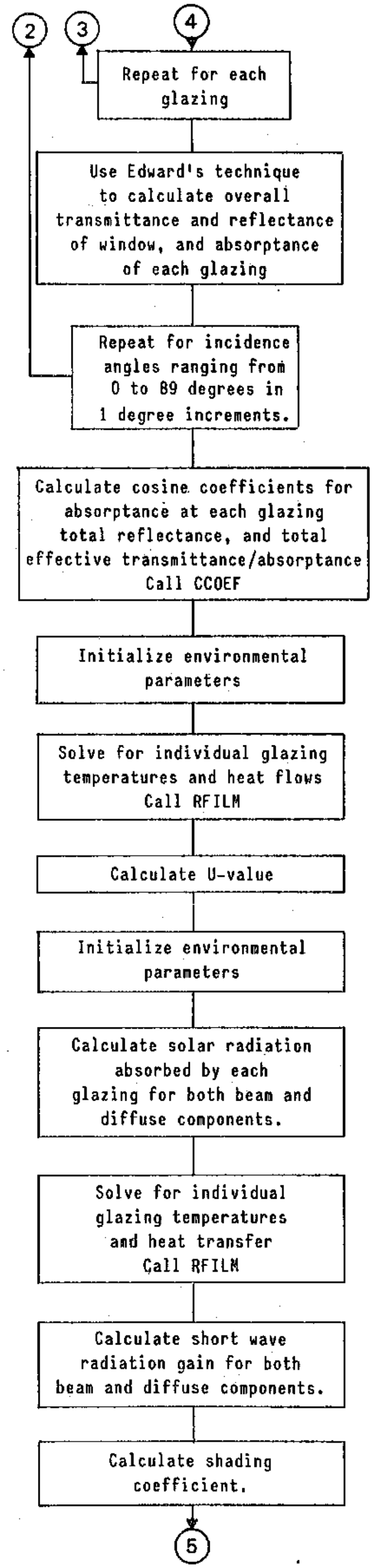

Figure 2.8 (Continued)

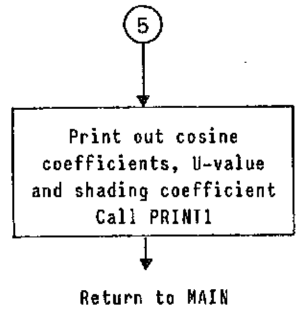

Figure 2.8 (Concluded)

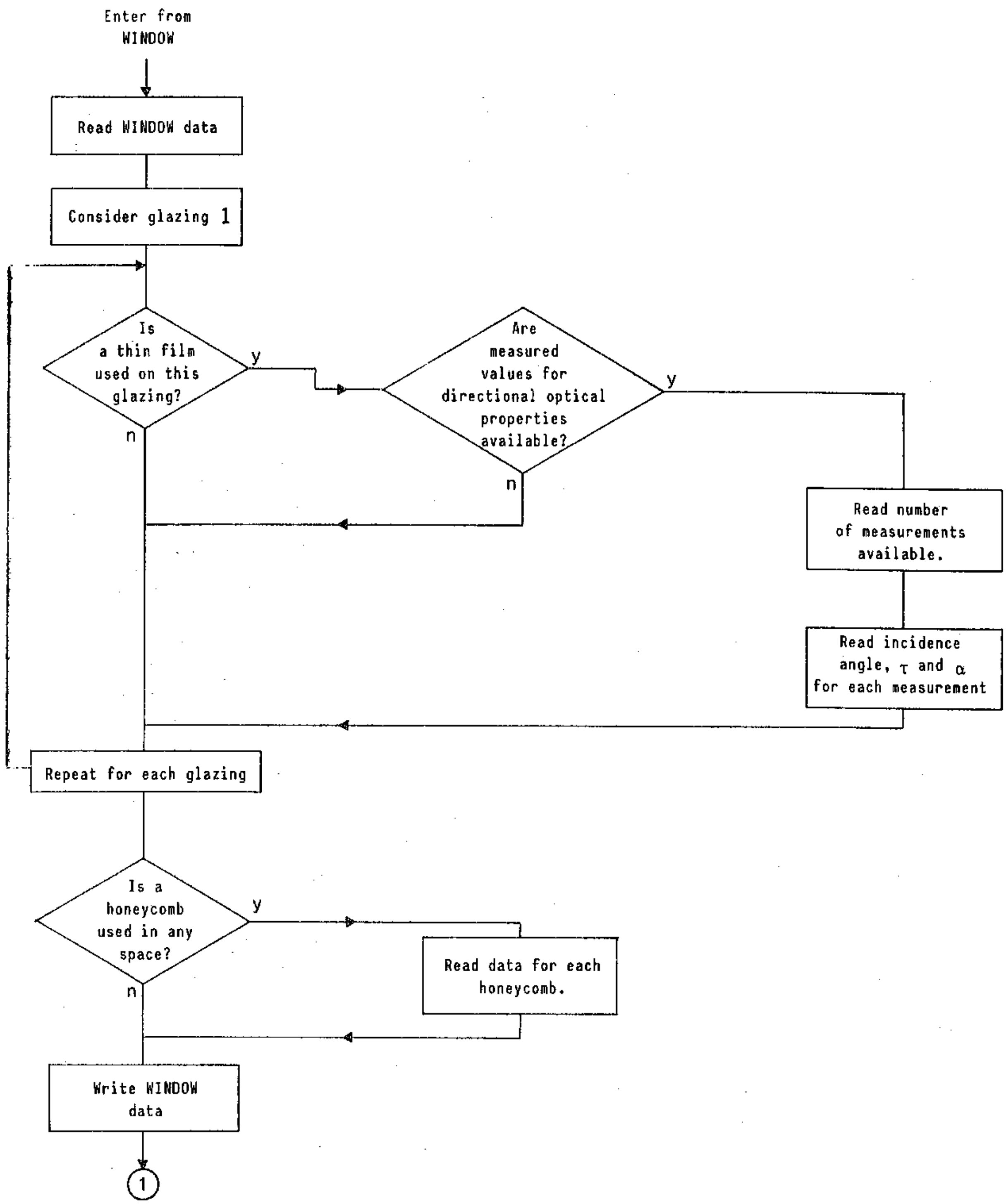

Figure 2.9. Program logic for READIN

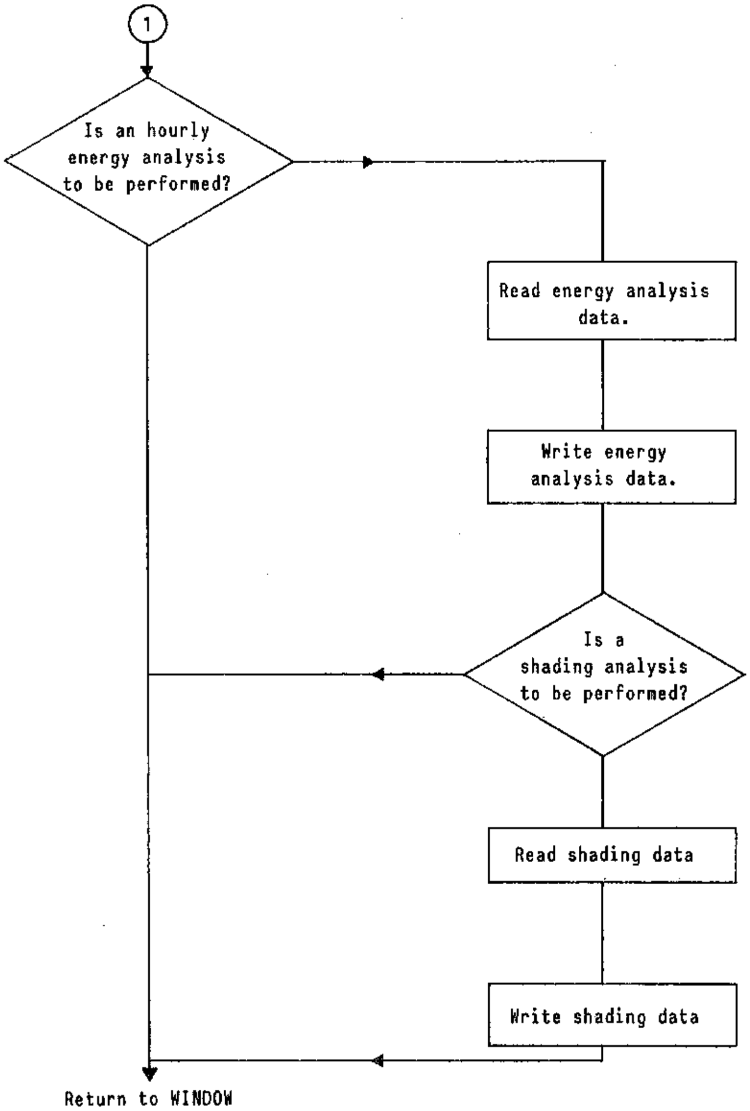

Figure 2.9 (Concluded)

