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Working Document

Switchable Window Modeling

A report of Task 12: Building Energy Analysis and Design Tools for Solar Applications

Subtask A.1: High Performance Glazings

June 1992

INTERNATIONAL ENERGY AGE
Solar Heating & Cooling Prograr

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Task 12: Building Energy Analysis and Design Tools for Solar Applications
Subtask A.1: High-Performance Glazing

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PREFACE

INTRODUCTION TO THE INTERNATIONAL ENERGY AGENCY

BACKGROUND

The International Energy Agency was founded in November 1974 as a cooperation among industrialized nations to address energy policy issues. It is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OEDC). Twenty-one countries are presently members, with the Commission of the European Communities also participating in the work of the IEA under a special agreement.

One element of the IEA's program involves cooperation in the research and development of alternative energy resources in order to reduce excessive dependence on oil. A number of new and improved energy technologies which have the potential of making significant contribution to global energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), comprising representatives from each member country, supported by a small Secretariat staff, is the focus of IEA RD&D activities. Four Working Paries (in Conservation, Fossil Fuels, Renewable Energy, and Fusion) are charged with identifying new areas for cooperation and advising the CRD on policy matters in their respective technology areas.

SOLAR HEATING AND COOLING PROGRAM

Solar Heating and Cooling was one of the technologies selected for joint activities. During 1976–1977, specific projects were identified in key area of this field and a formal Implementing Agreement drawn up. The Agreement covers the obligations and rights of the Participants and outlines the scope of each project or "task" in annexes to the document. There are now eighteen signatories to the Agreement:

Australia	Germany	Norway
Austria	Greece	Spain
Belgium	Italy	Sweden
Canada	Japan	Switzerland
Denmark	Netherlands	United Kingdom
Commission of the European Communities	New Zealand	United States

The overall program is managed by an Executive Committee, while the management of the individual tasks is the responsibility of Operating Agents. The tasks of the IEA Solar Heating and Cooling Program, their respective Operating Agents, and current status (ongoing or completed) are as follows:

Task 1 Investigation of the Performance of Solar Heating and Cooling Systems—Technical University of Denmark (Completed).

Task 2 Coordination of Research and Development of Solar Heating and Cooling—Solar Research Laboratory—GIRN, Japan (Completed).

Task 3 Performance Testing of Solar Collectors—Forschungszentrum Jülich, Germany, University College, Cardiff, U.K. (Completed).

Task 4 Development of an Isolation Handbook and Instrument Package—U.S. Department of Energy (Completed).

Task 5 Use of Existing Meterological Information for Solar Energy Application—Swedish Meterological and Hydrological Institute (Completed).

Task 6 Performance of Solar Heating, Cooling, and Hot Water Systems using Evacuated Collectors—U.S. Department of Energy (Completed).

Task 7 Central Solar Heating Plants with Seasonal Storage—Swedish Council for Building Research (Completed).

Task 8 Passive and Hybrid Solar Low Energy Buildings—U.S. Department of Energy (Completed).

Task 9 Solar Radiation and Pyranometry Studies—Forschungszentrum Jülich, Germany (Completed).

Task 10 Solar Materials R&D—AIST, Ministry of International Trade and Industry, Japan (Completed).

Task 11 Passive and Hybrid Solar Commercial Buildings—Swiss Federal Office of Energy (Completed).

Task 12 Building Energy Analysis and Design Tools for Solar Applications—U.S. Department of Energy (Ongoing).

Task 13 Advanced Solar Low Energy Buildings—Norwegian Institute of Technology (Ongoing).

Task 14 Advanced Active Solar Energy Systems—Canadian Department of Energy Mines and Resources (Ongoing).

Task 15 Advanced Central Solar Heating Plants with Seasonal Storage (In Planning Stage).

Task 16 Photovoltaics in Buildings—Forschungszentrum Jülich, Germany (Ongoing).

Task 17 Measuring and Modelling Spectral Radiation Affecting Solar Systems and Buildings—Forschungszentrum Jülich, Germany (Ongoing).

Task 18 Advanced Glazing Materials—U.K. Department of Energy (Ongoing).

Task 19 Solar Air Systems for Buildings—Swiss Federal Office of Energy (Ongoing).

Task 20 Solar Energy in Building Renovation—Swedish Council for Building Research (Ongoing).

TASK 12: BUILDING ENERGY ANALYSIS AND DESIGN TOOLS FOR SOLAR APPLICATIONS

The scope of Task 12 includes: (1) selection and development of appropriate algorithms for modeling of the interaction of solar energy related materials, components and systems with the building in which these solar elements are integrated; (2) selection of analysis and design tools and evaluation of the algorithms as to their ability to model the dynamic performance of the solar elements in respect to accuracy and ease of use; and (3) improvement of the usability of the analysis and design tools, through preparation of common formats and procedures and by standardization of specifications for input/output, default values and other user-related factors.

