INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

Thermochromic Switchable Glazing Modeling

A report of Task 12: Building Energy Analysis and Design Tools for Solar Applications
Subtask A: Model Development
Subtask A.1: High Performance Glazings

October 1993

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Glazing Modeling
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FhG iBP
Fraunhofer-Institut
für Bauphysik

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Task 12:	Building Energy Analysis and Design Tools for Solar Applications
Subtask A:	Model Development
Subgroup 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 (OECD). 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 Parties (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 areas 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
Austria
Federal Republic of Germany
Greece
Norway
Spain

Belgium
Canada
Denmark
Commission of the European Communities
Italy
Japan
Netherlands
New Zealand
Sweden
Switzerland
United Kingdom
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 -
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 Meteorological 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 Building -
U.S. Department of Energy (Completed).

Task 9	Solar Radiaton and Pyranometry Studies - KFA Jülich, Federal Republic of Germany (Completed).
Task 10	Solar Materials R&D-AIST, Ministry of International Trade and Industry, Japan (Completed).
Task 11	Passive and Hybrid Solar Commercial Building-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 - KFA, Jülich, Germany (Ongoing).
Task 17	Measuring and Modelling Spectral Radiation Affecting Solar Systems and Buildings - KFA, Jülich, Germany (Ongoing).
Task 18	Advanced Glazing Materials - U.K. Department of Energy (Ongoing).
Task 19	Solar Air Systems in 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 solar energy related materials, components and systems within 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, Finland, Federal Republic of Germany, Norway, Spain, Sweden, Switzerland, and the United States. The United States serves as Operating Agent for this Task. Michael Holtz of Architectural Energy Corporation serves as the Operating Agent on behalf of the U.S. Department of Energy.

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, Model Development, Subgroup A1, High-Performance Glazing, of Task 12 of the IEA Solar Heating and Cooling Program. The participants believe that thermochromic switchable glazing systems hold considerable promise, and that algorithms to accurately model their dynamic behavior are needed.

The purpose of this task was to develop algorithms for incorporation into a building energy analysis simulation tool for predicting the thermal and optical performance of thermochromic switchable glazing systems. The algorithms introduced in this report will make it possible to determine the interaction between thermochromic switchable glazing systems and a building's temperature behavior. These algorithms may be integrated into any building energy analysis simulation tool computing a building's energy balance on the basis of hourly climatic data sets. In doing so, it is a prerequisite that when considering solar gains from transparent building parts hourly variable optical material behavior may be included (incident angle-dependent absorption and transmission). The structure of computation and the algorithms underlying the subroutine presented in Annex D, are explained and presented in detail. Annex B contains an algorithm which allows to predict the effects thermochromic switchable glazings are likely to have on a building's daylighting performance. In the following, various simulation results are given which will illustrate the application of thermochromic switchable glazing system as a variable solar control device for optimizing the performance of a transparent insulation system. These results suggest thermochromic switchable systems to be highly efficient in avoiding material damage due to overheating.

Based on the results of the present study, the ideal switching temperature was derived to be set at 35 °C for average German climate conditions. This temperature will ensure optimum use of solar energy in winter, keeping the transparent materials from clouding too early as a result of the cover glazing's solar heating. For other climatic regions, further parametric studies will have to be run in order to determine respective optimum clouding temperatures. A building's energy efficiency cannot be substantially increased by applying thermochromic switchable glazing as compared to conventional shading devices.

The developed approaches correct some of the shortcomings in the existing techniques, and could be adapted for use in other similar programs. The developed approaches generally provide more detailed calculations needed for evaluating the short-term (hourly and daily) impact of thermochromic switchable glazing systems on the energy and daylighting performance of a building.

Thermochromic Switchable Glazing Modeling

Contents

Appendices A and B

1 Introduction

Modern glass architecture, including the trend to more articulate facades with window art design, enhances the quality of life by supplying living and working rooms with more daylight and view. On the other hand, the risk of overheating becomes critical and requires optimum solar control. Solar control is usually by heavily tinted glass or high performance glazings - low-emissivity, with the disadvantage of reduced passive solar utilization for displacing auxiliary heating energy. Solar control by building construction shading elements (e.g. horizontal overhangs, sidefins) is sufficient only for controlling direct solar radiation. During summertime, diffuse solar radiation in combination with an increased window surface area can result in high thermal loads requiring some additional shading devices like blinds and louvers. In some instances, self-regulating solar screens would be an ideal solution. A new approach incorporates solar control within the glazing element by varying the glazing's solar transmittance properties. There are two different types of glazing available for modulating the desired solar gains and associated daylighting properties, namely

- electrical voltage (electrochromic glazing)
- glazing surface temperature (thermochromic glazing).

Such systems are also known as 'smart' window systems. This report concentrates on describing ways of modelling thermochromic glazing systems and how integration of these models into a building energy analysis simulation program can be accomplished.

Several developments of thermochromic glazing systems according to [1], [2], [3] have been carried out. Commercial applications of these developments could not be asserted because of too limited material durability. A development according to [4] is promising to avoid this disadvantage by using a gel of organic polymers [5] which is placed in a layer of 0.3 mm thickness between two glass panes. As the switching setpoint temperature can be adjusted, variable shading is made possible which allows for a wide spectrum of applications.

2 Solar Concept

To demonstrate the thermochromic solar concept, a thermochromic glazing system according to [4] is used as an example. A gel of organic polymers [5] called TALD (Temperaturabhängige Lichtdurchlässigkeit = Temperature dependent Light transmittance) is placed between two cover glass panes. This gel will switch from a transparent into a clouded state and in reverse depending on a gel setpoint temperature which can be adjusted. In Figure 1 the two situations are illustrated.

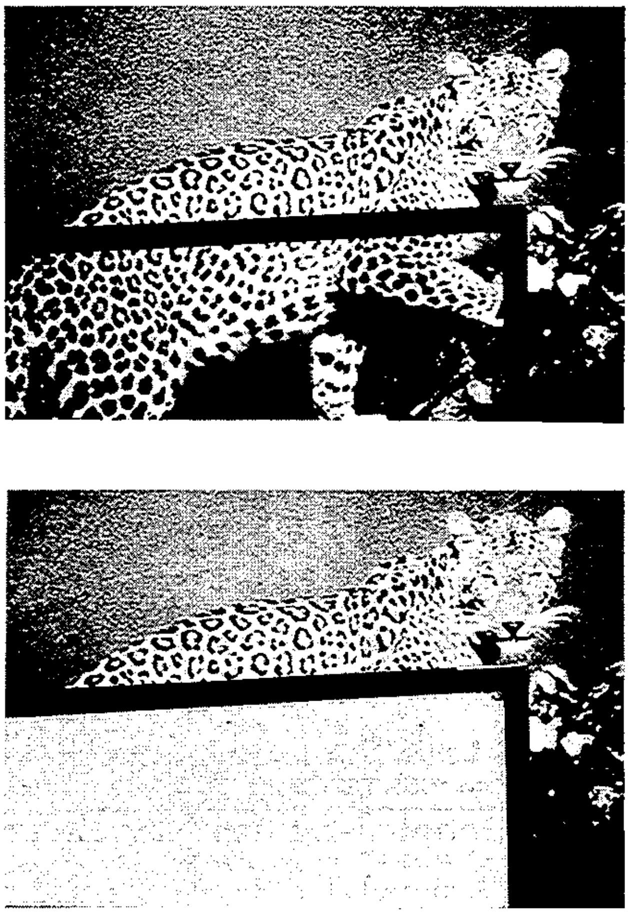

Fig. 1: Example of a TALD pane in both transparent and clouded state (at a higher temperature).

The variable and reversible solar shading effect as presented in Fig. 1, is achieved by way of two different reactions:

(1) <u>Temperature-dependent control of water soluble filamentary macromolecules</u>

In the transparent state the macromolecules are completely dissolved in water in the form of long chains. In this state their diameter is smaller than the wavelength of light. With increasing temperatures molecular chains begin to expand, thereby exceeding the light wavelength dimensions. A clouding effect occurs due to the refraction of light by chain particles.

The 'clouding point' temperature can be controlled and adjusted with an accuracy of 1.5 K within a range of 9 °C to 90 °C. A schematic drawing of this first clouding mechanism is presented in Fig. 2.

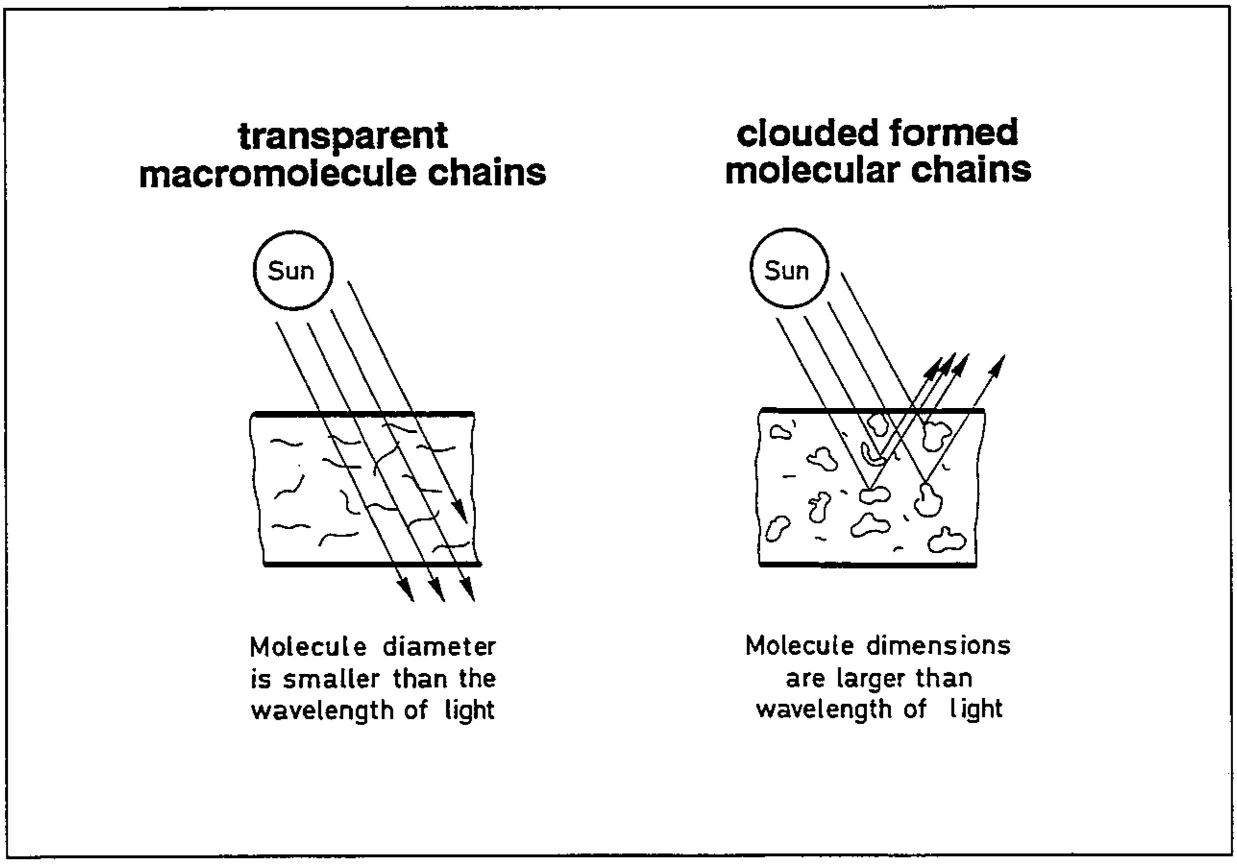

Fig. 2: Schematic drawing of the first shading effect (clouding mechanism) depending on the temperature expanded molecular dimensions.