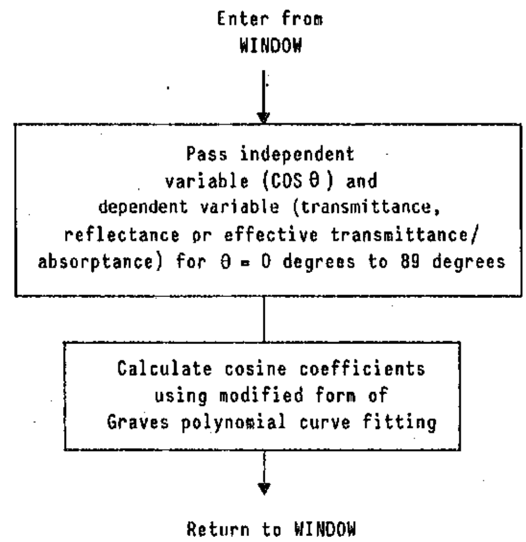

Figure 2.10. Program logic for CCOEF

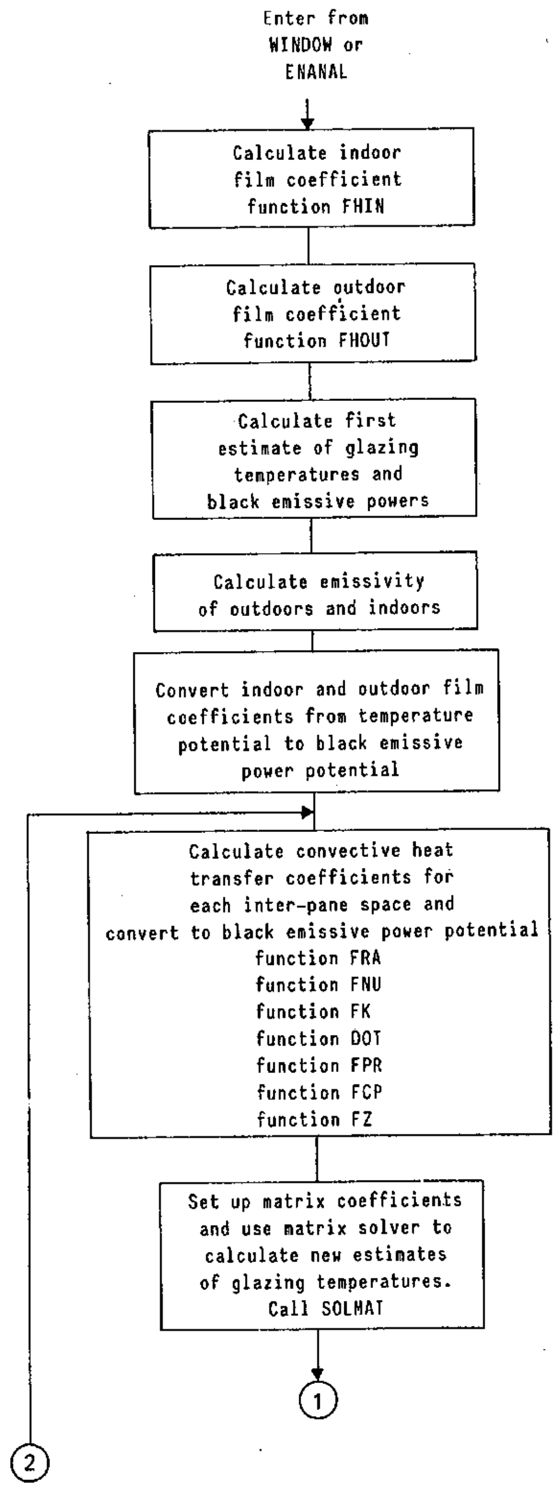

Figure 2.11. Program logic for RFILM

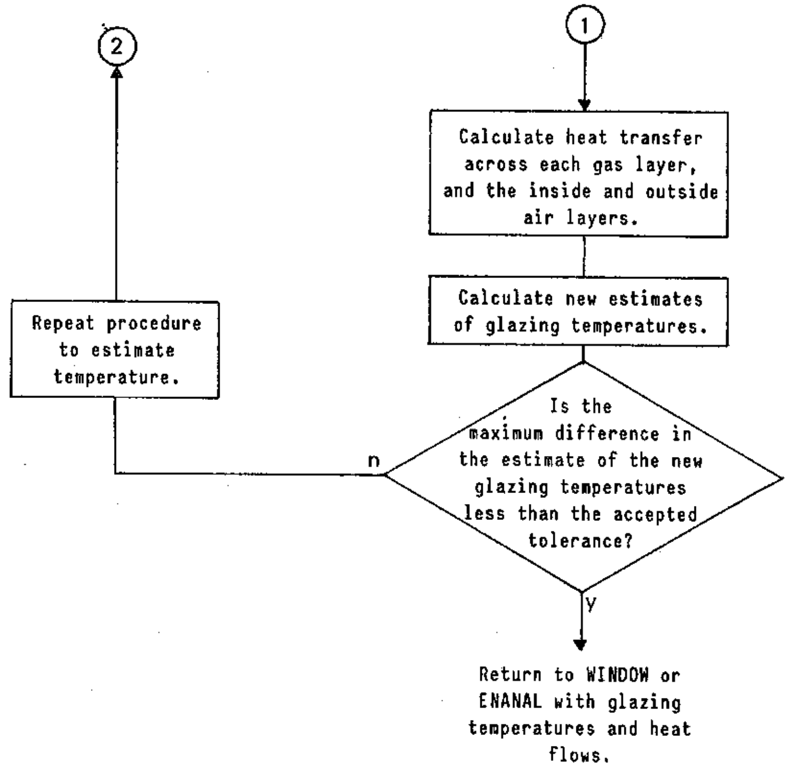

Figure 2.11 (Concluded)