The subtasks of this project are:

A : Model Development
B : Model Evaluation
C : Model Use

The participants in this Task are: Denmark, Germany, Norway, Sweden, Switzerland, and the United States. The United States serves as Operating Agent for this Task.

This report documents work carried out under Subtask A.1 of this Task entitled High Performance Glazing.

EXECUTIVE SUMMARY

This document presents the work conducted as part of Subtask A.1, High-Performance Glazing, of Task 12 of the IEA Solar Heating and Cooling Program. At the start of the task, the participants agreed that chromogenic technology (switchable glazing) held considerable promise, and that algorithms to accurately model their dynamic behavior were needed.

The purpose of this subtask was to develop algorithms that could be incorporated into building energy analysis programs for predicting the thermal and optical performance of switchable windows. The work entailed a review of current techniques for modelling switchable glazing in windows and switchable windows in buildings and methods for improving upon existing modeling approaches. The proposed approaches correct some of the shortcomings in the existing techniques, and could be adapted for use in other similar programs. The proposed approaches generally provide more detailed calculations needed for evaluating the short-term (hourly and daily) impact of switchable windows on the energy and daylighting performance of a building. Examples of the proposed algorithms are included.

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I. INTRODUCTION

1.1 Background

Switchable glazing, or smart glazing, have variable optical properties. The photochromic lenses in sunglasses that become darker as the surroundings become lighter are one common example of switchable glazing. The switching material incorporated into the glazing is known as a chromogenic device. There are electrochromic, thermochromic, and photochromic devices whose properties vary from a high transmittance "bleached" state to a low transmittance "colored" state. The optical properties of electrochromic devices change with applied current, those of thermochromic devices change with temperature, and those of photochromic devices change with the amount of incident radiation. For more detailed information on chromogenic devices, see Lampert (1989) for a review of switching technologies and an extensive reference listing.

Ineffective control of the amount of incoming solar radiation and visible light can render a space practically uninhabitable. Shading systems and sun control glazing have been developed to avoid excessive solar gains without excluding the daylight completely. These systems have lead to a strong interest in the development of switchable glazing which combine the attributes of shading systems and sun control glazing into a single glazing element. Some switchable glazing have the additional advantage of preserving the view through the window while responding to the varying environmental conditions.

1.2 Purpose of This Report

The purpose of this report is to review and improve upon existing algorithms for modeling switchable glazings.

In evaluating the performance of switchable windows in buildings, the thermal and optical properties of the window itself must be known. The switchable windows may be single-pane or multipane windows. Multipane windows may be necessary with some of the switchable glazing technologies to protect them from the surroundings or to provide adequate control over their response to environmental conditions.

The importance of modelling switchable glazing in building energy simulation programs lies in the need to predict the energy savings potential of this technology in buildings, and to formulate performance guidelines to aid researchers in their development efforts. This requires an hourly simulation model that adequately accounts for thermal, solar optical and daylighting impacts of the switchable glazings. The guidelines need to address questions concerning the switching range and behavior of the switching material, the angular dependence of the optical properties, and how each of these relate to building design issues such as window size and orientation and lighting requirements. Furthermore, the successful development of control strategies for switchable windows requires models that imitate the behavior of the window.

1.3 Structure of the Report

Section II of this report reviews current approaches for modeling switchable window glazings in terms of window performance and building energy performance.

Section III of this report looks at proposed algorithms for modeling switchable window glazings in terms of window performance and building energy performance.

Appendix A specifies models for electrochromic and thermochromic windows used as functions in the DOE-2 building energy simulation program. Appendix B describes the switchable window algorithms incorporated into the latest version of DOE-2, DOE-2.1E, which can be used in other building energy simulation programs.

1.4 Intended Audience

The primary audience for the switchable window modeling algorithms are researchers, engineers, and manufacturers. The intention of this work is to provide tools for more accurate assessment of the potential of switchable glazing technologies, and to further the development of the technology.

1.5 Acknowledgments

This report was instigated through cooperation between the IEA participating researchers and the government agencies which sponsored the work in the respective countries. The participants who provided comments and criticism on earlier drafts are thanked for their effort, without which this report could not have been completed.

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II. MODELING APPROACHES

2.1 Window System Properties

Incorporating switchable glazing into window systems and characterizing the systems' thermal and optical properties requires knowledge of the thermo-physical and optical properties of the system components. Given the necessary component data, the heat transfer coefficient for the system, the total solar and visible transmittance and reflectance, and the solar heat gain through the window can be calculated. These properties can be found for the maximum and minimum transmitting states of the switchable window, and properties for the intermediate states can be interpolated from the properties of the maximum and minimum states.