(2) Temperature-dependent release of polar bound water solution

The wetting agents within the gel contain water due to polar interaction. With increasing temperature the polar bound water is released and forms a highly light-diffusing dispersion of minute droplets within the gel. This process is also reversible. By adding different substances to the gel, its properties can be adjusted in such a way that the setpoint temperature at which water will be set free can be controlled. The principle of this second shading effect (clouding mechanism) is shown in Fig. 3.

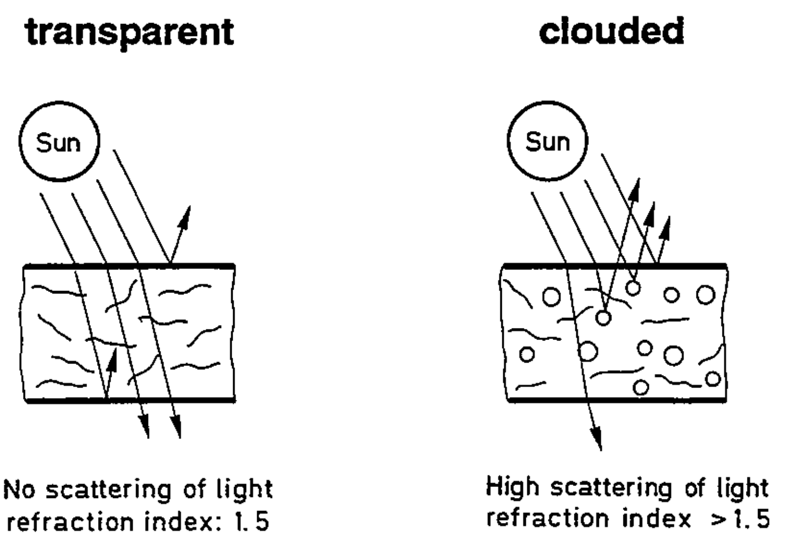

Fig. 3: Schematic drawing of the second shading effect (clouding mechanism) of a thermochromic system (TALD), triggered by increasing temperature. Polar bound water of wetting agents is released and forms a highly light-diffusing dispersion of minute droplets.

The combination of these two mechanisms is the characteristic feature of the TALD thermochromic system and has been proven in durability tests. The effects TALD reaction gel has on the interaction of solar reflection, absorption and transmission is illustrated in a cross section of a TALD system (see Fig. 4).

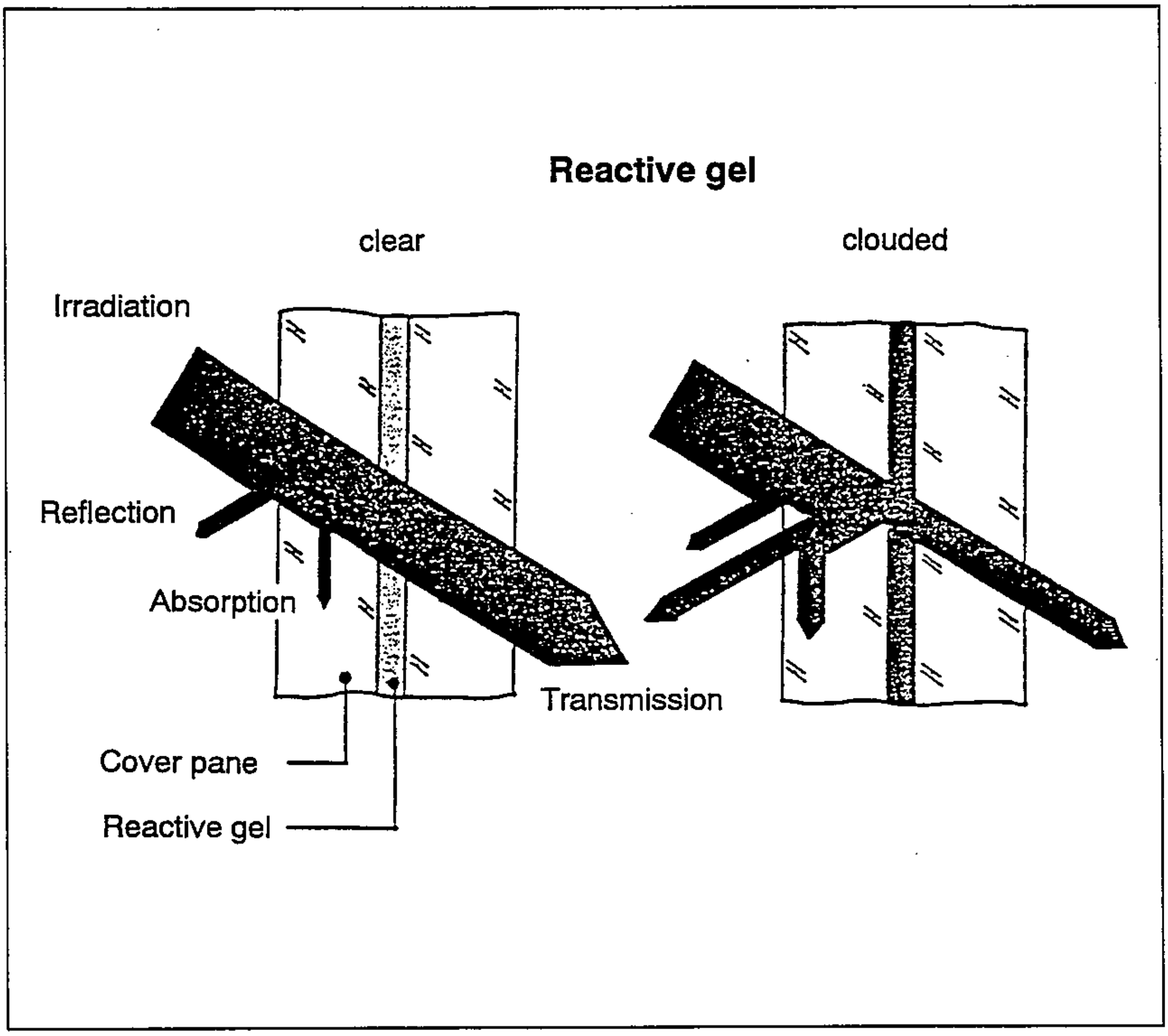

Fig. 4: **Cross section of a thermochromic TALD system with a schematic drawing of the relations of solar reflection, absorption and transmission as influenced by TALD reaction gel.**

3 Areas of Application

Thermochromic switchable systems can be applied to transparent facade areas (windows, glazings) as well as to mass walls.

TRANSPARENT INSULATION FACADES

If transparent thermal insulation (see also [6]) is applied to exterior walls, the insulating effects are enhanced by additional heat gains from solar radiation. Such a system is appropriate for moderate and cold climates with strong solar radiation. A glazing–integrated thermochromic switchable shading device will reduce maintenance costs effectively, because no service of mechanical elements like roller blinds or slatted blinds is necessary. Such service is cost intensive for large facade areas where scaffolds are needed to reach the mechanical shading elements.

With the present state of the art, and due to cost–effectiveness considerations, it is recommended that transparent thermal insulation with integrated thermochromic switchable shading devices be applied if large frame elements of uniform size can be used, namely

(1) to reduce the portion of wall surface covered by frames, which do not produce an energy gain area and have a lower insulating effect,

(2) to lower construction costs through mass production.

Commercial buildings which often have large windowless facade areas, frequently meet those conditions. Due to their visual aspect, many industrial buildings are often given the label "shoebox–architecture". In the industrial sector, energy considerations play only a small role since the price of energy is included in the price of the products. Under such conditions, it is not a miracle that a waste of energy takes place in many commercial buildings. If, for reasons of image, steps are taken to improve the visual aspect of facades, transparent thermal insulation together with a variable self–regulating clouding effect on the exterior surface should also be considered.

AGRICULTURE

The use of self-regulating thermochromic switchable shading devices in greenhouses has two evident advantages:

(1) painting or handling of mechanical shading elements is not necessary;

(2) increased diffuse light transmittance through clouded panes will stimulate plant growth.

COLLECTOR COVERING

Although overheating in case of loaded storage elements occurs rarely, some simple low-cost solar control is needed.

4 Physical Properties of Thermochromic Switchable Material

In the following, a detailed exemplary description of a material according to [5] will be given. The thermochromic switchable material (TALD) is a gel of organic polymers, which contains polyether compounds with ethylene oxide groups, mixed with wetting agents compiled of 5 - 10 ethylene oxide groups within a molecule. Additionally, carboxyvinyl co-polymers with a molecular weight in a range of 250,000 - 4,000,000 are included. The result is a stiff and stable gel with a freezing point temperature below -50 °C. TALD is chemically stable, resistant to ultra-violet radiation and stable in light. Glass surfaces act as sequestering agents with the gel. During use it has to be prevented from drying out. Layers of less than 1 mm thickness are sufficient to achieve optimum shading (clouding) effects.

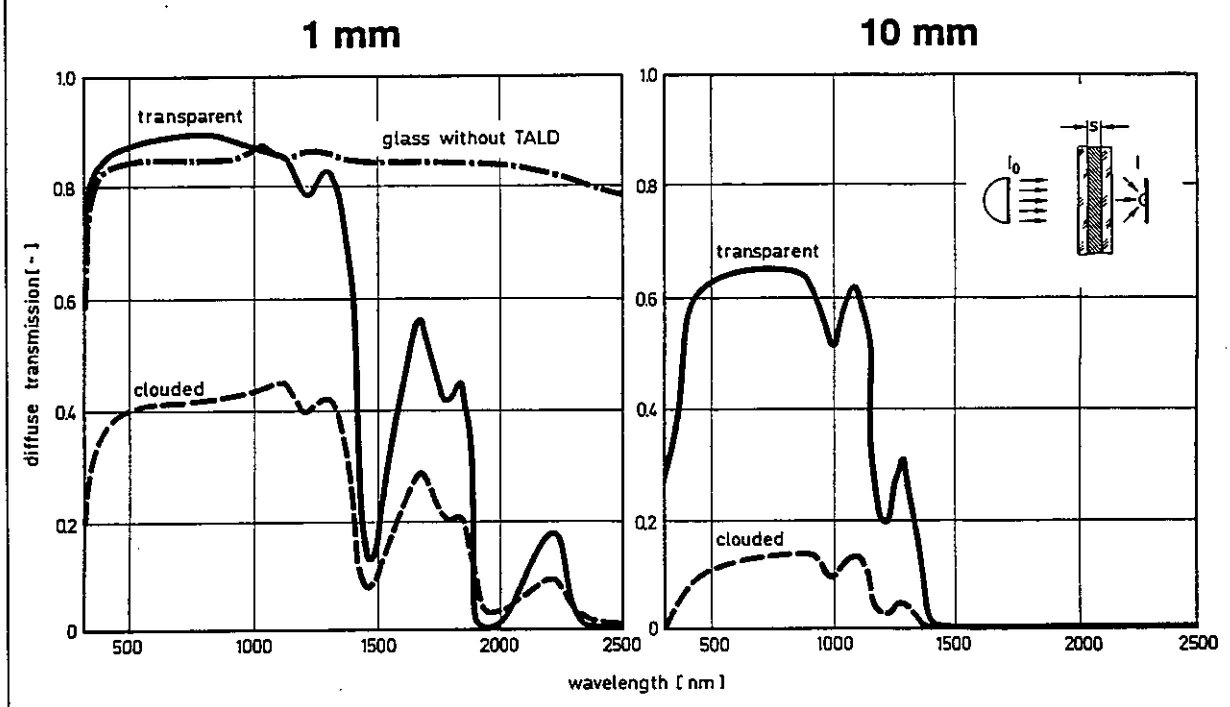

Fig. 5: Diffuse transmission properties of TALD systems with 1 mm (left) and 10 mm (right) layers of thermochromic switchable gel, dependent on wavelength [nm]

The diffuse transmission properties of a TALD system with a 1 mm (see graphs on left side) and a 10 mm (graphs on right side) layer of thermochromic switchable gel are presented in Fig. 5, depending on wavelength [nm] .