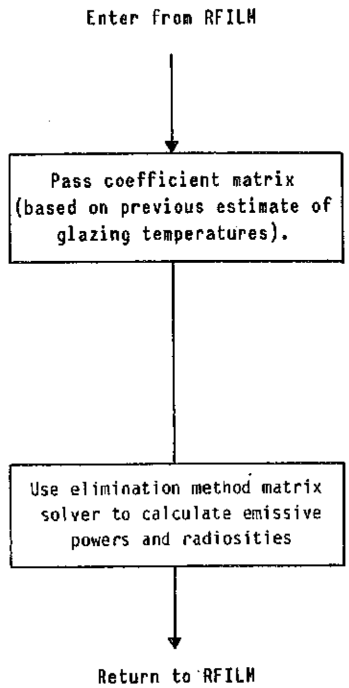

Figure 2.12. Program logic for SOLMAT

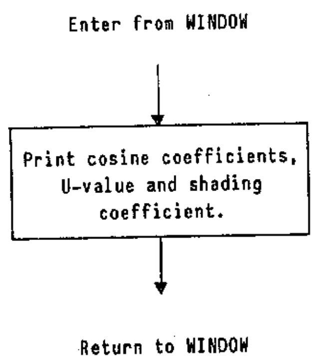

Figure 2.13. Program logic for PRINT1

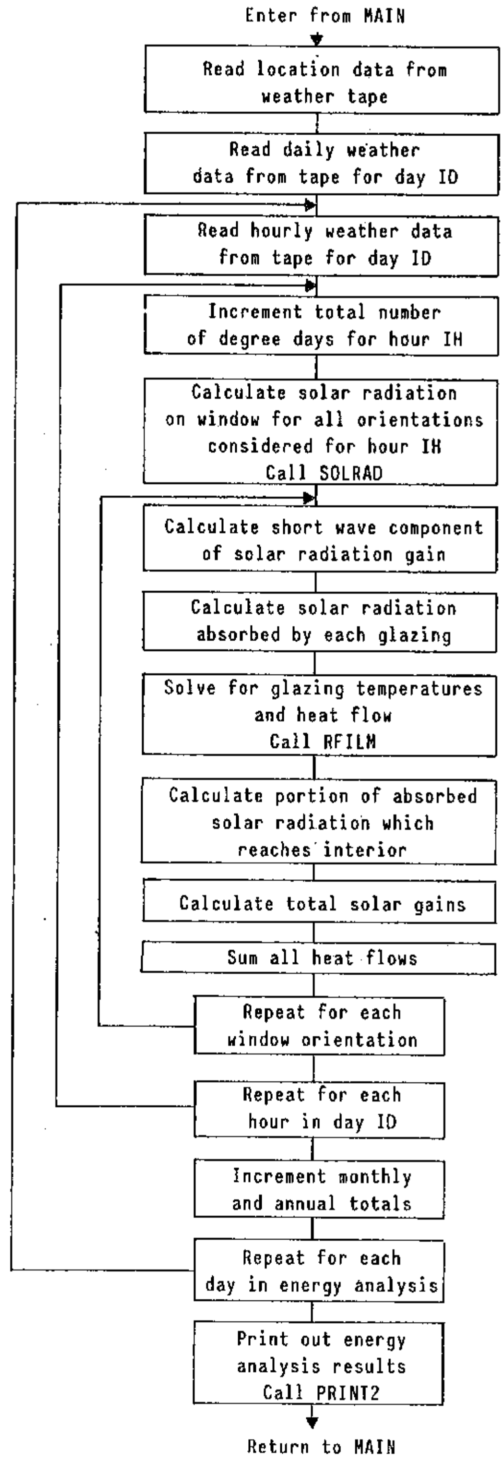

Figure 2.14. Program logic for ENANAL

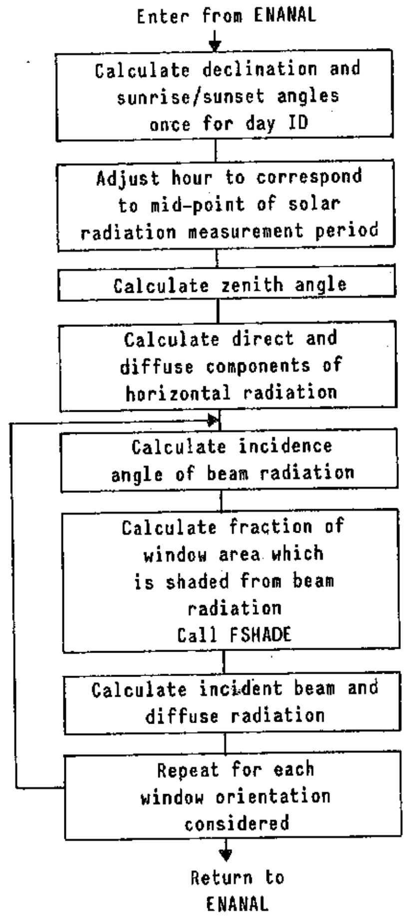

Figure 2.15. Program logic for SOLRAD

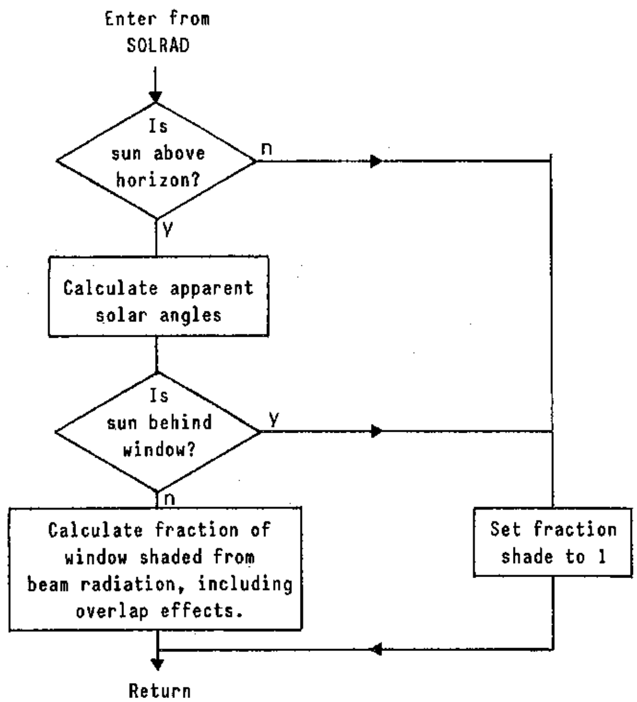

Figure 2.16. Program logic for SHADE

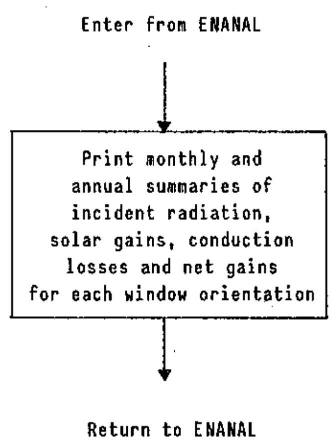

Figure 2.17. Program logic for PRINT2

2.4 Sample Results

VISION simulations were performed for two different window designs, to verify that the program produced reasonable performance results, and to illustrate its capability to model non-standard designs.

The first design is a standard double glazed window, the characteristics of which were chosen to match a window whose U-value and shading coefficient are reported by ASHRAE (Tables 13 and 28, Chapter 27, ref. 3). The window has 6 mm (¼ in.) thick clear glazings and a 13 mm (½ in.) air space.

The U-values predicted by VISION are 2.88 (winter), 2.87 (summer), and 2.92 W/m^2 °C (average). These estimates show good agreement with the corresponding ASHRAE values of 2.8 (winter) and 3.2 W/m^2 °C (summer).

The SC predicted by VISION is 0.85. This is slightly higher than the ASHRAE value of 0.82. The discrepency is most likely caused by differences in the assumed value of the extinction coefficient.

The second window modelled was triple glazed, incorporating a heat mirror on the outward facing surface of the inner glazing, 3 mm glazings and 6 mm air spaces. The uncoated glass surfaces were assumed to have emissivities of 0.84, and the coated surface an emissivity of 0.15. Since the directional optical performance of this hypothetical thin film was not known, optical properties were calculated based on a normal transmissivity of 0.75, and a normal solar reflectivity of 0.15 (upward) and 0.08 (downward).

The U-values estimated by VISION are 1.91 (winter), 1.91 (summer), and 1.98 W/m^2 °C (average). As an approximate comparison,[1] the corresponding ASHRAE values for a similar, but uncoated, triple glazed window are 2.2 (winter) and 2.5 W/m^2 °C (summer).

The SC predicted by VISION is 0.74. A corresponding ASHRAE estimate is not available for comparison, since values are tabulated for single and double windows only.

---

[1] For a direct comparison, the U-values for a window equivalent to the ASHRAE reference design are 2.26 (winter), 2.30 (summer), and 2.36 W/m^2 °C (average).

3.0. USER'S MANUAL

The following sections provide instruction on the use of VISION, including a description of the input requirements, the output, and computer requirements.

3.1 Input Requirements

VISION requires two types of input: a description of all relevant window and energy analysis information data, and the hourly weather data.

3.1.1 Window Design Data File

VISION reads all of the data necessary to describe the window characteristics and the hourly energy analysis parameters (excluding the weather data) from one input file. This input file may be created in one of two ways. The user may create the file using the conversational front end program TALK. When invoked, TALK prompts the user through a series of questions to input all of the required data. TALK automatically creates the formatted file of input data.