The component data, which consists of the optical properties and conductance of switchable glazing, are not easily obtainable. The technologies are still under development; researchers tend to be reluctant to release complete sets of spectral data on prototype devices; and private developers have proprietary rights. The properties can be idealized to bound the possible technology options. An example of such an approach using the WINDOW program (described below) is found in Reilly et al. (1991).

Methods for calculating the window properties are described in Arasteh (1989) and Wright and Sullivan (1989). Two computer programs exist for this purpose, WINDOW 4.0 (LBL, 1992) and VISION (Wright, 1991). The programs employ similar calculation procedures and differ only in the user-interface and special features. One advantage to the WINDOW program is its ability to access spectral data for the individual glazing components and calculate the total optical properties for the window. For glazings that exhibit a strong spectral dependence there is a considerable difference between properties calculated with spectral data and those calculated with the total glazing properties.

2.2 Building Simulation

A building energy analysis simulation program must be able to simulate the intrinsic dynamic behavior of switchable windows. The studies listed in Table 1 generally conclude that switchable windows warrant further development based on their promising reduction of energy use in residential and commercial buildings. All the building energy studies listed, except those using DOE-2.1(B,C,D), modelled the windows as switching between two states: bleached and colored. While this approach is adequate for thermochromic devices that switch between a clear, bleached state and a diffusing, colored state, it ignores the capability to vary the properties of electrochromic and photochromic devices between the bleached and colored states. Thus, they are inadequate for detailed energy and daylighting analyses of electrochromic and photochromic technologies.

Those studies employing the DOE-2.1 building energy simulation program use functions to simulate the behavior of the switchable windows. (A function is essentially an algorithm that is included in the input file along with the rest of the building specifications. See the DOE-2.1 instruction manual—1989.) Without functions, DOE-2 can model switchable windows as switching between an on and an off state. With functions, DOE-2 can model windows as having properties that vary between two states.

Table 1

AUTHORS	APPLICATION	PROGRAM
Donald Neeper, Et al. (1982)	Residential	SLR Method
S. Selkowitz, et al. (1983)	Commercial	DOE-2.1B
P. Coutier, et al. (1983)	Both	BLAST 3.0
W. Shadis (1983)	Both	EASE
William Bartovics (1983)	Commercial	1)
Bryant, et al. (1984)	Commercial	
R. Johnson, et al. (1985)	Commercial	DOE-2.1C
R. Rauh, et al. (1986)	Characterization	
Donald Neeper (1986)	Review of Technology	
Thomas Potter, et al. (1986)	Optimization	
H. Fine, et al. (1988)	Residential	ESPRE2)
S. Selkowitz (1989)	Review	
Nan Ruck, et al. (1989)	Commercial	DOE-2.1C
Susan Reilly, et al. (1991)	Characterization	WINDOW
Susan Reilly, et al. (1991)	Commercial	DOE-2.1D
Jeff Warner, et al. (1992)	Commercial	DOE-2.1D

(1) Used SUNPULSE data and a 4-node thermal network to simulate the building
(2) EPRI Simplified Program for Residential Energy.

Examples of two such functions are included in Appendix A. Example 1 is for an electrochromic window whose visible transmittance changes in response to the illuminance level at a reference point in an office of a building. The visible transmittance is adjusted to provide 540 lux (50 footcandles) at the reference point. As illuminance level increases, the visible transmittance decreases. Electric lighting supplements daylighting when the incoming daylight with the electrochromic in its maximum transmitting state is insufficient to meet the illuminance requirements. On days of high outside luminance, the illuminance level at the reference point can be exceeded even when the electrochromic window is in its minimum transmitting state. In this function, the corresponding shading coefficient (measure of solar heat gain) is calculated from the visible transmittance. The linear relationship between the properties was determined from the properties of the electrochromic window in its maximum and minimum transmitting states.

Example 2 is for a thermochromic window which switches between its clear state and its diffuse state in response to temperature. The thermochromic glazing serves as the center layer in a triple-pane window, thereby insulating the thermochromic layer from the highly changeable inside and outside environmental conditions. The temperature of the thermochromic glazing, as a function of environmental conditions, was found using WINDOW 3.2 (1989), and this relationship is incorporated into the DOE-2 function. If the temperature of the thermochromic layer exceeds 18°C the window switches to its diffuse state, and if it drops below 18°C it switches to its clear state.

While the thermochromic and photochromic glazing dictate the control strategy used for the switchable window, the electrochromic window lends itself to control based on a multitude of building and environmental parameters. The example above describes integration of the electrochromic window into the lighting system. Other possibilities include modulating the window properties in response to insolation levels, room temperature, peak load conditions, equipment operation, any combination of the above, and by any measured variable in a building automation system. This area has yet to be explored and deserves more attention as research continues on electrochromic glazing.