A surprising effect occurs:

- in the visible range of solar radiation (< 1000 nm) the diffuse transmission of a TALD glazing system is higher than that of a normal glazing without TALD.

With a TALD layer of 10 mm, diffuse light transmission is reduced by 25 %. The transparent gel has a refraction index of 1.43 [–] and an extinction coefficient of 0.14 mm^{-1}. In the clouded state the direct transmission is lower than 4 % at a layer thickness of only 0.3 mm. Solar transmittance normal to glass surface of 0.35 [–] and an absorption of 0.40 [–], according to [4], have been monitored for test examples of 0.3 – 1.0 mm TALD layers placed between panes of floatglass (at adjusted switch setpoint temperatures in a range of 23 °C to 30 °C).

TALD is a non–toxic, biodegradable and physiologically neutral material. It is also fungus neutral, i.e. it does not provide a nutrient medium for fungal growth.

5 Monitoring Results

Solar transmission normal to glass surfaces has been monitored for different thicknesses of the thermochromic switchable gel layers in transparent and clouded states. The switching point temperature was set to 23 °C. In Fig. 6, the results are plotted versus wavelength in the range from 200 - 900 m.

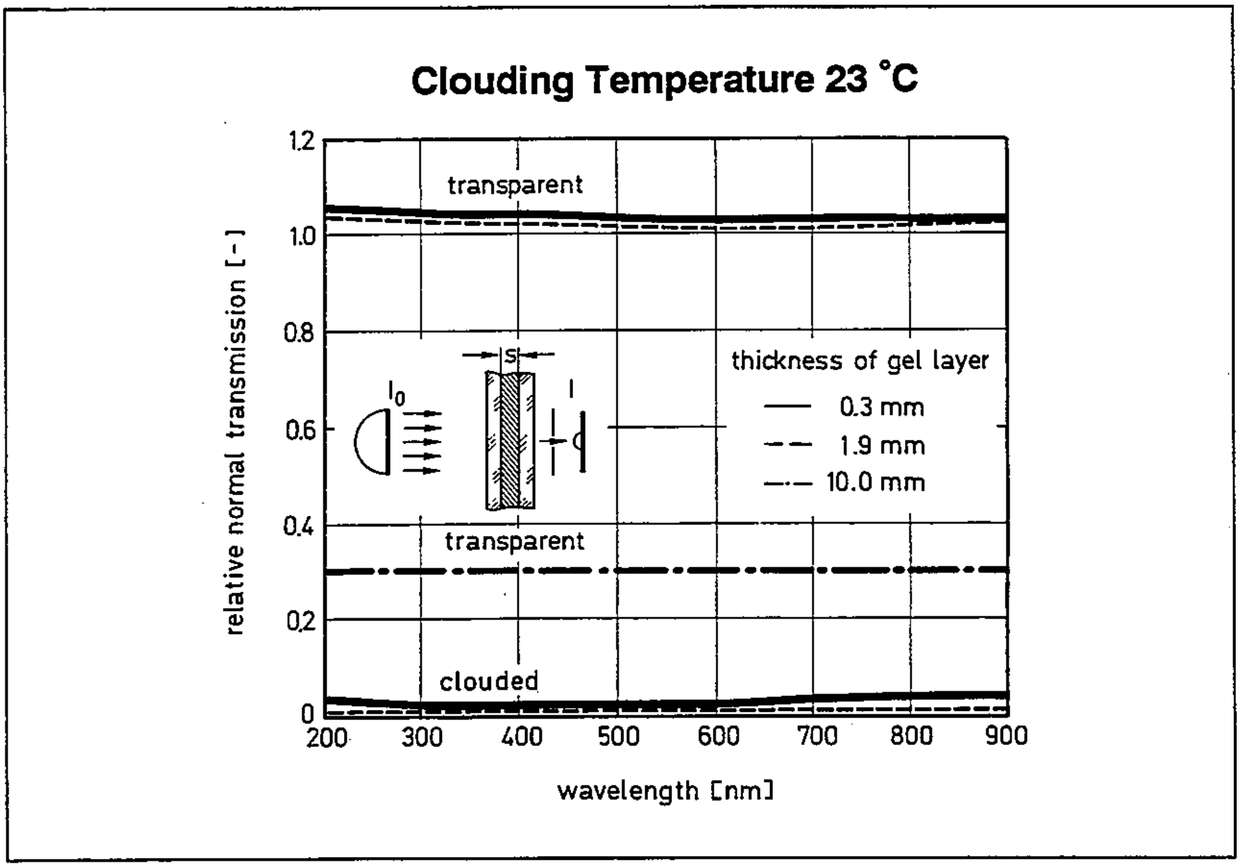

Fig. 6: Relative normal solar transmission of TALD glazing system in transparent and clouded states for varied gel layer thickness.

In Fig. 7 TALD's spectral diffuse solar transmission in the clouded state is contrasted with the performance of commonly available silicate glazing and solar protection glazing (i.e. gold-tinted and low-emissivity glazing). In relation to these glazing types the shading properties of TALD appear very favourable.

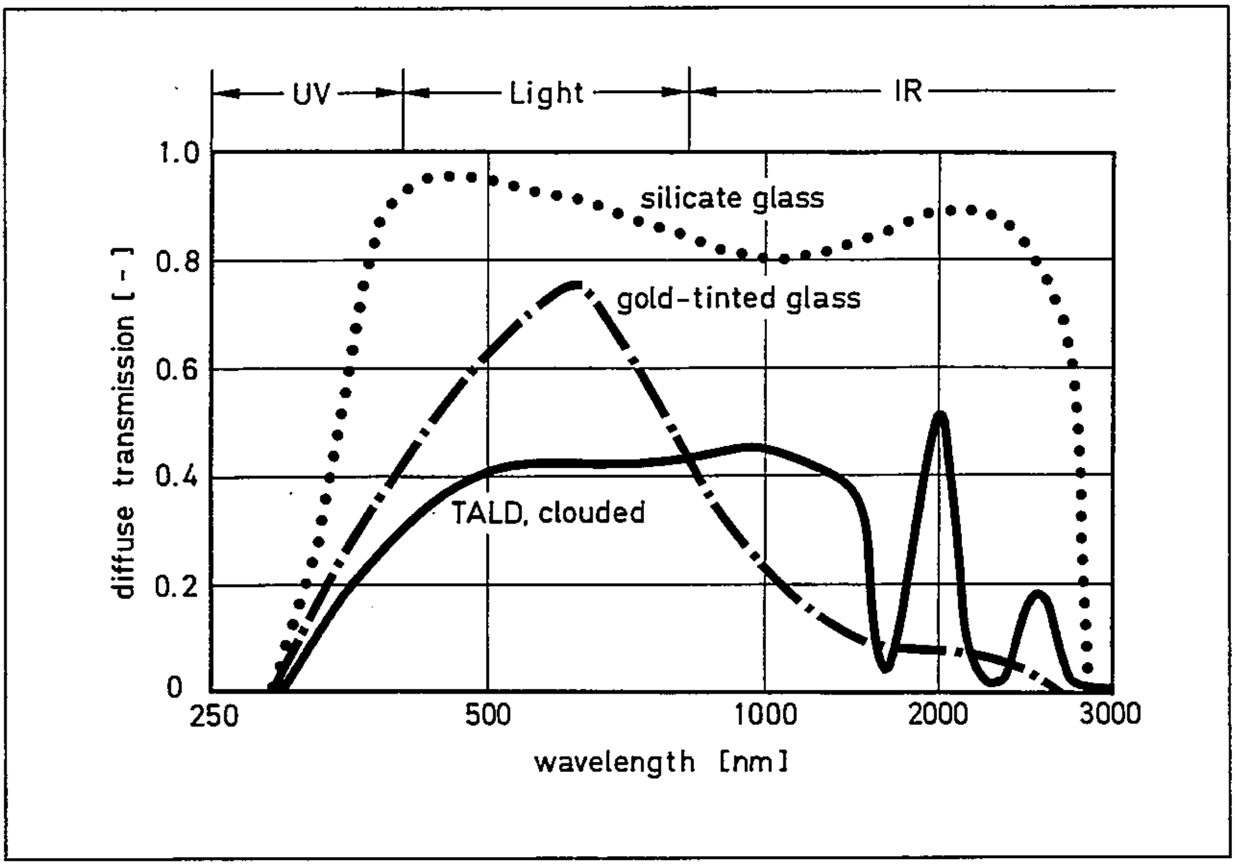

Fig. 7: Comparison of TALD 's spectral diffuse transmission with solar control glazings (gold-tinted, low-emissivity glazing) and with silicate glass.
Legend : ... silicate glass; -.- gold-tinted glass;
--- TALD, clouded.

The advantage offered by solar control glazings in summer will become a disadvantage during the heating period as over 50 % of solar gains are reduced together with a reduction of daylight transmittance by 34 %.

Here, the advantage of a thermochromic glazing system is impressive:

- during summer and winter periods optimum optical and energetic properties are provided according to gel type and internal loads (lights, equipment, number of people).

6 Simulation of Thermochromic Switchable Glazing

6.1 Thermochromic switchable glazing system in transparent state

From the view of physical theory, the sunshading effect of a thermochromic switchable glazing system, based on a reversible reactive gel placed within two glass panes, is similar to that of a double glazing system with an air gap in between. The physical mechanisms of such a system are illustrated in Fig. 8.

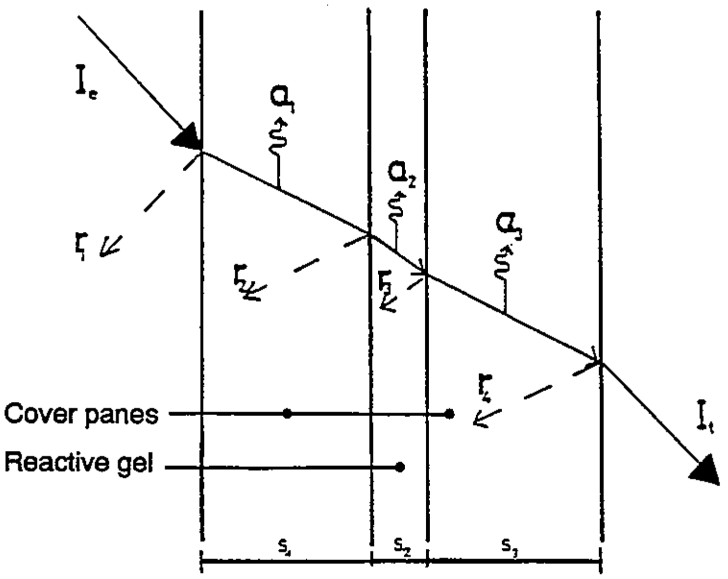

Fig. 8: Schematic drawing of a double glazing system with an included thermochromic reversible reaction gel, illustrating the physical effects of radiative transmission through transparent layers with different materials.

The difference in using the thermochromic reaction gel instead of an air gap is that the extinction coefficient of the gel is not equal zero and the refractive index is not equal 1.0. The simulation of radiation transfer through different media is based on

FRESNEL'S equations. An example of direct radiation transfer through a single glass pane is given in Fig. 9.