Alternatively, the user may create the file by typing in all of the required information according to format which will be specified shortly. All data are input as real numbers. This facilitates the input procedures, as the numerical values may be placed anywhere within the designated columns provided a decimal point is used, and no exponent is required. The 'E12.6' read format used covers 12 columns. If the number is input without a decimal point, six digits are placed to the right of the decimal point. It is recommended, however, that all values be input using a decimal point to take advantage of the placement flexibility within the columns. Exponents may be also used using E-format. For example, the value 0.000123 may be input as '1.23E-4'. Care should be taken to **right** justify any number using the E-format since blanks following an exponent are interpreted as zeros.

The information stored in the input file can be divided into three main sections: window data, energy analysis information, and shading data.

The first section, window data, contains all of the information required to describe the window - dimensions, number of glazings, optical properties, etc. The specific data and required format are presented in Table 3.1.

Following window data is the section containing the necessary information required for the energy analysis. Table 3.2 describes the input format required. If the user chooses not to perform an energy analysis, the energy analysis flag (i.e., first entry) is simply set to zero, and all remaining read statements are bypassed. The user need not specify any additional data.

If an energy analysis is to be performed, the user also has the option to specify various types of shading devices. Table 3.3 describes the data required. Once again, if the window does not have any shading devices, a zero is placed in the first entry, and no additional data are required. A shading analysis is only performed during an energy analysis, and is not used in the first half of the program which calculated the U-value and SC. Therefore, if an energy analysis is not performed, no shading data are read regardless of the value of the shading flag.

Figure 3.1 presents a sample input file created for a conventional double glazed window with an overhang.

3.1.2 Weather Data

Weather data are read from weather tapes created for use by the solar simulation program WATSUN [32]. The weather tapes have the following characteristics:

- 180 m
- 9 track
- 800 bpi
- unlabelled
- LRECL 23
- BLKSIZE 3105
- RECFM FB
- EBCDIC

Tapes are currently available for 66 Canadian locations. Information concerning access of the tapes can be obtained from the WATSUN User's Service in Waterloo.

Output Format

A file concerning output data is created following every VISION simulation. This output can be divided into two sections. The first section contains a complete listing of all the data read from the input file. This allows the user to check the accuracy of the input data and provides a permanent record of the design details of the window.

Table 3.1. Window input data

LINE	COLUMN	FORMAT	UNITS	DESCRIPTION	NOTES
1	1-12	REAL		Number of lines in output title	
2a	1-72	18A4		Line 1 of output title	
2b	1-72	18A4		Line 2 of output title	
⋮	⋮	⋮		⋮	
2x	1-72	18A4		Line NLINES of output title	
3	1-12	REAL		Number of glazings (maximum of 4)	
4	1-12	REAL	m	Thickness of first (i.e., interior) glazing	
	13-24	REAL	m	Thickness of glazing number 2	1
	25-36	REAL	m	Thickness of glazing number 3	1
	37-48	REAL	m	Thickness of glazing number 4	1
4a	1-12	REAL	W/m K	Thermal conductivity of glazing number 1	Aerogel simulation only
	13-24	REAL	W/m K	Thermal conductivity of glazing number 2	
	25-36	REAL	W/m K	Thermal conductivity of glazing number 3	
	37-48	REAL	W/m K	Thermal conductivity of glazing number 4	
5	1-12	REAL	m	Distance between glazings 1 and 2	1
	13-24	REAL	m	Distance between glazings 2 and 3	1
	25-36	REAL	m	Distance between glazings 3 and 4	1
6				Long-wave emissivity of upward (i.e. outer)	
	1-12	REAL		facing surface of glazing 1	
	13-24	REAL		facing surface of glazing 2	1
	25-36	REAL		facing surface of glazing 3	1
	37-48	REAL		facing surface of glazing 4	1

Table 3.1 (Continued)

LINE	COLUMN	FORMAT	UNITS	DESCRIPTION	NOTES
7				Long wave emissivity of downward (i.e. inward)	
	1-12	REAL		facing surface of glazing 1	
	13-24	REAL		facing surface of glazing 2	1
	25-36	REAL		facing surface of glazing 3	1
	37-48	REAL		facing surface of glazing 4	1
8				Long-wave reflectivity of upward-facing	
	1-12	REAL		surface of glazing 1	
	13-24	REAL		surface of glazing 2	1
	25-36	REAL		surface of glazing 3	1
	37-48	REAL		surface of glazing 4	1
9				Long-wave reflectivity of downward-facing	
	1-12	REAL		surface of glazing 1	1
	13-24	REAL		surface of glazing 2	1
	25-36	REAL		surface of glazing 3	1
	37-48	REAL		surface of glazing 4	1
10	1-12	REAL		Thin film flag for glazing 1 if = 0. Thin-film not used if = 1. Thin film used	
	13-24	REAL		Thin film flag for glazing 2	1
	25-36	REAL		Thin film flag for glazing 3	1
	37-48	REAL		Thin film flag for glazing 4	1
11a	1-12	REAL		Index of refraction of glazing 1	2
	13-24	REAL		Product of the extinction coefficient and thickness of glazing 1	2
	25-36	REAL		Normal solar transmittance of glazing 1	3
	37-48	REAL		Normal solar reflectance of upward facing surface of glazing 1	3

Table 3.1 (Continued)

LINE	COLUMN	FORMAT	UNITS	DESCRIPTION	NOTES
11a	49-60	REAL		Normal solar reflectance of downward facing surface of glazing 1	3
	61-72	REAL		Thin film optical property flag if = 0 measured directional properties available if = 1 only optical properties for normal incidence angles available	
11b	1-72			Short-wave properties for glazing 2	2, 3, 4
11c	1-72			Short-wave properties for glazing 3	2, 3, 4
11d	1-72			Short-wave properties for glazing 4	2, 3, 4
12	1-12	REAL		Number of measured optical property data points used for glazing 1	5, 6
13a	1-12	REAL	degrees	Incidence angle used for first data point	5
	13-24	REAL		Measured solar transmittance	
	25-36	REAL		Measured solar reflectance of upward-facing surface	
	37-48	REAL		Measured solar reflectance of downward-facing surface	
13b	1-48	REAL		Incidence angle and measured solar optical properties for second data point	5
. . . .	. . . .	. . . .		. . . .	
13x	1-48	REAL		Incidence angle and measured solar optical properties for xth data point	

Table 3.1 (Continued)

LINE	COLUMN	FORMAT	UNITS	DESCRIPTION	NOTES
14	1-12	REAL		Number of measured optical property data points used for glazing 2	5, 6
15a-x	1-48	REAL		Incidence angle and measured solar optical properties for each data point	
16	1-12	REAL		Number of measured optical property data points used for glazing 3	5, 6
17a-x	1-48	REAL		Incidence angle and measured solar optical properties for each data point	5
18	1-12	REAL		Number of measured optical property data points used for glazing 4	5, 6
19a-x	1-48	REAL		Incidence angle and measured solar optical properties for each data point	5
20	1-12	REAL		Solar absorptivity of room	7
	13-24	REAL	m	Height of window	
	25-36	REAL	m	Width of window	
	37-48	REAL	degrees	Slope of window used to calculate U-value	8
	49-60	REAL		Flag for interstitial gas: air = 1 argon = 2 krypton = 3 argon/Freon = 4 argon/SF_6 = 5	
	61-72	REAL	kPa	Interstitial gas pressure	
20a	1-12	REAL		Mole fraction of argon in gas mixture	14
	13-24	REAL		Mole fraction of second component (Freon or SF_6) in gas mixture	14

Table 3.1 (Concluded)