III. PROPOSED MODELING APPROACHES

3.1 Window System Properties

Major revisions of WINDOW and VISION have recently been completed. WINDOW 4.0 provides for a more detailed input of the window elements—glazing, frame members, and dividers, extends the library capabilities of WINDOW versions 3.1 and 3.2, has the same spectral data utility as WINDOW 3.2, and incorporates an updated angular function algorithm (Furler, 1991), and includes an environmental conditions library so that the calculations can be performed under different standards.

VISION changes include the incorporation of the glass thermal conductance into the heat transfer calculations, revised convection correlations to match those used in WINDOW 4.0, and a more user-friendly interface. The program is written in C and has graphical output. Presently the program has no spectral-averaging capabilities, although this change is planned for the near future.

3.2 Building Simulation

In order to capture the short-term (hourly, daily) influence of switchable windows on building energy-use patterns, building energy analysis simulation programs must not only accurately represent the window but need to perform detailed thermal calculations on the window which account for the effect of changing environmental conditions on the heat transfer and solar gain through the window. Preliminary studies with DOE-2 have shown that for a conventional window, predictions for annual energy consumption are comparable for the version using the detailed thermal and optical calculations for the window and the version using the constant heat transfer coefficient and shading coefficient approach. However, differences +/– 30% are often seen with hourly calculations (Winkelmann, 1991).

The recently modified DOE-2 (version 1.E) incorporates the WINDOW thermal and optical algorithms. The new version includes an extensive library of windows created using WINDOW and an option for modelling switchable windows directly. The user chooses two different windows from the window library as the bounding states of the switchable window. DOE-2 uses the detailed thermal and optical calculations on the window. This method replaces the previous constant heat transfer and shading coefficient approach using functions. Appendix B includes the description of the option and examples from the DOE-2 Users Manual (LBL, 1992).

IV. FUTURE

As the interest in switchable windows grows, the number of methods for modelling the windows increases. The detailed model recently built into DOE-2 (version 1.E) provides a good basis from which to develop new approaches. The DOE-2.1E version requires further validation work, and future studies within the International Energy Agency may wish to address this. Concurrently, a database containing the optical data for existing electrochromic glazing is being created at Lawrence Berkeley Laboratory (Mike Rubin, 1991). The data could serve as input to WINDOW or VISION and DOE-2.1E for the analysis of actual systems.

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APPENDIX A - SWITCHABLE WINDOW ALGORITHMS

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These algorithms are written in the form of DOE-2 functions. For details on DOE-2 terminology refer to the DOE-2 documentation.

ELECTROCHROMIC GLAZING

The following algorithm is used for simulating electrochromic windows which respond to the level of daylight in a zone. The electrochromic window is characterized by a line with the shading coefficient defined as a function of the visible transmittance. The equation of the line is found from the maximum and minimum shading coefficients and visible transmittances corresponding to the clear and colored states of the electrochromic glazing. The function FNANGS fixes the visible transmittance to maintain 50 footcandles in a zone and finds the shading coefficient

(GSHACOE = SLO*NEWVT + BINT)

where GSHACOE is the shading coefficient, SLO is the slope of the line, NEWVT is the visible transmittance, and BINT is the value of the shading coefficient when the visible transmittance is zero.