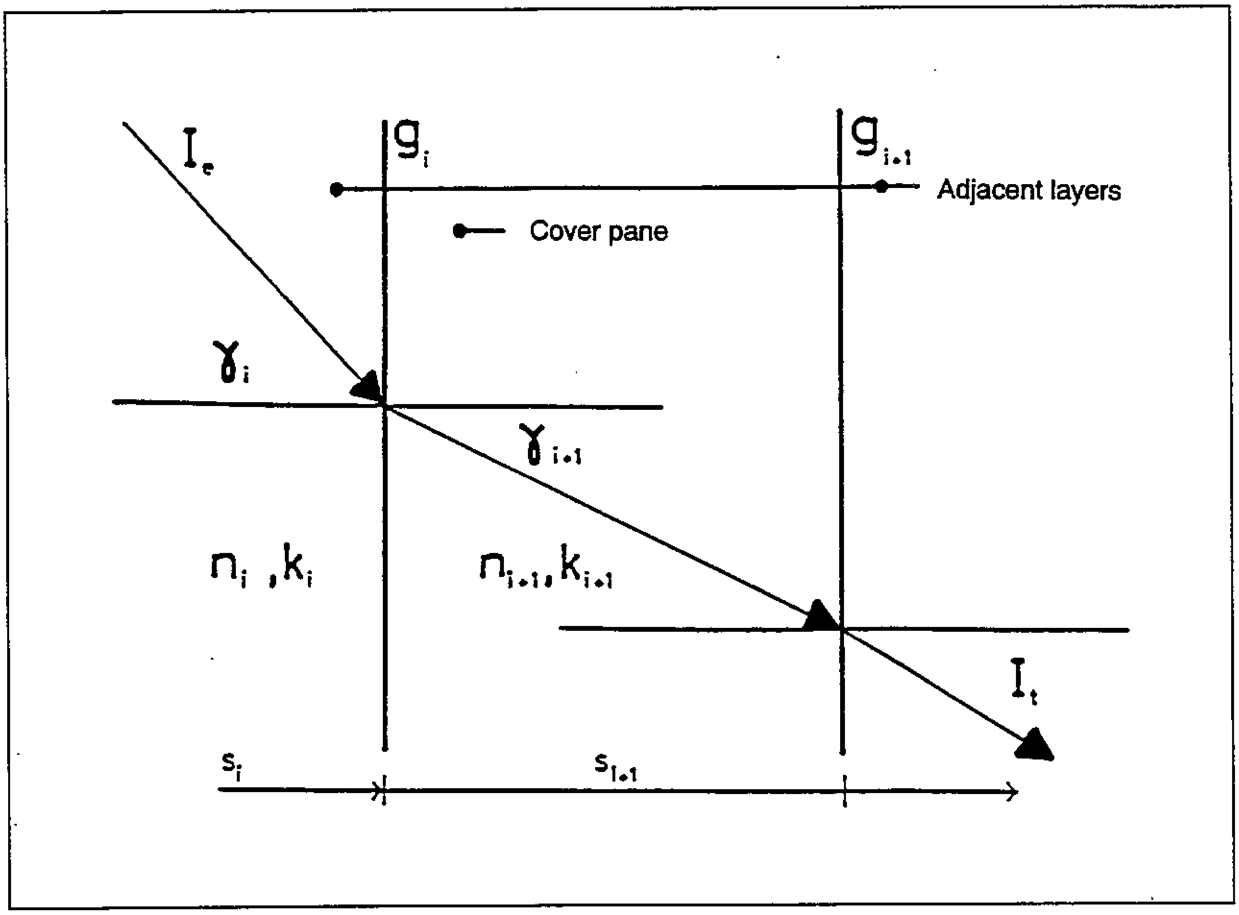

Fig. 9: Principle drawing of direct radiation transfer through a single glass pane.

Light transmission through a boundary plane (t_{bi}) is expressed by:

$$t_{bi} = \frac{4 \cdot n_{i+1} / n_i}{(1 + n_{i+1} / n_i)^2} \qquad [-]$$

with

n : index of refraction
i : number of medium

Light transmission through a layer of same medium :

$$t_{i+1} = e^{-k_{i+1} \cdot s_{i+1}} \qquad [-]$$

with

k : extinction coefficient [1/mm]
s : thickness of layer [m]

If angle of incidence γ is not equal zero then vertical (—⊥—) and parallel (| |) components of radiation vector are considered separately :

$$tbi(\perp) = \frac{n_{i+1} \cdot \cos\gamma_{i+1} \cdot (2 \cdot \sin\gamma_{i+1} \cdot \cos\gamma_i)^2}{n_i \cdot \cos\gamma_i \cdot (\sin(\gamma + \gamma_{i+1}))^2} \qquad [-]$$

$$tbi(\,|\,|\,) = \frac{n_{i+1} \cdot \cos\gamma_{i+1} \cdot (2 \cdot \sin\gamma_{i+1} \cdot \cos\gamma_i)^2}{n_i \cdot \cos\gamma_i \cdot (\sin(\gamma + \gamma_{i+1}) \cdot \cos(\gamma_i - \gamma_{i+1}))^2} \qquad [-]$$

Light transmission through a layer of same medium :

$$t_{i+1} = e^{-k_{i+1} \cdot s_{i+1} / \cos\gamma_{i+1}}$$

The interaction of multiple reflections at boundary planes can be summarized by way of convergent infinite geometric sums to:

Reflection factor ρ_{si}

$$\rho_{si} = r_{bi} + \frac{t_{bi} \cdot t_{bi+1} \cdot r_{bi+1} \cdot t^2_{i+1}}{1 - (r_{bi+1} \cdot t_{i+1})^2} \qquad [-]$$

with

r_{bi} : reflection at boundary plane i [–]
r_{bi+1} : reflection at boundary plane i+1 [–]

Transmission factor τ_{si}

$$\tau_{si} = \frac{t_{bi} \cdot t_{bi+1} \cdot t_{i+1}}{1 - (r_{bi+1} \cdot t_{i+1})^2} \qquad [-]$$

Absorption factor α_{si}

$$\alpha_{si} = \frac{(1 - t_{bi}) \cdot t_{bi}}{1 - (r_{bi+1} \cdot t_{bi+1})^2} \qquad [-]$$

The thermochromic sunshading effect by interaction of multiple reflections at boundary planes within a three layer system is illustrated in Fig. 10.

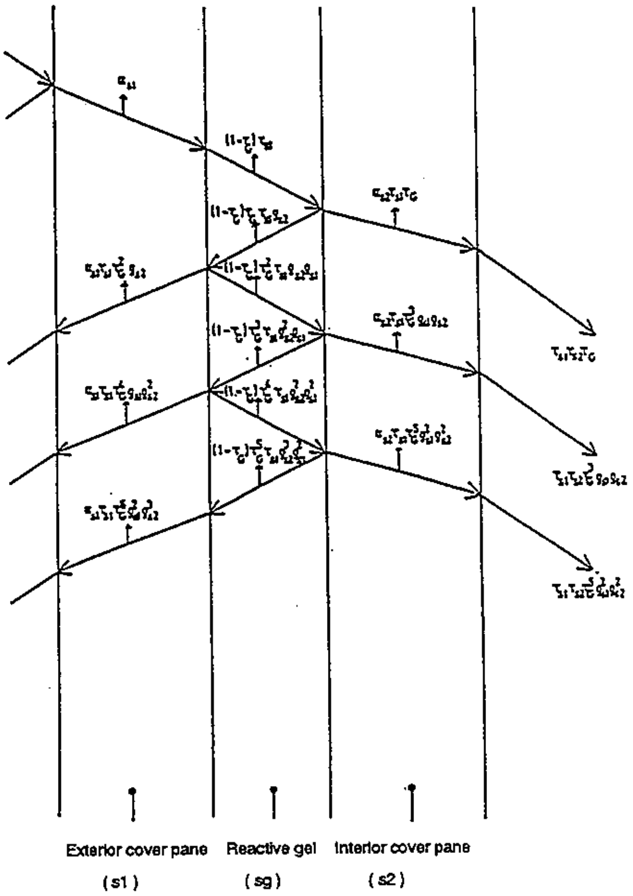

Fig. 10: Schematic drawing of the thermochromic sunshading effect by interaction of multiple reflections at boundary planes within a three-layer system.

For such a three–layer system, the interaction of terms at boundary planes and within the layers can also be summarized by way of convergent infinite geometric sums to:

Total reflectance ρtot

$$\rho tot = \rho s1 + \frac{\rho s2 \cdot (\tau sg \cdot \tau s1)^2}{1 - \tau^2 sg \cdot \rho s1 \cdot \rho s2} \qquad [-]$$

Total transmittance τ_{tot}

$$\tau_{tot} = \frac{\tau_{sg} \cdot \tau_{s1} \cdot \tau_{s2}}{1 - \tau^2_{sg} \cdot \rho_{s1} \cdot \rho_{s2}} \qquad [-]$$

By determination of total absorptance, terms are summarized for each layer :

Total absorptance α_{ts1} of exterior cover pane (s1)

$$a_{ts1} = a_{s1} + \frac{\alpha_{s1} \cdot \rho_{s2} \cdot \tau_{s1} \cdot \tau^2_{sg}}{1 - \tau^2_{sg} \cdot \rho_{s1} \cdot \rho_{s2}} \qquad [-]$$

Total absorptance within reaction gel (sg) α_{tsg} [–]

$$\alpha_{tsg} = (1 - \tau_{sg}) \cdot \tau_{s1} \cdot \left[1 + \tau_{sg} \cdot \rho_{s2} \cdot \frac{(1 + \tau_{sg} \cdot \rho_{s2})}{(1 - \tau^2_{sg} \cdot \rho_{s1} \cdot \rho_{s2})} \right]$$

Total absorptance of interior glass pane (s2) α_{ts2}

$$\alpha_{ts2} = \frac{\alpha_{s2} \cdot \rho_{s2} \cdot \tau_{s1} \cdot \tau_{sg}}{1 - \tau^2_{sg} \cdot \rho_{s1} \cdot \rho_{s2}} \qquad [-]$$

where radiative transmission in reaction gel (t_{sg}) is expressed by :

$$\tau_{sg} = e^{-k_{sg} \cdot S_{sg}/\cos \gamma_{sg}} \qquad [-]$$

If the angle of incidence is unequal zero then at first the parallel (| |) and vertical (—┴—) components of the radiation vector are determined.

6.2 Thermochromic switchable glazing system in clouded state

The description of the reactive gel`s physical behaviour in its clouded state is based on monitored data of spectral transmission, reflection and absorption for different thicknesses according to [4]. These monitoring results show that the portion of transmitted radiation is almost totally diffuse scattered. The direct undiffused part of the transmitted radiation can be neglected.

The transmitted radiation is mainly influenced by the exterior cover pane. This fact is considered by an algorithm weighting the monitoring results for vertically incident direct radiation through the clouded thermochromic reactive gel with the radiative characteristics of the exterior cover pane.

According to [7] a simplified algorithm for determining the transmission behaviour of a pane subject to direct and diffuse radiation has been derived:

Direct irradiation

$$\tau_{DIR}(\gamma_i) \quad = \quad \tau_{DIR}(0°) \cdot (1 - (1 - \cos\gamma_i)^{\kappa}) \qquad [-]$$

with

$$\kappa \quad = \quad \frac{\ln(1 - \tau_{DIR}(60°) / \tau_{DIR}(0°))}{\ln(1 - \cos(60°))} \qquad [-]$$

Diffuse irradiation

$$\tau_{DIF} \quad = \quad \tau_{DIR}(0°) \cdot \frac{\kappa \cdot (3 + \kappa)}{(2 + \kappa) \cdot (1 + \kappa)} \qquad [-]$$

The transmission factors of the exterior cover pane for angles of incidence of 0° and 60° are calculated according to the equations given in section 6.1. The reaction gel's index of refraction is assumed to be equal in both its transparent and clouded state.