LINE	COLUMN	FORMAT	UNITS	DESCRIPTION	NOTES
21	1-12	REAL		Maximum error tolerance for temperature estimate in RFILM	9
		REAL		Maximum error tolerance for coefficient estimates in CCOEF	10
22	1-12	REAL		Number of interstitial spaces which employ slit-type honeycomb systems	
23	1-12	REAL		Position of first honeycomb (1 = air space closest to interior. 2 air space next closest to interior, etc.)	11
24	1-12	REAL	m	Vertical spacing between slits for first honeycomb	11, 12
	13-24	REAL		Radiant heat transfer coefficient 'a' (See eqn. 7.41)	12
	25-36	REAL		Radiant heat transfer coefficient 'b'	12
	37-48	REAL		Radiant heat transfer coefficient 'c'	12
	49-60	REAL		Radiant heat transfer coefficient 'd'	12
	61-72	REAL		Radiant heat transfer coefficient 'e'	12
25	1-12	REAL		Convection heat transfer coefficient$_1$ (See equation 7.43)	11, 13
	13-24	REAL		Convective heat transfer coefficient$_2$	13
26	1-12	REAL		Position of second honeycomb	11
27	1-72			Properties of second honeycomb	11, 12, 13
28	1-24			Properties of third honeycomb	
29	1-12	REAL		Position of third honeycomb	11
30	1-72			Properties of third honeycomb	11, 12, 13
31	1-24			Properties of third honeycomb	

1. Values need not be specified if element does not exist.
2. These values can be set to 0, if a thin film is used on the glazing, and measured solar optical properties are to be specified for a range of incidence angles.
3. These values can be set to 0, if a thin film is not used on the glazing, or if measured thin film optical properties are to be specified (see line 13).
4. These lines are deleted if the element does not exist.
5. If a thin film is **not** used on any glazing (i.e., if the thin film flag on line 10 is set to 0) or if measured solar optical properties are not specified (i.e., optical flag on line 11 set to 1) these lines are deleted.
6. Number of measured data points may range from 7 to 18.
7. Usually set equal to 1.
8. Slope may range from 0° (horizontal, upward facing) to 180° (horizontal, downward facing).
9. Usually set equal to 10^{-4}.
10. usually set equal to 10^{-7}.
11. If there are no honeycombs (i.e., line 17 equals 0) these lines are deleted.
12. For a honeycomb bounded by uncoated glass [9]: a = 0.92, b = -0.4097, c = -0.298, d = -0.1526, e = 1.09.
    For a honeycomb bounded by uncoated glass outside and coated glass (ε = 0.35) inside: a = 0.3404, b = -0.5448, c = -0.1647, d = -0.2458, e = 0.84.
    For a honeycomb bounded by coated glass inside and outside: a = 0.1631, b = 0.6513, c = -0.1023, d = -0.3285, e = 0.32.
13. Suggested values of γ are [10]: $\gamma_1 = 2.3 \times 10^{-6}$, $\gamma_2 = 0.488$.
14. Value must be $0.0 \leq MFRAC \leq 1.0$. If the gas code is 1, 2, or 3 (i.e., not a mixture) then the value can simply be set to 0.0.

Table 3.2. Energy analysis input data

LINE	COLUMN	FORMAT	UNITS	DESCRIPTION	NOTES
32	1-12	REAL		Energy analysis flag if = 0 no energy analysis if = 1 energy analysis performed	
33	1-12	REAL		Number of windows to be analysed (1 to 8)	1
	13-24	REAL		Number of days in energy simulation (1 to 365)	
	25-36	REAL		First day of heating season	
	37-48	REAL		Last day of heating season	
34	1-12	REAL	degrees	Slope of window number 1	1
	13-24	REAL	degrees	Slope of window number 2	2
	25-36	REAL	degrees	Slope of window number 3	2
	37-48	REAL	degrees	Slope of window number 4	2
	49-60	REAL	degrees	Slope of window number 5	2
	61-72	REAL	degrees	Slope of window number 6	2
35	1-12	REAL	degrees	Slope of window number 7	1, 2
	13-24	REAL	degrees	Slope of window number 8	2
36	1-12	REAL	degrees	Azimuth angle of window 1 (Counter clockwise from south)	1
	13-24	REAL	degrees	Azimuth angle of window 2	2
	25-36	REAL	degrees	Azimuth angle of window 3	2
	37-48	REAL	degrees	Azimuth angle of window 4	2
	49-60	REAL	degrees	Azimuth angle of window 5	2
	61-72	REAL	degrees	Azimuth angle of window 6	2
37	1-12	REAL	degrees	Azimuth angle of window 7	1, 2
	13-24	REAL	degrees	Azimuth angle of window 8	2

1. Delete lines if an energy analysis is not required (i.e., energy analysis flag (line 27) = 0).
2. Values need not be specified if element does not exist.

Table 3.3. Shading input data

LINE	COLUMN	FORMAT	UNITS	DESCRIPTION	NOTES
38	1-12	REAL		Shading flag if = 0 no shading modelled if = 1 shading used	1
39	1-12	REAL	m	Overhang height above window	1, 2
	13-24	REAL	m	Overhang length beyond left end of window	
	25-36	REAL	m	Overhang length beyond right end of window	
	37-48	REAL	m	Overhang projection beyond window	
	49-60	REAL	m	Depth of vertical projection	
40	1-12	REAL	m	Left fin height above top of window	1, 2
	13-24	REAL	m	Left fin height above bottom of window	
	25-36	REAL	m	Left fin distance from side of window	
	37-48	REAL	m	Left fin distance beyond window	
	49-60	REAL	m	Right fin height above top of window	
	61-72	REAL	m	Right fin height above bottom of window	
41	1-12	REAL	m	Right fin distance from side of window	1, 2
	13-24	REAL	m	Right fin distance beyond window	

1. Delete lines if an energy analysis is not required.
2. Delete lines if a shading analysis is not required (i.e., line 33 = 0).

```
    7.000000
REFERENCE
DOUBLE GLAZED WINDOW
 - 6 MM GLAZINGS
 - 12.7 MM AIR SPACE
 - 25 CM OVERHANG
 - ENERGY ANALYSIS FOR 8 ORIENTATIONS
-------------------------------------
    2.000000
    0.006350    0.006350
    0.012700
    0.840000    0.840000
    0.840000    0.840000
    0.160000    0.160000
    0.160000    0.160000
    0.000000    0.000000
    1.520000    0.100000    0.000000    0.000000    0.000000    0.000000
    1.520000    0.100000    0.000000    0.000000    0.000000    0.000000
    1.000000    1.000000    1.000000   90.000000    1.000000  101.300003
0.100000E-030.100000E-06
    0.000000
    1.000000
    8.000000  365.000000  258.000000  135.000000
   90.000000   90.000000   90.000000   90.000000   90.000000   90.000000
   90.000000   90.000000
    0.000000   45.000000   90.000000  135.000000  180.000000  225.000000
  270.000000  315.000000
    1.000000
    0.000000    0.000000    0.000000    0.250000    0.000000
    0.000000    0.000000    0.000000    0.000000    0.000000    0.000000
    0.000000    0.000000
```

Figure 3.1. Sample input data

The second section contains the optical and thermal performance results. This section can be further sub-divided into two sections. The first section presents the polynomial coefficients for the optical properties of any individual glazings which utilized a thin film coating and whose measured directional properties were specified as input, as well as the optical properties of the window system, the U-values and the SC. The second section contains the monthly and annual summaries of the energy analysis results for each of the window orientations considered and is produced only if the user chooses to perform an energy analysis. The window slope is measured from the horizontal (i.e., a 90° slope refers to a vertical window), and azimuth angle is measured counterclockwise from south (i.e., 270° refers to a west-facing window). As previously mentioned, degree days are calculated only for those days which fall within the heating season.

Figure 3.2 presents the output for the double glazed window whose input file appeared previously in Figure 3.1.