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ELECTROCHROMIC (1)
ILLUMINANCE CONTROL

```
$ PARAMETERS VARIED FOR EACH RUN $

NPANES = 2
WWR = .001           $ WINDOW/WALL RATIO 0 .15 .30 .45 .60 $
SILLHT = 5.5         $ SILL HEIGHT 5.5  4.6  3.7  2.8  1.9 $
UWALL = .09          $ OPAQUE WALL U-VALUE FOR EACH WWR $
SC = .57             $ SHADING COEFFICIENT $
VISTRAN = .58        $ VISIBLE TRANSMITTANCE $
SLOPE = .90          $ FOR DAYLIGHT FN TO CALC SC $
BINTER = .05         $ FOR DAYLIGHT FN TO CALC SC $
GLASCON = .25        $ GLASS CONDUCTANCE $


SET-DEFAULT  FOR WINDOW  Y = SILLHT
                         WIN-SHADE-TYPE = NO-SHADE
                         DAY-X-DIVISION = 10
                         DAY-Y-DIVISION = 8
                         WINDOW-SPEC-FN = *FNANGS* $
                         ..
SET-DEFAULT  FOR SPACE  DAYLIGHTING = DAYLT
                        LIGHT-REF-POINT1 = (5,10,2.5)
                        LIGHT-REF-POINT2 = (5,5,2.5)
                        ZONE-FRACTION1 = 1.0
                        ZONE-FRACTION2 = 0.0
                        LIGHT-SET-POINT1 = 50
                        LIGHT-SET-POINT2 = 50
                        LIGHT-CTRL-TYPE1 = LCTYP1
                        LIGHT-CTRL-TYPE2 = LCTYP1
                        LIGHT-CTRL-STEPS = LCSTPS
                        MIN-POWER-FRAC = 0.1
                        MIN-LIGHT-FRAC = 0.00001
                        DAYL-ILLUM-FN = (*FNANGS*,*FNANGS*)
                        ..


FUNCTION  NAME = FNANGS
      ..

ASSIGN  SLO = SLOPE  BINT = BINTER
        IPRDFL = IPRDFL  DAY = IDAY  MON = IMO  SPACE = IZNM  SC0 = SC
        HR = ISCHR  GSHACOE = GSHACO-EDTT  VT0 = VISTRAN
        DILL1 = DAYLIGHT-ILLUM1  LSP1 = LIGHT-SET-POINT1  NEWVT = VIS-TRANS
        WKDAY=ISCDAY ZNUM = IZNUM
        SUNUP = ISUNUP

        FNTYPE=FNTYPE
        ..

     CALCULATE  ..

     IF((FNTYPE .GT. 1.).AND.(FNTYPE .LT. 5.))RETURN
     IF(FNTYPE .GT. 6.)RETURN
```



```
 150  VISTRAN = VT0
```

```
      IF (FNTYPE.EQ.O.) RETURN

      IDILL1 = DILL1
      LFTOVER = DILL1-LSP1
      IF (IPRDFL.GT.0.) GO TO 33
C     PRINT 20,VT0,IDILL1,LSP1,LFTOVER,SC0
 20   FORMAT (1X,4HVT0=,F4.2,2X,7HIDILL1=,F5.0,2X,5HLSP1=,F3.0,2X,
     $        18HLFTOVER=,F5.0,2X,4HSC0=,F4.2,2X,10HDAYLTSETPT)
 33   IF (LFTOVER.LE.0.) GO TO 66
      NEWVT = LSP1*VISTRAN/DILL1
      DILL1 = LSP1
      GSHACOE = SLO*NEWVT+BINT
 66   IF (IPRDFL.GT.0.) RETURN

C     IF ((HR.LT.6.).OR.(HR.GT.21.)) RETURN
C     PRINT 10,SPACE,MON,DAY,HR,DILL1,NEWVT
 10   FORMAT (1X,6HSPACE=,A4,2X,6HMONTH=,F3.0,2X,4HDAY=,F3.0,2X,3HHR=,
     $        1F3.0,2X,6HDILL1=,F3.0,2X,6HNEWVT=,F4.2)

      IF((HR.LT.8.).OR.(HR.GT.18.).OR.(SUNUP.EQ.0))RETURN
      IF((WKDAY.LT.2.).AND.(WKDAY.GT.6.))RETURN
      IF(MON.EQ.LMON)GO TO 77
      PRINT 60,LMON,PERC1,PERC2,PERC3,PERC4,PERC5,PERC6,HRSUM
 60   FORMAT(2X,7HMONTH= ,F3.0,7F8.0)


 61   FORMAT(2X,7HMONTH= ,F3.0,8H SPACE= ,A4,7F8.0)

 88   CONTINUE


  200 RETURN

      END

END-FUNCTION ..
```