For direct non-vertical incidence the transmission and absorption factors of the thermochromic layer will decrease according to the angle-dependent reduction of the transmission factor of the exterior cover pane. For diffuse radiation the calculation procedure is analogous. Here, the transmission and absorption factors are computed from the difference of the exterior cover pane transmittances at direct, vertical, and diffuse irradiation. In both cases, the reduction in transmittance and absorptance will lead to an increase in reflectance in the thermochromic layer.

By considering the above equations, the following resultant terms for transmission, absorption and reflection are derived for a thermochromic layer in the clouded state:

Direct irradiation

Transmission factor of thermochromic layer in clouded state for direct radiation $\tau_{C,DIR}$:

$$\tau_{C,DIR} = \tau_{MES} \cdot \frac{\tau(\gamma i)_{DIR}}{\tau(0°)_{DIR}} \qquad [-]$$

with

τ_{MES} : transmission factor, measured for direct radiation vertical normal to thermochromic layer

Absorption factor of thermochromic layer in clouded state for direct radiation $\alpha_{C,DIR}$:

$$\alpha_{C,DIR} = \alpha_{MES} \cdot \frac{\tau(\gamma i)_{DIR}}{\tau(0°)_{DIR}} \qquad [-]$$

with

α_{MES} : absorption factor, measured for direct radiation vertical normal to thermochromic layer

Reflection factor of thermochromic layer in clouded state for direct radiation $r_{C,DIF}$

$$\rho_{C,DIR} = 1 - \alpha_{C,DIR} - \tau_{C,DIR} \qquad [-]$$

Diffuse irradiation

Transmission factor of thermochromic layer in clouded state for diffuse radiation $\tau_{C,DIF}$:

$$\tau_{C,DIF} = \tau_{MES} \cdot \frac{\tau_{DIF}}{\tau(0°)} \qquad [-]$$

with

τ_{MES} : transmission factor, measured for diffuse radiation vertical normal to thermochromic layer

Absorption factor of thermochromic layer in clouded state for diffuse radiation $\alpha_{C,DIF}$:

$$\alpha_{C,DIF} = \alpha_{MES} \cdot \frac{\tau_{DIF}}{\tau(0°)} \qquad [-]$$

with

a_{MES} : absorption factor, measured for diffuse radiation vertical normal to thermochromic layer

Reflection factor of thermochromic layer in clouded state for diffuse radiation $r_{C,DIF}$

$$\rho_{C,DIF} = 1 - \alpha_{C,DIF} - \tau_{C,DIF} \qquad [-]$$

These basic equations have been compiled into subroutines, which can be integrated in a building energy analysis simulation program. The subroutines, coded in FORTRAN 77, are listed in Appendix A. The subroutines have been extended by a feature to be able to calculate a combination of thermochromic switchable glazing systems with transparent insulation materials.

According to [8] an algorithm has been developed and incorporated in the WINDOW program for calculating window system properties by using spectral data. With this algorithm a triple–pane window with a central, thermochromic layer is simulated. It was found that the greatest variation in the temperature of the thermochromic layer depended on the outside windspeed (WNDSPD). The algorithm interpolates the temperature of a clear and colored thermochromic layer (TCLR,TCOL) for the existing windspeed. It then compares this value with the switching temperature of the thermochromic layer and fixes the state of the thermochromic layer accordingly. The source code of the algorithm according to [8] is listed in Appendix B.

7 Simulation Results

A parametric study [9] has been carried out to calculate the optimum setpoint temperature to switch from transparent to clouded state of the thermochromic reaction gel. Of special interest was the application of a thermochromic system in front of a mass wall with transparent insulation in order to replace mechanical shading devices.

The boundary conditions of the simulation study concerning material data of exterior wall constructions, transparent insulation and thermochromic sun protection are compiled in Tables 1 – 3. Indoor temperatures are set to constant 20 °C. Exterior climate is considered by using a test reference year hourly data set.

A compilation of results is presented in Figures 11 – 16.

Table 1: Compilation of material properties of the investigated wall constructions.

Physical Parameter	**Unit**	**Concrete**	**Limebrick**	**Claybrick (vertical gaps)**	**Porous Concrete**
Conductivity	W/mK	2.1	0.79	0.45	0.19
Density	kg/m^3	2400	1600	1000	600
Heat capacity	kJ/kgK	1.0	1.0	1.0	1.0
Thermal effusivity	Ws$^{1/2}$/m^{2}K	2245	1124	671	338

Table 2: Compilation of material properties of the investigated transparent insulation systems.

Physical Parameter	**Unit**	**Acrylic Foam (20 mm)**	**Capillary Structure (80 mm)**
Heat conductance	W/m^{2}K	1.0/ 1.75/ 3.5	1.0/ 1.75/ 3.5
Density	kg/m^3	35	35
Heat capacity	kJ/kgK	1.4	1.4
Transmissivity $g_I = 0°$	-	0.60	0.98

Table 3: Compilation of material properties of the investigated thermochromic switchable system.

Physical Parameter	**Unit**	**Cover panes (4 mm)**	**Reaction gel (0.3 mm)**
Heat conductance	W/m^2K	1.0/ 1.75/ 3.5	1.0/ 1.75/ 3.5
Density	kg/m^3	2500	1000
Heat capacity	kJ/kgK	1.0	4.187
Extinction coefficient	1/mm	0.025	0.14
Index of refraction	-	1.532	1.43
		Complete system	
Transmissivity clouded	-	0.35	
Reflectivity clouded	-	0.40	
Absorptivity clouded	-	0.25	

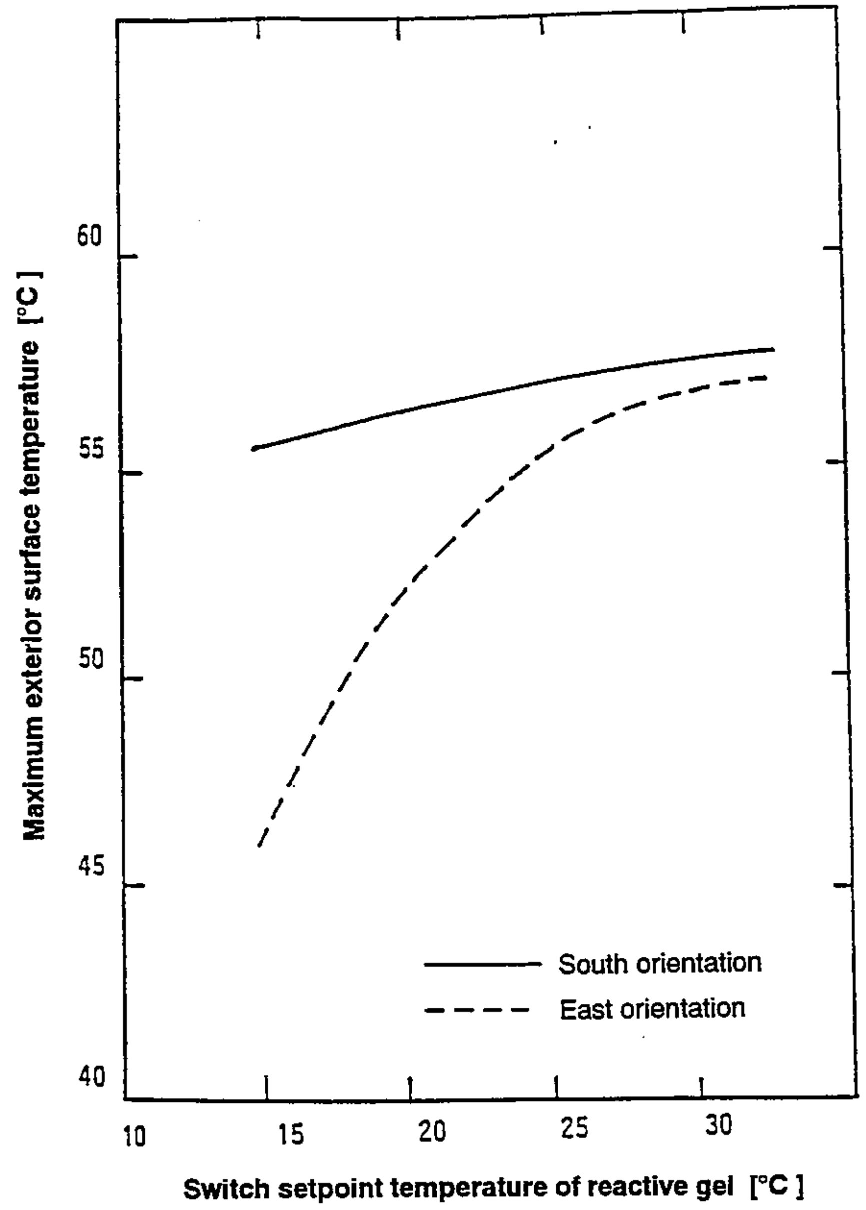

Fig. 11: Maximum exterior surface temperature of a 200 mm concrete wall covered with transparent insulation (capillary structure, $\Lambda = 1.0$ W/m^{2}K) versus a switch setpoint temperature range from 15 – 30 °C.

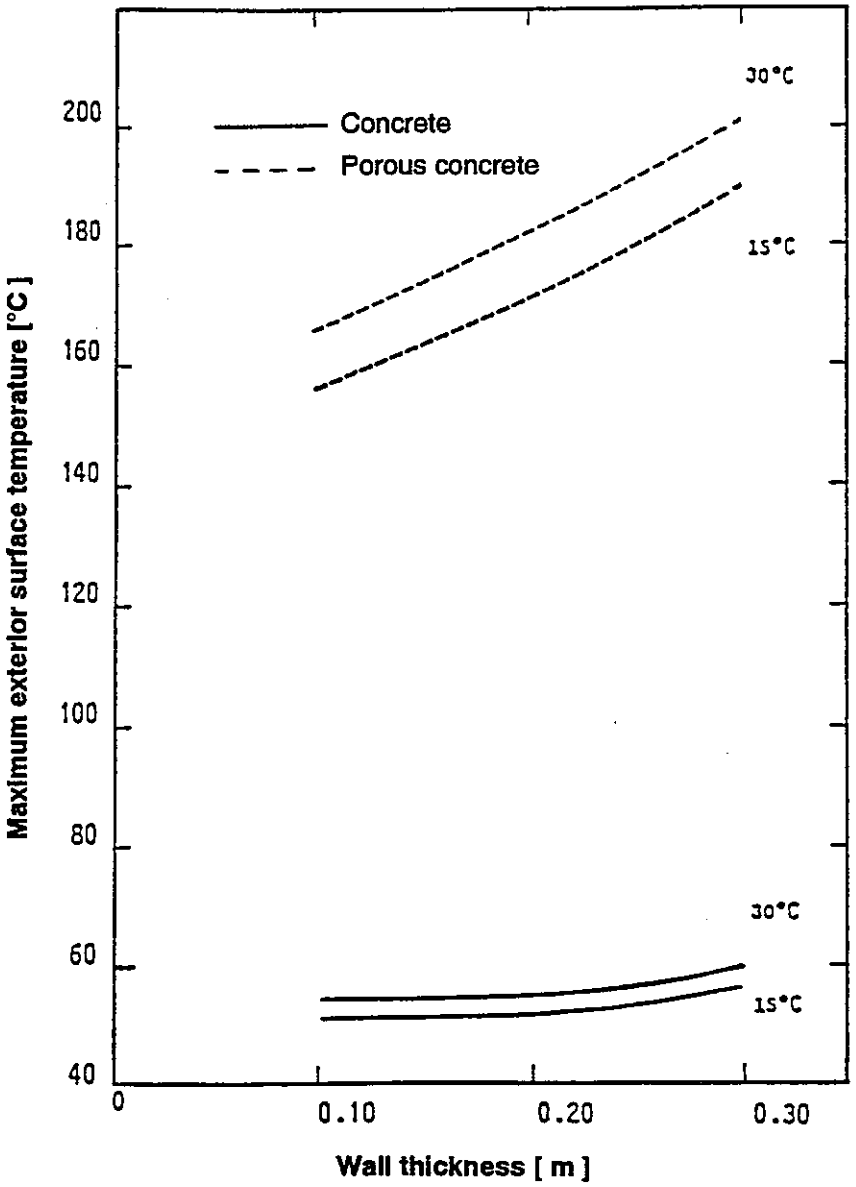

Fig. 12: Maximum exterior surface temperature of a south wall covered with transparent insulation (capillary structure, $\Lambda = 1.0$ W/m²K) versus wall thickness for two wall materials:

a. reinforced concrete

b. light porous concrete.