REFERENCE
DOUBLE GLAZED WINDOW
- 6 MM GLAZINGS
- 12.7 MM AIR SPACE
- 25 CM OVERHANG
- ENERGY ANALYSIS FOR 8 ORIENTATIONS

WINDOW DATA

GLAZING PROPERTIES	
NUMBER OF GLAZINGS..............................	2
GLAZING NUMBER 1 (INTERIOR)	
THICKNESS (M)...................................	0.0063
LONG WAVE EMISSIVITY (UPWARD)...................	0.8400
LONG WAVE EMISSIVITY (DOWNWARD).................	0.8400
LONG WAVE REFLECTIVITY (UPWARD).................	0.1600
LONG WAVE REFLECTIVITY (DOWNWARD)...............	0.1600
THIN FILM COATING?..............................	NO
REFRACTION INDEX................................	1.5200
EXTINCTION COEFFICIENT X THICKNESS..............	0.1000
GLAZING NUMBER 2 (EXTERIOR)	
THICKNESS (M)...................................	0.0063
LONG WAVE EMISSIVITY (UPWARD)...................	0.8400
LONG WAVE EMISSIVITY (DOWNWARD).................	0.8400
LONG WAVE REFLECTIVITY (UPWARD).................	0.1600
LONG WAVE REFLECTIVITY (DOWNWARD)...............	0.1600
THIN FILM COATING?..............................	NO
REFRACTION INDEX................................	1.5200
EXTINCTION COEFFICIENT X THICKNESS..............	0.1000
WINDOW AIR SPACE THICKNESSES (M)	
AIR SPACE 1 (CLOSEST TO INTERIOR)...............	0.0127
FILL GAS TYPE...................................	AIR
FILL GAS PRESSURE (KPA).........................	101.3000
WINDOW HEIGHT (M)...............................	1.0000
WINDOW WIDTH (M)................................	1.0000
SLOPE OF REFERENCE WINDOW.......................	90.0000
SHORT WAVE ABSORPTIVITY OF INTERIOR.............	1.0000
CONVERGENCE TOLERANCE FOR GLAZING TEMPERATURES	0.D-03
CONVERGENCE TOLERANCE FOR COSINE COEFFICIENTS.	0.D-06

ENERGY ANALYSIS DATA

NUMBER OF WINDOWS CONSIDERED....................	8
ORIENTATION (DEGREES CCW FROM SOUTH)	
WINDOW 1..	0.0000
WINDOW 2..	45.0000
WINDOW 3..	90.0000

WINDOW 4..	135.0000
WINDOW 5..	180.0000
WINDOW 6..	225.0000
WINDOW 7..	270.0000
WINDOW 8..	315.0000

SLOPE OF WINDOW (DEGREES FROM HORIZONTAL)

WINDOW 1..	90.0000
WINDOW 2..	90.0000
WINDOW 3..	90.0000
WINDOW 4..	90.0000
WINDOW 5..	90.0000
WINDOW 6..	90.0000
WINDOW 7..	90.0000
WINDOW 8..	90.0000

NUMBER OF DAYS IN ANALYSIS....................	365
FIRST DAY OF HEATING SEASON..................	258
LAST DAY OF HEATING SEASON...................	135

SHADING DATA (LENGTH IN M)

OVERHANG HEIGHT ABOVE WINDOW..................	0.0000
OVERHANG LENGTH BEYOND LEFT END OF WINDOW.....	0.0000
OVERHANG LENGTH BEYOND RIGHT END OF WINDOW....	0.0000
OVERHANG PROJECTION BEYOND WINDOW.............	0.2500
DEPTH OF VERTICAL PROJECTION..................	0.0000
LEFT FIN HEIGHT ABOVE TOP OF WINDOW...........	0.0000
LEFT FIN HEIGHT ABOVE BOTTOM OF WINDOW........	0.0000
LEFT FIN DISTANCE FROM SIDE OF WINDOW.........	0.0000
LEFT FIN PROJECTION BEYOND WINDOW.............	0.0000
RIGHT FIN HEIGHT ABOVE TOP OF WINDOW..........	0.0000
RIGHT FIN HEIGHT ABOVE BOTTOM OF WINDOW.......	0.0000
RIGHT FIN DISTANCE FROM SIDE OF WINDOW........	0.0000
RIGHT FIN PROJECTION BEYOND WINDOW............	0.0000

OPTICAL PERFORMANCE SUMMARY

OPTICAL COEFFICIENTS FOR WINDOW SYSTEM

COEFFICIENT	TA(EFF)	ABS(1)	ABS(2)	REFL
1	-0.0170	0.0027	0.0591	0.9552
2	0.7407	0.4960	1.0830	-2.3196
3	4.7294	-1.2975	-4.7636	1.3364
4	-12.6546	1.9125	9.0103	1.7326
5	11.7416	-1.5229	-7.8822	-2.3373
6	-3.8475	0.4886	2.6005	0.7587
DIFFUSE	0.5942	0.0816	0.1164	0.2077

MON	DD	+ORIENT. +SLOPE	0. 90.	45. 90.	90. 90.	135. 90.	180. 90.	225. 90.	270. 90.	315. 90.
1	1006.	INC. RADN	347.6	277.2	151.2	84.3	82.3	83.7	139.3	260.2
		SOL. GAIN	252.4	193.1	97.4	54.9	54.6	54.9	89.7	179.6
		COND.LOSS	259.1	258.8	258.4	258.2	258.2	254.6	254.7	255.1
		NET GAIN	-6.6	-65.7	-161.0	-203.3	-203.6	-199.7	-165.1	-75.5
2	793.	INC. RADN	343.4	285.0	188.4	115.4	103.4	111.6	179.9	277.6
		SOL. GAIN	241.8	197.2	125.8	73.2	68.5	71.8	118.9	192.8
		COND.LOSS	209.0	208.8	208.5	208.3	208.2	205.5	205.6	205.9
		NET GAIN	32.9	-11.6	-82.8	-135.0	-139.7	-133.7	-86.7	-13.1
3	667.	INC. RADN	409.1	377.7	291.2	196.6	165.8	190.9	271.6	354.9
		SOL. GAIN	275.3	260.3	196.3	126.5	109.7	123.6	182.5	243.3
		COND.LOSS	185.0	185.0	184.9	184.7	184.7	182.4	182.5	182.6
		NET GAIN	90.3	75.3	11.4	-58.1	-75.0	-58.8	0.0	60.7
4	378.	INC. RADN	319.5	332.3	296.3	215.4	166.9	206.8	279.9	318.2
		SOL. GAIN	202.1	225.1	201.3	139.2	109.2	133.8	189.6	215.2
		COND.LOSS	116.2	116.3	116.3	116.3	116.3	114.9	114.9	114.9
		NET GAIN	85.9	108.8	85.0	22.9	-7.1	18.9	74.7	100.3
5	113.	INC. RADN	236.2	273.2	283.0	238.9	194.3	227.8	268.5	265.1
		SOL. GAIN	146.2	179.9	191.5	157.4	124.2	149.7	180.8	174.8
		COND.LOSS	70.5	70.5	70.5	70.5	70.5	69.9	69.8	69.8
		NET GAIN	75.7	109.4	121.0	86.8	53.6	79.8	111.0	105.0
6	0.	INC. RADN	250.1	288.2	302.3	261.2	225.2	278.6	324.7	301.8
		SOL. GAIN	154.0	187.8	203.7	172.7	142.6	184.4	219.3	195.6
		COND.LOSS	26.8	27.1	27.2	27.2	27.1	26.2	25.9	25.9
		NET GAIN	127.2	160.7	176.5	145.4	115.5	158.3	193.4	169.6
7	0.	INC. RADN	240.5	276.0	286.9	248.2	211.0	250.2	289.2	277.0
		SOL. GAIN	150.0	182.3	194.4	164.7	136.2	164.8	194.5	181.4
		COND.LOSS	5.0	6.0	6.0	6.0	6.3	4.7	4.3	4.4
		NET GAIN	144.9	176.3	188.4	158.7	129.9	160.0	190.3	177.0
8	0.	INC. RADN	279.0	310.5	298.0	234.7	187.1	224.3	278.0	291.6
		SOL. GAIN	173.2	208.5	202.6	153.9	121.8	146.0	186.6	193.2
		COND.LOSS	13.6	14.8	15.1	15.2	15.4	14.4	13.4	13.2
		NET GAIN	159.5	193.6	187.5	138.7	106.4	131.7	173.2	180.0
9	77.	INC. RADN	232.8	223.3	187.9	142.2	121.7	144.5	189.4	223.1
		SOL. GAIN	151.6	150.7	125.5	91.4	79.6	93.1	127.0	150.8
		COND.LOSS	53.5	53.5	53.6	53.6	53.7	53.3	53.2	53.2
		NET GAIN	98.1	97.1	71.9	37.8	25.9	39.8	73.8	97.6
10	264.	INC. RADN	266.0	221.1	150.7	96.9	88.0	97.0	151.4	221.9
		SOL. GAIN	184.6	151.8	99.5	61.4	57.7	61.5	99.9	152.6
		COND.LOSS	91.1	91.3	91.4	91.4	91.5	90.6	90.4	90.3
		NET GAIN	93.5	60.5	8.1	-30.1	-33.8	-29.1	9.5	62.3