THERMOCHROMIC GLAZING

The following algorithm is used for simulating a triple-pane window with a center, thermochromic layer. A thermochromic glazing is either in a clear or colored state depending on the temperature of the thermochromic layer. The behavior of the window under varying environmental conditions was first modeled in the WINDOW program. It was found that the greatest variation in the temperature of the thermochromic layer depended on the outside windspeed (WNDSPD). So, the algorithm interpolates the temperature of a clear and colored thermochromic layer (TCLR, TCOL respectively) for the existing windspeed. It then compares this with the switching temperature of the thermochromic layer and fixes the state of the thermochromic layer accordingly.

```
      SET-DEFAULT  FOR GLASS-TYPE  VIS-TRANS = VISTRAN  ..
      SET-DEFAULT  FOR WINDOW  Y = SILLHT
                               WIN-SHADE-TYPE = WINSHADE
                               VIS-TRANS-SCH =ROLLOVTSCH
                               SHADING-SCHEDULE=ROLLOSCSCH
                               DAY-X-DIVISION = 10
                               DAY-Y-DIVISION = 8
                               FUNCTION = (*TCANGS*,*TCANGS*)
                               WINDOW-SPEC-FN = *TCANGS* $
                               ..


FUNCTION  NAME = TCANGS
          LEVEL = WINDOW ..

ASSIGN
        FNTYPE=FNTYPE
        DBT=DBT   WNDSPD=WNDSPD  SHADF=SHADING-FLAG
        IPRDFL=IPRDFL   JJ=IHR   DAY=IDAY  MON=IMO     SPACE=IZNM
        MR=MR    MWI=MWI   ETA=ETA
        GSHACOE=GSHACO-EDTT
        RR=RDIR          HR=ISCHR
        RDIF=RDIF
        WKDAY=ISCDAY ZNUM = IZNUM
        ..

      ..
ASSIGN
      TCCLRTAB = TABLE (0.0,7.4)(5.83,6.8)(13.04,6.3)
      ..
ASSIGN
      TCCOLTAB = TABLE (0.0,11.9)(5.83,11.2)(13.04,10.3)
      ..

      CALCULATE  ..

      IF((FNTYPE.EQ.2.) .OR. (FNTYPE .GT. 6.))RETURN


C         THERMOCHROMIC MODEL
  150 IF(FNTYPE .EQ. 1)GOTO 180
      IF((MON .EQ. 1).AND.(HR .LT. 6).AND.(DAY .EQ. 1))SHADF=1
      IF((MON .EQ. 1).AND.(HR .LT. 6).AND.(DAY .EQ. 1))SH1CNT=0
      IF((MON .EQ. 1).AND.(HR .LT. 6).AND.(DAY .EQ. 1))SH2CNT=0
      IF((MON .EQ. 1).AND.(HR .LT. 6).AND.(DAY .EQ. 1))SHDHR=0
      QTOT = RR + RDIF
C TSET IS 64.4 F
      TSET = 64.4
      DBTM = (DBT-32.0)*5./9.
      TBM = 0.71*DBTM + 6.8
      TBASE = TBM * 1.8 + 32.0
      TCLR = PWL(TCCLRTAB,WNDSPD)
      TCOL = PWL(TCCOLTAB,WNDSPD)
      IF(SHADF .EQ. 1)TSOL=TCLR
```

```
      IF (TTC .GT. TSET)SHADF=2
      IF(TTC  .LT.  TSET)SHADF=1

      IF((HR.LT.6.).OR.(HR.GT.21.))SHADF=1

      IF((FNTYPE.EQ.0.0) .OR. (FNTYPE .EQ. 4.0))RETURN

  180 IF((HR.LT.8.).OR.(HR.GT.18.))RETURN
      IF((FNTYPE.EQ.3.).AND.(SHADF.EQ.1))SH1CNT=SH1CNT+1
      IF((FNTYPE.EQ.3.).AND.(SHADF.EQ.2))SH2CNT=SH2CNT+1
      IF(FNTYPE .EQ. 3.)SHDHR=SHDHR+1
      IF((MON.EQ.12).AND.(DAY.EQ.31).AND.(HR.EQ.18))
     $ PRINT 11,SHDHR,SH1CNT,SH2CNT
   11 FORMAT(2X,6HSHDHR=,F8.0,2X,7HSH1CNT=,F8.0,2X,7HSH2CNT=,F8.0)
C
C     PRINT 12,SPACE,MON,DAY,HR,DBT,TTC,SHADF
C  12 FORMAT(1X,6HSPACE=,A4,2X,6HMONTH=,F3.0,2X,4HDAY=,F3.0,2X,3HHR=,
C    $1F3.0,2X,5HTOUT=,F5.2,2X,4HTTC=,F5.2,2X,6HSFLAG=,F4.1)

  200 RETURN

      END
```

APPENDIX B - SWITCHABLE WINDOW MODELING IN DOE-2.1E

SWITCHABLE GLAZING

In DOE-2.1E a model has been added for switchable glazing. This is glazing whose solar-optical properties, such as transmittance, can change according to environmental conditions. An example is electrochromic glass that can be switched from a clear to a colored state by changing the applied voltage in response to a control variable such as outside temperature or solar radiation. Switchable glazing has the potential for a higher level of solar gain control than is possible with conventional glazing having fixed solar-optical properties.

To model switchable glazing the user enters the glass type for the unswitched state, the glass type for the fully switched state, the control variable, the switching set points, and a schedule that tells when switching is allowed. Figure 2.25 shows the control action that DOE-2 uses for all control options except SWITCH–CONTROL = DAYLIGHT–LEVEL.

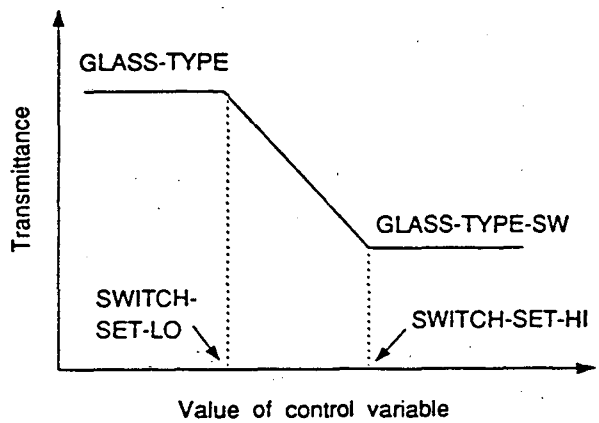

Figure 2.25: Control action for switchable glazing. Glass properties, such as solar transmittance, depend on the value of a user-specified control variable.