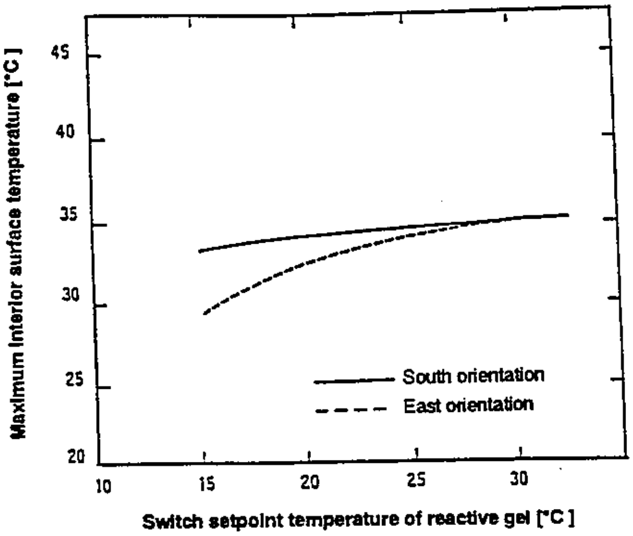

Fig. 13: Maximum interior surface temperature of a 200 mm concrete wall covered with transparent insulation (capillary structure, Λ = 1.0 W/m²K) versus a switch setpoint temperature range of 15 – 30 °C.

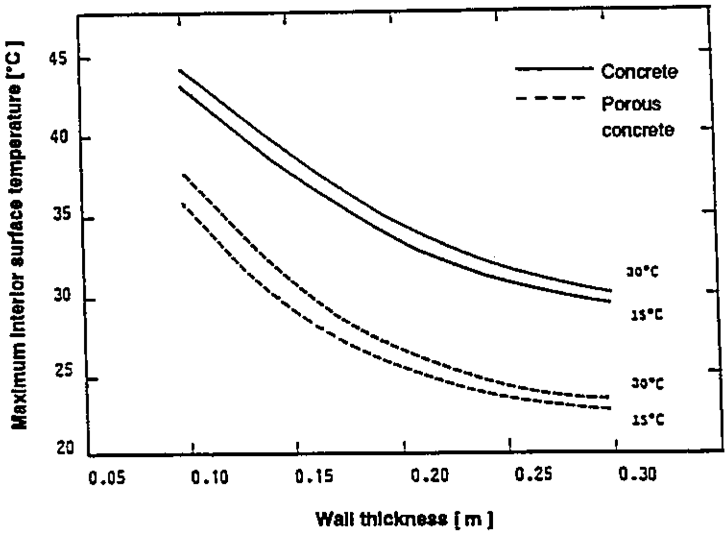

Fig. 14: Maximum interior surface temperature of a south wall covered with transparent insulation (capillary structure, Λ = 1.0 W/m²K) versus wall thickness for wall materials (a) reinforced concrete, (b) light porous concrete, for setpoint temperatures of 15 °C and 30 °C.

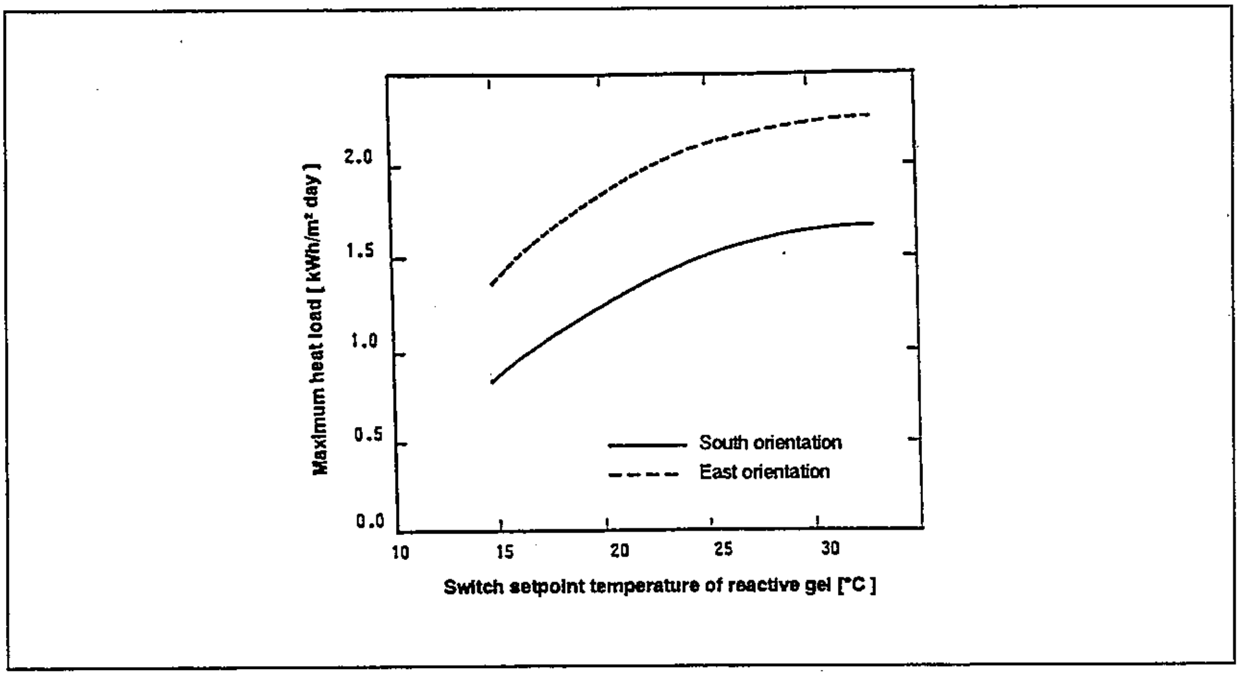

Fig. 15: Maximum heat load of a 200 mm concrete wall covered with transparent insulation (capillary structure, Λ = 1.0 W/m²K) versus a switch setpoint temperature range of 15 – 30 °C in a room of constant 20 °C.

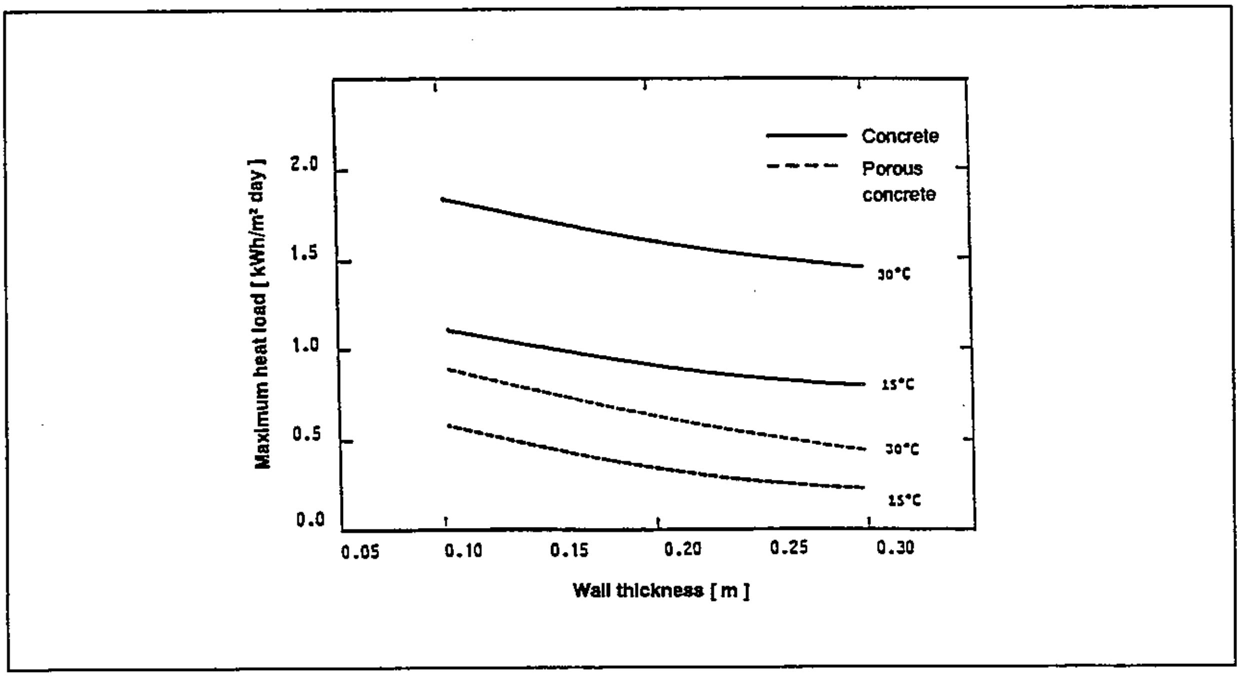

Fig. 16: Maximum heat load of a south wall covered with transparent insulation (capillary structure, Λ = 1.0 W/m²K) versus wall thickness for wall materials (a) reinforced concrete, (b) light porous concrete, switch setpoint temperatures of 15 °C and 30 °C, in a room of constant 20 °C.

8 Conclusions

Possible applications, physical properties and algorithms for modelling thermochromic switchable glazing systems have been described. As one example of the temperature and energy benefit of thermochromic switchable systems, results of a parametric sensitivity study have been presented for an application of high interest:

- thermochromic switchable shading of an exterior mass wall covered with transparent insulation.

The effect of thermochromic switchable glazing systems can be summarized as follows :

- The function of a thermochromic sunshading device is based on a reversible reaction gel which in its basic state is transparent.
- A switch setpoint temperature can be adjusted between 15 and 55 °C to change from transparent into a clouded state.
- With a thermochromic layer thickness lower than 1 mm, a substantial reduction of solar transmission is achieved.
- The thermochromic switching criteria are of special interest for passive utilisation of solar energy. During heating periods with low ambient temperatures, solar gains will displace the need for auxiliary energy.
- Thermochromic control of solar gains may reduce exterior wall temperatures by 50 K in lightweight facades with transparent insulation. With heavyweight construction, a reduction of 15 K will be achieved.
- For facade constructions with a thermal effusivity higher than 800 $Ws^{1/2}/m^2K$ in east/west orientation resp. 1000 $Ws^{1/2}/m^2K$ in a southern orientation, the maximum temperature behind the thermochromic layer will not exceed 80 °C.