11	454.	INC. RADN	158.5	124.3	75.4	50.6	49.0	50.8	79.0	129.6
		SOL. GAIN	113.2	85.1	48.9	32.7	32.3	32.8	51.3	89.8
		COND.LOSS	136.3	136.3	136.3	136.3	136.3	134.9	134.8	134.8
		NET GAIN	-23.1	-51.1	-87.4	-103.6	-104.0	-102.1	-83.5	-45.0
12	881.	INC. RADN	273.2	213.9	115.5	67.7	66.9	67.6	112.2	208.9
		SOL. GAIN	198.6	148.4	73.9	44.4	44.3	44.5	72.1	144.5
		COND.LOSS	231.6	231.5	231.3	231.2	231.2	228.1	228.2	228.4
		NET GAIN	-33.1	-83.1	-157.4	-186.8	-186.8	-183.6	-156.0	-83.9
TOT	4632.	INC. RADN	3355.9	3202.8	2626.6	1952.2	1661.8	1933.8	2563.1	3130.0
		SOL. GAIN	2243.0	2170.3	1760.7	1272.3	1080.8	1260.6	1712.3	2113.6
		COND.LOSS	1397.7	1400.0	1399.4	1398.9	1399.4	1379.3	1377.6	1378.5
		NET GAIN	845.3	770.3	361.4	-126.7	-318.6	-118.7	334.7	735.1

Figure 3.2. Sample output data

3.3 Executing VISION

The execution of VISION can be controlled by two 'exec' files. The purpose of an exec file is to define all of the files used to run a program and to initiate its execution.

The first exec file controls the execution of TALK, the program used to create the input file. The user accesses this exec file by simply typing TALK on the terminal. The user will then be prompted to answer all of the questions required to create the input file.

As previously mentioned, the user could alternatively elect to create the input file manually.

The second exec file controls the execution of VISION. By typing the word VISION, the necessary routines are executed.

Figures 3.3 and 3.4 present the TALK and VISION exec files.

It should be noted that exec file format is system-dependent. These files were created for a system using a VM (virtual machine) operating system.

Computer Requirements

3.4.1 Language

VISION is written in Fortran 77 compatible code.

3.4.2 Hardware

VISION was developed on an IBM 4341 series computer, a powerful, high speed mainframe computer. It is anticipated, however, that VISION could be successfully implemented on a powerful micro/mini computer, provided the machine enabled the use of Common Blocks and double precision calculations.

3.4.3 Execution Time

Within the IBM 4341 environment, the calculation of the U-value, shading coefficient and optical coefficients (i.e., execution of the first stage) requires less than ½ CPU s of execution time. The execution time requirements for the hourly energy analysis are naturally dependent on the number of window orientations and days considered. Simulation of the maximum eight orientations and 365 days requires approximatley 250 CPU s.

```
&TYPE ENTER WINDOW NUMBER
&READ VARS &1
FI 10 TERM (LRECL 80 RECFM F
FI  3 TERM (LRECL 80 RECFM F
FI 11 DISK VISION INPUT&1 A (LRECL 80 RECFM FB BLOCK 800
TALK
T VISION INPUT&1 A
```

Figure 3.3. Talk exec file

```
&TYPE ENTER WINDOW NUMBER
&READ VARS &1
FI 10 DISK VISION INPUT&1 A (LRECL 80 RECFM FB BLKSIZE 800
FI 11 TAP1 (LRECL 23 BLKSIZE 3105 RECFM FB
FI  8 DISK VISION OUTPUT&1 A
VISION
```

Figure 3.4. Vision exec file

4.0 REFERENCES

1. Mitalas, G.P., and Arseneault, J.G., "Fortran IV Program to Calculate Absorption and Transmission of Thermal Radiation by Single and Double-Glazed Windows", DBR Computer Program No. 34, National Research Council, Ottawa, Ont., March, 1972.

2. Barakat, S.A., "A Fortran IV Program to Calculate Net Heat Gains Through Windows", DBR Computer Program No. 47, National Research Council, Ottawa, Ont., November, 1980.

3. ASHRAE, "Handbook of Fundamentals", Atlanta, GA, 1981.

4. Harrison, S.J., and Barakat, S.A., "A Method for Comparing the Thermal Performance of Windows", ASHRAE Transactions, Vol. 89, Part 1, 1983.

5. Kreith, F., and Kreider, J.F., "Principles of Solar Engineering", Hemisphere Publishing Corp., Washington, DC, pp. 169-179, 1978.

6. Rubin, M., "Solar Optical Properties of Windows", International Journal of Energy Research, Vol. 6, pp. 123-133, 1982.

7. Rubin, M., "Calculating Heat Transfer Through Windows", Lawrence Berkeley Laboratories preprint LBL - 12486, May 1981.

8. Stephenson, D.G., "Equations for Solar Heat Gains through Windows", Solar Energy, Vol. 9, No. 2, pp. 81-86, April - June, 1965.

9. Hollands, K.G.T., Marshall, K.N., and Wedel, R.K., "An Approximate Equation for Predicting the Solar Transmittance of Transparent Honeycombs", Solar Energy, Vol. 21, pp. 231-236, 1978.

10. Shewen, E.C., and Hollands, K.G.T., "An Optimization Study of a Honeycomb Window", Department of Mechanical Engineering, University of Waterloo, Waterloo, Ont., October 1979.

11. Edwards, D.K., "Solar Absorption by Each Element in an Absorber-Coverglass Array", Technical Note, Solar Energy, Vol. 19, pp. 401-402, 1977.

12. Orgill, J.F., and Hollands, K.G.T., "Correlation Equation for Hourly Diffuse Radiation on a Horizontal Surface", Solar Energy, Vol. 19, p. 357, 1977.

13. Bekooy, R.G., "Computer Shadow Analysis Technique for Tilted Windows Shaded by Overhangs, Vertical Projections, and Side Fins", ASHRAE Transactions, Vol. 89, Part 1, 1983.

14. Wright, J.L., "Free Convection in Inclined Air Layers Constrained by a V-Corrigated Teflon Film", M.A.Sc. Thesis, Department of Mechanical Engineering, University of Waterloo, Waterloo, Ont., May, 1980.

15. Hollands, K.G.T., and Wright, J.L., "Heat Loss Coefficients and Effective $\tau\alpha$ Products for Flat-Plate Collectors with Diathermanous Covers", Solar Energy, Vol. 30, pp. 211-216, 1982.

16. Hollands, K.G.T., and Wright, J.L., "Theory and Experiment on Heat Loss Coefficients for Plastic Covers", Proceedings of the American Section of the International Solar Energy Society, Phoenix, AZ, pp. 441-445, 1980.

17. Siegel, R., and Howell, J.R., "Thermal Radiation Heat Transfer", Chapter 8, McGraw-Hill Book Company, 1972.

18. Kreith, F., "Principles of Heat Transfer", 3rd Edition, IEP, New York, pp. 261.

19. Swinbank, W.C., Journal of the Royal Meteorological Society, Vol. 89, pp. 339-348, 1963.

20. El Sherbiny, S.M., Raithby, G.D., and Hollands, K.G.T., "Heat Transfer by Natural Convection Across Vertical and Inclined Air Layers", Journal of Heat Transfer, Vol. 104, 1982.

21. Hollands, K.G.T., Unny, T.E., Raithby, G.D., and Konicek, L., "Free Convection Heat Transfer Across Inclined Air Layers", Journal of Heat Transfer, Vol. 98, pp. 189-193, 1976.