If the value of the control variable is less than SWITCH–SET–LO, the glass is in the *unswitched* state, with solar-optical properties given by GLASS–TYPE. If the control variable is greater than SWITCH–SET–HI, the glass is in the *fully switched* state, with solar-optical properties given by GLASS–TYPE–SW. If the control variable is between SWITCH–SET–LO and SWITCH–SET–HI, the glass is in a *partially switched* state, with solar-optical properties given by a weighted average of GLASS–TYPE and GLASS–TYPE–SW. For example, if T_1 and T_2 are the direct solar transmittances for GLASS–TYPE and GLASS–TYPE–SW, respectively, and V is the value of the control variable in a particular hour, then the resultant transmittance is $T = T_1 * S + T_2 * (1 - S)$, where S, the "switching factor", is calculated by the program according to:

$$S = 1.0, \text{ if } V \leq \text{SWITCH–SET–LO}$$

$$S = \frac{(\text{SWITCH–SET–HI}) - V}{(\text{SWITCH–SET–HI}) - (\text{SWITCH–SET–LO})}, \quad \text{if } (\text{SWITCH–SET–LO}) < V < (\text{SWITCH–SET–HI})$$

$$S = 0.0, \text{ if } V \geq \text{SWITCH–SET–HI}$$

Hourly values of S for each window are printed by hourly report VARIABLE-TYPE = u-name of WINDOW, Variable-List Number 18.

For daylit spaces, a different control scheme can be used by specifying SWITCH-CONTROL = DAYLIGHT-LEVEL. In this case, the visible transmittance of the window is modulated between unswitched and fully switched values in order to provide daylight illuminance that is as close as possible to the illuminance setpoint at the first reference point. This type of control is a way of avoiding unwanted solar gain during the cooling season.

As of this writing (March 1992), the Window Library does not yet contain specific electrochromic products since they are still in the experimental stage. For now, runs with switchable glazing are made by choosing conventional glazings from the Window Library to represent the unswitched and switched states. Actual electrochromic examples will be added to the Window Library in the future.

WINDOW

GLASS-TYPE — accepts the u-name of the glass type for the *unswitched* state. For switchable glazing, glass types *must* be chosen from the Window Library. These glass types have GLASS-TYPE-CODE ≥ 1000 (see "New Window Library" p.2.89).

GLASS-TYPE-SW — accepts the u-name of the glass type for the *fully switched* state. For switchable glazing, glass types *must* be chosen from the Window Library. These glass types have GLASS-TYPE-CODE ≥ 1000 (see "New Window Library"). An error will result if the number of glass layers is different for GLASS-TYPE and GLASS-TYPE-SW.

SWITCH-CONTROL — accepts a code-word that specifies the control variable for switching. The choices are:

- *NO-SWITCH* — No switching (the default).
- *DIR-SOL-INC* — Direct solar incident on the glazing (W/m^2) after shading by overhangs, setback, neighboring buildings, etc.
- *TOT-SOL-INC* — Total (direct plus diffuse) solar radiation incident on the glazing (W/m^2) after shading by overhangs, setback, neighboring buildings, etc.
- *DIR-SOL-TR* — Direct solar radiation transmitted by the glazing in the unswitched state (W/m^2).
- *TOT-SOL-TR* — Total (direct plus diffuse) solar radiation transmitted by the glazing in the unswitched state (W/m^2).

In the left column above, bold-faced words are commands, non-bold words are keywords, and italicized words are code-words.

TOT-SOL-HOR	Total (direct plus diffuse) solar radiation incident on an unobstructed horizontal plane (W/m^2).
OUTSIDE-TEMP	Outside drybulb temperature (°F).
SPACE-LOAD	Previous-hour thermal load per square foot of floor area for the space that contains the window (W/m^2 [floor area]). Note that cooling loads in DOE-2 are positive and heating loads are negative. Switching control based on space load should be modeled only if the actual space temperature for hours that the control is in effect is within a few degrees of the LOADS calculation temperature (as given by the TEMPERATURE keyword in SPACE-CONDITIONS).
DAYLIGHT-LEVEL	The visible transmittance of the glazing is adjusted continuously between the values corresponding to GLASS-TYPE and GLASS-TYPE-SW in order to provide a daylight illuminance that is as close as possible to the illuminance setpoint at the first daylighting reference point. The solar properties of the glazing are adjusted accordingly. For this control option, an error will result if the visible transmittance (at normal incidence) for GLASS-TYPE is greater than that for GLASS-TYPE-SW.

SWITCH-SET-LO	is the lower setpoint value for the control variable (see Fig. 2.25). Unused if SWITCH-CONTROL = DAYLIGHT-LEVEL.
SWITCH-SET-HI	is the upper setpoint value for the control variable (see Fig. 2.25). Unused if SWITCH-CONTROL = DAYLIGHT-LEVEL. SWITCH-SET-HI should be ≥ SWITCH-SET-LO.
SWITCH-SCH	accepts the u-name of a schedule the specifies when switching is allowed (schedule value = 1) and not allowed (schedule value = 0). This schedule allows switching to be disabled at times of the day or year when it might be disadvantageous. If SWITCH-SCH is not entered, the program will assume that switching is allowed all the time.