- Solar control devices will succeed in preventing material destruction due to overheating, provided certain conditions are met, i.e. certain combinations of orientation and facade construction are given, namely:
    - east/west orientation of exterior walls made from building materials with a thermal effusivity higher than 700 $Ws^{1/2}/m^2K$
    - south orientation of exterior walls constructed from building materials with a thermal effusitvity exceeding 900 $Ws^{1/2}/m^2K$.

- For south orientations, switch setpoint temperatures in the range of 15 – 30 °C will have only minor influence on maximum indoor surface temperatures, while east orientation can bring about deviations of up to 5 K in the control range of the gel, and west orientation may even result in deviations of up to 8 K.

Further development of thermochromic switchable materials should concentrate on reducing the relatively high absorption within the thermochromic reaction gel.

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APPENDIX A

Heim, U :

Calculation of Required Switchable Set Point Temperature of Thermochromic Glazings Applied to Transparent Insulated Exterior Walls.

Subroutine TRANSPARENZ for calculating solar transmission of different transparent material structures (acrylfoam, aerogel, cell and cappillar structures) in combination with thermochrome switchable shading (TALD).

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```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      SUBROUTINE TRANSPARENZ(IOPAK,IW,PHI,NMAT,DMAT,EMAT,SYS,DIF,ABSW
     &                       ,TAUGS,ROGES,ABSGS,ABS4)
C
C     computes TALD system transmissions in angular dependency,
C     determining light transmission in both directions
C     (outside/inside and inside/outside)
C
C     Input :
C     -------
C
C     IOPAK     =  TALD switching control (1=opaque,0=transparent)
C     IW        =  number of wall
C     PHI       =  angle of incidence
C     NMAT      =  refractive indexes to air
C     DMAT      =  layer thickness
C     EMAT      =  layer extinction coefficients
C     SYS       =  system characteristics
C     DIF       =  control parameter for diffuse (0) or direct (1) radiation
C     ABSW      =  short-wave absorption coefficient of absorbing surface
C
C     Output :
C     --------
C
C     TAUGS     =  total transmission
C     ROGES     =  total reflection
C     ABSGS     =  layer absorption
C     ABSW      =  short-wave absorption coefficient of absorbing surface (corrected)
C     ABS4      =  additional absorption due to multiple reflection
C                  (assumed to be a heat source located at the interior surface
C                  of the second exterior glazing, as a detailed consideration appears
C                  negligible regarding the small quantity)
C
C
      PARAMETER(NW=4)
      CHARACTER*1 LDD
      REAL     PHI,NMAT(4),DMAT(4),EMAT(4),TAUGS(2),ROGES(2),ABSGS(2,4)
      REAL     RS(6),RP(6),TS(6),TP(6),N(4),ROS(2,4),TAS(2,4),ABSR(2,4)
      REAL     ROP(2,4),TAP(2,4),ABP(2,4),A(6),WI(6),RG(2),TG(2)
      REAL     AWI,PI,AG(2,3),RGS,TGS,AGS,KAPPA
      REAL     TAO(NW),XKP(NW),RODIFA(NW),TADIFA(NW)
      INTEGER SYS,DIF,ABSO,IT(3)
      COMMON /const1/ pi,pid1800,pid2,pid3,pid180,d3p6,d3600p
      COMMON  /LEGIS/LDD,tltdif(nw),tltdir(nw)
      COMMON  /OPAKTR/TLOTD(NW),TLORD(NW)
      COMMON /pmma/ pmmaa(4),pmmab(4),pmmac(4),pmmad(4)
      COMMON /aero/ aeroa(4),aerob(4),aeroc(4),aerod(4)
      COMMON /pchc/ pchcm(nw,3),pchcb(nw,3)
      COMMON /kapi/ akapm(nw,3),akapb(nw,3)
      COMMON /opak/ tg,ta0,td
C
C
      ROWA=1-ABSW
      IF(DIF.EQ.1) THEN
      WI(1)= pid3
      ELSE
        WI(1)=PHI
      END IF
C
```

```
C
C     Determining relative refractive indexes at boundary layers
C     ----------------------------------------------------------
C
      N(1)=NMAT(1)
C
C     Transparency properties in the opaque TALD range
C     ------------------------------------------------
C
      IF(IOPAK.EQ.1.AND.DIF.EQ.1) THEN
        AG(1,2)=1-TLOTD(IW)-TLORD(IW)
        AG(2,2)=AG(1,2)
        N(2)=1/N(1)
        DO 295 I=1,3
  295   IT(I)=1
C
C     Transparency of exterior glazing at PHI=0.0 dgr
C     ...............................................
C
        DO 300 J=1,2
        RS(J)=((1-N(J))/(1+N(J)))**2
 300    TS(J)=4*N(J)/(1+N(J))**2
        A(1)=EXP(-EMAT(1)*DMAT(1)*1000)
        CALL EINZELTRANS(IT,RS,TS,A,ROP,TAP,ABP)
        TAO(IW)=TAP(1,1)
C
C     Transparency of exterior glazing at PHI=60.0 dgr
C     ................................................
C
        DO 305 J=2,3
        AWI=SIN(WI(J-1))/N(J-1)
        IF(AWI.GT.1.0) AWI=1.0
  305   WI(J)=ASIN(AWI)
C
C     Vertical E-vector
C     .................
C
        DO 310 J=1,2
        RS(J)=(SIN(WI(J)-WI(J+1))/SIN(WI(J)+WI(J+1)))**2
  310   TS(J)=N(J)*COS(WI(J+1))/COS(WI(J))*
     &        (2*COS(WI(J))*SIN(WI(J+1))/SIN(WI(J)+WI(J+1)))**2
C
C     Parallel E-vector
C     .................
C
        DO 315 J=1,2
        RP(J)=(TAN(WI(J)-WI(J+1))/TAN(WI(J)+WI(J+1)))**2
  315   TP(J)=N(J)*COS(WI(J+1))/COS(WI(J))*
     &        (2*COS(WI(J))*SIN(WI(J+1))/SIN(WI(J)+WI(J+1))/
     &        COS(WI(J)-WI(J+1)))**2
C
C     Internal transmission
C     .....................
C
        A(1)=EXP(-EMAT(1)*DMAT(1)*1000/COS(WI(2)))
C
C     Computation of transmission, reflection and absorption components
C     of single glazings (for separate E-vectors)
C     .................................................................
```

```
C
        CALL EINZELTRANS(IT,RS,TS,A,ROS,TAS,ABSR)
        CALL EINZELTRANS(IT,RP,TP,A,ROP,TAP,ABP)
        T60=0.5*(TAS(1,1)+TAP(1,1))
        R60=0.5*(ROS(1,1)+ROP(1,1))
C
C     Kappa value of exterior glazing
C     ...............................
C
      XKP(IW)=LOG(1-T60/TAO(IW))/LOG(1-COS(pid3))
C
C     Diffuse transmission and reflection of the exterior system in the opaque state
C     ..............................................................................
C
        TD=TAO(IW)*XKP(IW)*(XKP(IW)+3)/(XKP(IW)+2)/(XKP(IW)+1)
      TG(1)=TLOTD(IW)*TD/TAO(IW)
        TG(2)=TG(1)
      AG(1,2)=AG(1,2)*TD/TAO(IW)
        AG(2,2)=AG(1,2)
        RG(1)=1-AG(1,2)-TG(1)
      RG(2)=RG(1)
        GOTO 66
C
C     Direct radiation in the opaque state
C     ....................................
C
      ELSE IF(IOPAK.EQ.1.AND.DIF.NE.1) THEN
        AG(1,2)=1-TLOTD(IW)-TLORD(IW)
        AG(2,2)=AG(1,2)
        TPH=TAO(IW)*(1-(1-COS(WI(1)))**XKP(IW))
        TG(1)=TLOTD(IW)*TPH/TAO(IW)
        TG(2)=TG(1)
        AG(1,2)=AG(1,2)*TPH/TAO(IW)
        AG(2,2)=AG(1,2)
        RG(1)=1-AG(1,2)-TG(1)
        RG(2)=RG(1)
        DIF=1
        GOTO 66
      END IF
C
C
C     Determining transparency parameters for the base-case system
C     ------------------------------------------------------------
C                    Glazing-TALD-Glazing in the transparent state
C                    ---------------------------------------------
C
      N(2)=NMAT(2)/NMAT(1)
      N(3)=NMAT(3)/NMAT(2)
      N(4)=1/NMAT(3)
C
      DO 5 I=1,3
    5 IT(I)=I
C
C     Normal (vertical) incidence
C     ...........................
C
      IF(WI(1).EQ.0.0) THEN
        DO 10 J=1,4
        WI(J+1)=0.0
```

```
        RS(J)=((1-N(J))/(1+N(J)))**2
  10    TS(J)=4*N(J)/(1+N(J))**2
        DO 15 J=1,3,2
  15    A(J)=EXP(-EMAT(J)*DMAT(J)*1000)
        CALL EINZELTRANS(IT,RS,TS,A,ROP,TAP,ABP)
        DO 20 L=1,2
        DO 20 J=1,4
        ROS(L,J)=ROP(L,J)
        TAS(L,J)=TAP(L,J)
  20    ABSR(L,J)=ABP(L,J)
      ELSE
C
C     Non-Vertical incidence
C     ......................
C
        DO 25 J=2,5
        AWI=SIN(WI(J-1))/N(J-1)
        IF(AWI.GT.1.0) AWI=1.0
  25    WI(J)=ASIN(AWI)
C
C     Vertical E-vector
C     .................
C
        DO 30 J=1,4
        RS(J)=(SIN(WI(J)-WI(J+1))/SIN(WI(J)+WI(J+1)))**2
  30    TS(J)=N(J)*COS(WI(J+1))/COS(WI(J))*
     &        (2*COS(WI(J))*SIN(WI(J+1))/SIN(WI(J)+WI(J+1)))**2
C
C     Parallel E-vector
C     .................
C
        DO 35 J=1,4
        RP(J)=(TAN(WI(J)-WI(J+1))/TAN(WI(J)+WI(J+1)))**2
  35    TP(J)=N(J)*COS(WI(J+1))/COS(WI(J))*
     &        (2*COS(WI(J))*SIN(WI(J+1))/SIN(WI(J)+WI(J+1))/
     &        COS(WI(J)-WI(J+1)))**2
C
C     Internal transmission
C     .....................
C
        DO 40 J=1,3,2
  40    A(J)=EXP(-EMAT(J)*DMAT(J)*1000/COS(WI(J+1)))
C
C     Computation of transmission, reflection and absorption components
C     of single glazings (for separate E-vectors)
C     .................................................................
C
        CALL EINZELTRANS(IT,RS,TS,A,ROS,TAS,ABSR)
        CALL EINZELTRANS(IT,RP,TP,A,ROP,TAP,ABP)
      END IF
C
C     Transmission inside TALD layer
C     ..............................
C
      TATAL=EXP(-EMAT(2)*DMAT(2)*1000/COS(WI(3)))
C
C     Determining the system parameters transmission, reflection and
C     absorption
C
```