22. Arnold, J.N., Bonaparte, P.N., Catton, I., and Edwards, D.K., "Experimental Investigation of Natural Convection in a Finite Rectangular Region Inclined at Various Angles from 0 to 180°", Proceedings of the 1974 Heat Transfer and Fluid Mechanics Institute, Corvalles, OR, Stanford University Press, Stanford, CA, 1974.

23. Konrad, A., and Larsen, B.T., "ENCORE - CANADA: Computer Program for the Study of Energy Consumption of Residential Buildings in Canada", Proceedings, 3rd International Symposium on the Use of Computers for Environmental Engineering Related to Buildings, Banff, Alta., 1978.

24. Lokmanhekim, J., ed., "Procedure for Determining Heating and Cooling Loads for Computerizing Energy Calculations: Algorithms for Building Heat Transfer Subroutines", ASHRAE, New York, 1975.

25. Tables of Thermal Properties of Gases, National Bureau of Standards Circular 564, U.S. Government Printing Office, Nov. 1955.

26. Cowan, J.A., Physics Department, University of Waterloo, Waterloo, Ont., personal communication, April 1983.

27. Bolz, R.E., and Tuve, G.L., "C.R.C. Handbook of Tables for Applied Engineering Science", 2nd Edition, C.R.C. Press, p. 50.

28. Hanley, J.J.M., McCarty, R.D., and Haynes, W.M., "The Viscosity and Thermal Conductivity Coefficients for Dense and Liquid Argon, Krypton, Xenon, Nitrogen, and Oxygen", Journal of Physical and Chemical Reference Data, Vol. 3, No. 4, pp. 979-1017, 1974.

29. Juza, J., and Sifner, O., "Modified Equation of State and Formulation of Properties of Krypton in a Canonical Form in the Range from 120 to 423 K and 0 to 300 MPa", ACTA TECHNICA CSAV, No. 1, 1976.

30. Rohsenow, W.M., and Hartnett, J.P. (Editors). "Handbook of Heat Transfer", McGraw Hill Book Company, 1973.

31. Rubin, M., and Lampert, C.M., "Transparent Silica Aerogels for Window Insulation", Solar Energy Materials, Vol. 7, pp. 393-400, 1983.

32. "WATSUN 3.1 - Solar Domestic Hot Water System with Pre-Heating Storage, and Exchangers", University of Waterloo, Waterloo, Ont., May 1981.

APPENDIX A - GLOSSARY OF TERMS

A	gas space height to thickness aspect ratio
A	parameter defined by equation (1.10)
A'	fraction of radiation absorbed in a single pass through a glazing
$ABSOR_{i,M}$	fraction of incoming radiation on a M-element array which is absorbed by the ith element
AHC	parameter defined by equation (1.21)
ALFA	total solar absorptivity of single glazing
ALFAE, ALFAM	total solar abosrptivity of single glazing for electric and magnetic polarization
ALFAD ALFAU	solar absorptivity of downward (i.e., inward) facing and upward (i.e., outward) facing surface of single glazing with a thin film coating
ASPRAT	elevation aspect ratio of honeycomb slits
AZMTH	azimuth angle measured counter-clockwise from south, deg
BETA	thermal expansion coefficient, K^{-1}
$CFTFT_j$	jth coefficient for polynomial used to calculate solar transmissivity of glazing with thin film
$COEFR_j$	jth coefficient for polynomial used to calculate reflectance of M-element array
COEFTD	diffuse transmittance
CP	specific heat, J/g mol K
D	spacing between honeycomb slits, m
DAY	day number

DECL declination angle, deg

E_{sky} clear sky emittance

EB black-body emissive power, W/m^2

ED_i, EU_i hemispherical long wave emissivity of the downward and upward facing surfaces of element i

ECC eccentricity of earth's orbit

Fc fraction of sky which is clear

F_{sky} window to sky shape factor

FSHADE fraction of window area shaded from incident beam radiation

G parameter defined by equation (7.22)

H_i convective-conductive heat transfer coefficient for interstitial space i, W/m^2 K

H_i convective-conductive heat transfer coefficient for interstitial space i based on black emissive powers

HR long wave radiation heat transfer coefficient for honeycomb, W/m^2 K

HGHT window height, m

HHB horizontal beam radiation, W/m^2

HHD horizontal diffuse radiation, W/m^2

HHT horizontal total radiation, W/m^2

HHEX extra-terrestrial radiation, W/m^2

HTB beam radiation incident on a tilted surface, W/m^2

HTD diffuse radiation incident on a tilted surface, W/m^2

HCOR	mid-point in radiation measurement time period, h
HRANG	solar azimuth angle, deg
IH	time at end of radiation measurement, h
JD_i, JU_i	radiosity of downward and upward facing surfaces of element i, W/m^2 K
k	thermal conductivity, W/m^2 K
KL	product of extinction coefficient and glazing thickness
LAT	location latitude, deg
M	number of elements in interior/window array (= number of glazings + 1)
N	number of elements in interior/window/exterior array (= number of glazings + 2)
NEXP	truncated value of RAT
Nu	Nusselt number
Nu_V	Nusselt number for vertical window
P	pressure, kPa
PHI	angle defined by equation (1.19)
PHIP	angle defined by equation (1.20)
PR	Prandtl number
PROFIL	projected incidence angle, deg
Q	thermal heat transfer, W/m^2
QCOND	inward heat transfer due to temperature potential, W/m^2
QNET	net (thermal plus direct solar) heat transfer, W/m^2

QSOL	direct solar heat gain, W/m^2
QSOLT	total solar heat gain, W/m^2
QSOLLW	absorbed and redirected solar heat gain, W/m^2
R	interface reflectivity
RE, RM	interface reflectivity for electric and magnetic polarization components of radiation
R_{sky}	long wave sky radiation falling on horizontal surface, W/m^2
RA	Rayleigh number
RADTN	total incident radiation
RAT	parameter defined by equation (1.22)
RB	ratio of beam horizontal and beam incident radiation
RD	ratio of incident diffuse and total horizontal diffuse radiation
RR	ratio of the incident reflected radiation to the total horizontal radiation
$REFL_i$	total reflectance of first i elements of an M-element array
RES	thermal resistance, $K\ m^2/W$
RESOUT	thermal resistance of window from element i to the outdoor, $K\ m^2/W$
RHO	total solar reflectivity of single glazing
RHOD, RHOU	total solar reflectivity of downward and upward facing surface of single glazing
RHOG	ground reflectivity
RHOE, RHOM	reflectivity of single glazing for electric and magnetic radiation components

RHOHC	parameter defined by equation (1.17)
RD_i, RU_i	hemispherical long wave reflectivity of the downward and upward facing surfaces of element i
RINDX	index of refraction
RPHI	parameter defined by equation (1.18)
S, SLOPE	window slope, deg
SC	shading coefficient
SOLCON	solar constant
$SOURCE_i$	amount of incident solar radiation which is absorbed by element i, W/m^2
SSRMAX	hour angle ½ h before/after sunset/sunrise
TAS_i	thickness of interstitial space i, m
TAU	solar transmissivity of single glazing
TAUE, TAUM	solar transmissivity for electric and magnetic components of radiation
TAUN	normal solar transmissivity of thin film/substrate
TAUS	solar transmissivity of substrate only
TAUSN	normal solar transmissivity of substrate only
TEMP	temperature, K
THETAZ	incidence angle, deg
THETAP	angle of refraction, deg
THETA	zenith angle
TM	mean interstitial space temperature, K

$TRANS_i$	ratio of radiation flux flowing downward **from** element i to the radiation flux flowing downward **onto** element i
UVAL	thermal conductance, W/m^2 K
V	wind speed, m/s
XKT	parameter defined by equation (5.8)
Z	compressibility factor
a,b,c,d,e	correlation parameters used in equation (7.41)
γ_1, γ_2	correlation parameters used in equation (7.43)
θ	incidence angle
σ	Stefan-Boltzmann constant, W/m^2 K^4