Notes:

(1) If there is more than one window in a space, some may have switching control and others not. For example, skylights might be controlled and view windows not. Also, multiple windows in a space can have different control types.

(2) Switching control is applicable only to exterior windows (windows in EXTERIOR-WALLs). It does not work for interior windows.

(3) Switching control is in effect only during sun-up hours. It does not work at night. It should not be used to switch between window U-values; use the WINDOW keyword

CONDUCT-TMIN-SCH instead.

(4) Shading devices such as blinds and drapes (as specified with WINDOW keywords SHADING-SCHEDULE, VIS-TRANS-SCH, etc.) can be used in conjunction with switching control of the glazing. In this case, the program decides what state the glazing should be switched to, ignoring the possible presence of shading devices, and then adjusts the solar intensity through the switched glazing for the presence of the shading device. For example, if MAX-SOLAR-SCH is used to deploy a shading device when the transmitted direct solar gain exceeds a trigger value, the program will first apply the switching control to the glazing and then calculate the transmitted solar intensity based on the solar properties of the switched glass.

Example (1):
During the summer, the outer pane of insulating glass switches from clear to fully tinted over a range of 20 to 100 Btu/ft^2-h of incident solar radiation.

```
$ --- SWITCHING CONTROLLED BY INCIDENT SOLAR DURING THE SUMMER --- $

CLEAR-IG-1   = GLASS-TYPE  GLASS-TYPE-CODE = 2003 ..

TINTED-IG-1  = GLASS-TYPE  GLASS-TYPE-CODE = 2203 ..

SUMMER-1    = SCHEDULE   THRU MAY 31 (ALL)(1,24)(0) $ no switching $
                         THRU SEP 30 (ALL)(1,24)(1) $ switching ok $
                         THRU DEC 31 (ALL)(1,24)(0) $ no switching $ ..

WIN-1 = WINDOW   GLASS-TYPE        = CLEAR-IG-1
                 GLASS-TYPE-SW     = TINTED-IG-1
                 SWITCH-CONTROL    = TOT-SOL-INC
                 SWITCH-SET-LO     = 20
                 SWITCH-SET-HI     = 100
                 SWITCH-SCH        = SUMMER-1
                 .
                 .
                 .
                 ..
```

Example (2):
For a window in a daylit space, the visible transmittance is adjusted to a value between 0.78 and 0.38 during the summer so that the resulting daylight illuminance is as close as possible to the illuminance setpoint. At other times of the year, the switching does not occur.

```
        $--- SWITCHING  CONTROLLED  BY DAYLIGHT  ILLUMINANCE --- $

SUMMERONLY-1        = SCHEDULE         THRU MAY 31 (ALL)(1,24)(0) $ no switching $
                                       THRU SEP 30 (ALL)(1,24)(1) $ switching ok $
                                       THRU DEC 31 (ALL)(1,24)(0) $ no switching $ ..

CLEAR-IG-1          = GLASS-TYPE       GLASS-TYPE-CODE = 2003 .. $ Tvis=.78 $

GREY-IG-1           = GLASS-TYPE       GLASS-TYPE-CODE = 2215 .. $ Tvis=.38 $

WIN-2 = WINDOW      GLASS-TYPE         = CLEAR-IG-1
                    GLASS-TYPE-SW      = GREY-IG-1
                    SWITCH-CONTROL     = DAYLIGHT-LEVEL
                    SWITCH-SCH         = SUMMERONLY-1
                    .
                    .
                    .
                    ..
```

Example (3):
The glazing switches from clear (shading coefficient = 0.81) to reflective (shading coefficient = 0.17) when the space has a cooling load the previous hour (i.e., when the previous-hour space load is greater than zero).

```
    $--- SWITCHING  CONTROLLED  BY  SPACE  LOAD  ALL  YEAR --- $

CLEAR-IG-1 = GLASS-TYPE    GLASS-TYPE-CODE = 2003 .. $ SC=.81 $

REFL-IG-1 = GLASS-TYPE     GLASS-TYPE-CODE = 2400 .. $ SC=.17 $

ALLYEAR-1 = SCHEDULE       THRU DEC 31 (ALL)(1,24)(1) ..

WIN-3 = WINDOW      GLASS-TYPE         = CLEAR-IG-1
                    GLASS-TYPE-SW      = REFL-IG-1
                    SWITCH-CONTROL     = SPACE-LOAD
                    SWITCH-SET-LO      = 0
                    SWITCH-SET-HI      = 0
                    SWITCH-SCH         = ALLYEAR-1
                    .
                    .
                    .
                    ..
```

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