```
C     INDEX=1    :   light transmission from outside to inside
C     INDEX=2    :              "            "  inside to outside
C     .........................................................
C
      INDEX=1
      CALL KOMBITRANS(INDEX,TATAL,ROP,ROS,TAP,TAS,ABP,ABSR
     &                ,RG,TG,AG)
      INDEX=2
      CALL KOMBITRANS(INDEX,TATAL,ROP,ROS,TAP,TAS,ABP,ABSR
     &                ,RG,TG,AG)
C
666   CONTINUE
C
C     System adaptation
C     -----------------
C
C     Systems without air gap and without LDD
C     ---------------------------------------
C
  66  IF (SYS.EQ.10 .OR. SYS.EQ.-10 .OR. SYS.EQ.0) THEN
        DO 45 J=1,2
        TAUGS(J)=TG(J)
        ROGES(J)=RG(J)
        DO 45 L=1,3
  45    ABSGS(J,L)=AG(J,L)
        GOTO 55
C
C     Systems with air gap but without LDD
C     ------------------------------------
C
      ELSE IF (SYS.EQ.20 .OR. SYS.EQ.-20) THEN
                IT(1)=4
                IT(2)=1
                IT(3)=4
           IF(DIF.EQ.1)  WI(4)= pid3
             IF(PHI.EQ.0.0) THEN
C
C     Normal (vertical) incidence
C     ...........................
C
                RS(4)=((1-NMAT(4))/(1+NMAT(4)))**2
                RS(5)=RS(4)
                TS(4)=4*NMAT(4)/(1+NMAT(4))**2
                TS(5)=TS(4)
                A(4)=EXP(-EMAT(4)*DMAT(4)*1000)
                CALL EINZELTRANS(IT,RS,TS,A,ROP,TAP,ABP)
                RGS=ROP(1,4)
                TGS=TAP(1,4)
                AGS=ABP(1,4)
C
              ELSE
C
C     Non-Vertical incidence
C     ......................
C
              IF(WI(4).NE.pid3) THEN
                 WI(4)=WI(5)
                END IF
                WI(5)=ASIN(SIN(WI(4))/NMAT(4))
```

```
C
C     Vertical E-vector
C     ................
C
              RS(4)=(SIN(WI(4)-WI(5))/SIN(WI(4)+WI(5)))**2
              RS(5)=RS(4)
              TS(4)=NMAT(4)*COS(WI(5))/COS(WI(4))*
     &             (2*COS(WI(4))*SIN(WI(5))/SIN(WI(4)+WI(5)))**2
              TS(5)=TS(4)
C
C     Parallel E-vector
C     ................
C
              RP(4)=(TAN(WI(4)-WI(5))/TAN(WI(4)+WI(5)))**2
              RP(5)=RP(4)
              TP(4)=NMAT(4)*COS(WI(5))/COS(WI(4))*
     &              (2*COS(WI(4))*SIN(WI(5))/SIN(WI(4)+WI(5))/
     &              COS(WI(4)-WI(5)))**2
              TP(5)=TP(4)
C
C     Internal transmission
C     ....................
C
              A(4)=EXP(-EMAT(4)*DMAT(4)*1000/COS(WI(5)))
C
C     Computation of transmission, reflection and absorption components
C     of single glazing (for separate E-vectors)
C     ................................................................
C
              CALL EINZELTRANS(IT,RS,TS,A,ROS,TAS,ABSR)
              CALL EINZELTRANS(IT,RP,TP,A,ROP,TAP,ABP)
C
C     Parameters of third glazing (both transmitting directions identical)
C     ...................................................................
C
              RGS=0.5*(ROS(1,4)+ROP(1,4))
              TGS=0.5*(TAS(1,4)+TAP(1,4))
              AGS=0.5*(ABSR(1,4)+ABP(1,4))
            END IF
C
      ELSE IF (SYS.GE.30 .OR. SYS.LE.-30) THEN
C
C     Systems with LDD
C     ----------------
C
            DM=DMAT(4)*1000
          IF(LDD.EQ.'P') THEN
C
C     Acrylic foam insulation (empirical approximation of transparency behaviour)
C     .........................................................................
C
              IF(DIF.EQ.1) THEN
            TGS=t1tdif(iw)
              ELSE
            TO= t1tdir(iw)
            IF(ABS(PI/2-WI(5)).LT.0.0001) WI(5)= pid2-PI/360
                IF(WI(5).EQ.0.0) THEN
                  TGS=TO
                ELSE
```

```
               IF(WI(5).LT.pid3) THEN
                 KAPPA=TAN(pmmaa(1)*WI(5)**3+pmmab(1)*WI(5)**2
     &                        +pmmac(1)*WI(5)   + pmmad(1))
                   ELSE
                 KAPPA=TAN(pmmaa(2)*WI(5)**3+pmmab(2)*WI(5)**2
     &                        +pmmac(2)*WI(5)   + pmmad(2))
                   END IF
                   TGS=T0*(1-(1-COS(WI(5)))**KAPPA)
                 END IF
               END IF
               AGS=0.025
               RGS=1-TGS-AGS
C
C     Aerogel
C     .......
C
           ELSE IF(LDD.EQ.'A') THEN
C
               IF(DIF.EQ.1) THEN
             TGS=t1tdif(iw)
               ELSE
             T0= t1tdir(iw)
             IF(ABS(PI/2-WI(5)).LT.0.0001) WI(5)= pid2-PI/360
                 IF(WI(5).EQ.0.0) THEN
                   TGS=T0
                 ELSE
               IF(WI(5).LT.pid3) THEN
                 KAPPA=TAN(aeroa(1)*WI(5)**3+aerob(1)*WI(5)**2
     &                        +aeroc(1)*WI(5)   + aerod(1))
                   ELSE
                 KAPPA=TAN(aeroa(2)*WI(5)**3+aerob(2)*WI(5)**2
     &                        +aeroc(2)*WI(5)   + aerod(2))
                   END IF
                   TGS=T0*(1-(1-COS(WI(5)))**KAPPA)
                 END IF
               END IF
               AGS=0.025
               RGS=1-TGS-AGS
C
C
C
C     PC Honeycomb structure (PCHC)
C     .............................
C
           ELSE IF(LDD.EQ.'H') THEN
C
                   IF(DIF.EQ.1) THEN
                TGS=t1tdif(iw)
                  ELSE
                    IF(WI(5).EQ.0.0) THEN
                  TGS=0.98
                ELSE
                  IF (ABS(WI(5)-pid2).LT.0.0001) THEN
                            TGS=0.0
                            AGS=0.0
                            RGS=1.0
                      GOTO 48
                  ELSE
                      IF(WI(5).LT.pid3) THEN
```

```
                        tgs = pchcm(iw,2)*wi(5) + pchcb(iw,2)
                      ELSE
                        tgs = pchcm(iw,3)*wi(5) + pchcb(iw,3)
                      END IF
                  END IF
                    END IF
                  END IF
                  AGS=1.0-TGS
                  RGS=0.0
  48              CONTINUE
C
C
C     Cappillary structure
C     ....................
C
             ELSE IF(LDD.EQ.'K') THEN
C
                  IF(DIF.EQ.1) THEN
                TGS=tltdif(iw)
                  ELSE
                    IF(WI(5).EQ.0.0) THEN
                  TGS=0.98
                ELSE
                  IF (ABS(WI(5)-pid2).LT.0.0001) THEN
                            TGS=0.0
                            AGS=0.0
                            RGS=1.0
                      GOTO 488
                  ELSE
                      IF(WI(5).LT.pid3) THEN
                        tgs = akapm(iw,2)*wi(5) + akapb(iw,2)
                      ELSE
                        tgs = akapm(iw,3)*wi(5) + akapb(iw,3)
                      END IF
                  END IF
                    END IF
                  END IF
                  AGS=1.0-TGS
                  RGS=0.0
  488         CONTINUE
           END IF
      END IF
C
C     Combined values of transparency, reflection and layer absorption
C     for a four-layer system
C     ----------------------------------------------------------------
C
      absgs(2,4) = 1./(1.-RG(2)*RGS)
      taugs(1) = TGS * absgs(2,4)
      taugs(2) = TG(2) * absgs(2,4)
      ROGES(1)=RG(1)+RGS*TG(1) * taugs(2)
      ROGES(2)=RGS+RG(2)*TGS * taugs(1)
      TAUGS(1)=TG(1) * taugs(1)
      TAUGS(2)=TGS * taugs(2)
        DO 50 J=1,3
      ABSGS(1,J)=AG(1,J)+TG(1)*RGS*AG(2,J) * absgs(2,4)
  50  ABSGS(2,J)=TGS*AG(2,J) * absgs(2,4)
      ABSGS(1,4)=AGS*TG(1) * absgs(2,4)
      ABSGS(2,4)=AGS+TGS*RG(2)*AGS * absgs(2,4)
```

```
C
C     Absorbed energy of short-wave radiation reflected from absorbing surface.
C     The percentage determined for the insulating system is assumed to be a
C     heat source and assigned to the internal surface of the TALD-system
C     interior pane. The amount being rather low, this is considered
C     approximately permissible.
C     Regarding multiple reflections at the absorbing wall, the TALD system's
C     inside/outside diffuse transmission and reflection properties are taken
C     as the basic condition. For the opaque state, multiple reflections and
C     associated effects are neglected on account of the low system
C     transparency.
C     -------------------------------------------------------------------------
C
   55 IF(IOPAK.EQ.1) THEN
        ABSGS(1,1)=0.0
        ABSGS(1,3)=0.0
      IF(SYS.EQ.0) ABSGS(1,4)=0.0
        ABS4=0.0
        ABSW=1-ROWA
        GOTO 75
      END IF
C
      IF(DIF.EQ.1) THEN
        RODIFA(IW)=ROGES(2)
        TADIFA(IW)=TAUGS(2)
      END IF
C
      absw = 1./(1.-ROWA*RODIFA(IW))
      ABS4 = ROWA*absw - TADIFA(IW)*ROWA*absw
     &          -ROWA*RODIFA(IW)*absw
      ABSW=(1-ROWA)*absw
C
   75 RETURN
C
      END
C


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C
      SUBROUTINE EINZELTRANS(IT,R,T,A,RO,TA,AB)
C
C     computes transparency, reflection and absorption of single TALD
C     system cover panes for both light transmission directions.

C     Input :
C     -------
C
C     IT       =  control quantity
C     R        =  layer reflection factor
C     T        =  internal transmission
C     A        =  layer absorption
C
C     Output :
C     --------
C
```

```
C     RO        =  reflection factor of single glazing
C     TA        =  transmission factor of single glazing
C     AB        =  absorption coefficient of single glazing
C
C
      REAL    R(6),T(6),RO(2,4),TA(2,4),AB(2,4),A(6)
      INTEGER IT(3)
C
      IZ=3
C
C     INDEX = 1  :  light transmission from outside to inside
C     INDEX = 2  :  light transmission from inside to outside
C
C     Outside/Inside
C     --------------
C
      DO 10 J=IT(1),IT(3),IT(2)
      RO(1,J)=R(J)+T(J)*T(J+1)*R(J+1)*A(J)**2/(1-(R(J+1)*A(J))**2)
      TA(1,J)=T(J)*T(J+1)*A(J)/(1-(R(J+1)*A(J))**2)
      AB(1,J)=(1-A(J))*T(J)/(1-R(J+1)*A(J))
C
C     Inside/Outside
C     --------------
C
      RO(2,IZ)=R(J+1)+T(J+1)*T(J)*R(J)*A(J)**2/(1-(R(J)*A(J))**2)
      TA(2,IZ)=T(J+1)*T(J)*A(J)/(1-(R(J)*A(J))**2)
      AB(2,IZ)=(1-A(J))*T(J+1)/(1-R(J)*A(J))
   10 IZ=IZ-2
C
      RETURN
      END
C

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CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE KOMBITRANS(I,TAT,PR,SR,PT,ST,PA,SA,GR,GT,GA)
C
C
C     computes transparency, reflection and absorption for TALD systems
C     with a glazing/TALD/glazing composition by way of averaging the
C     separately calculated system values for parallel and vertical
C     E-field vectors.
C
C     Input :
C     -------
C
C     I         =  transmitting direction index
C     TAT       =  internal transmission inside TALD layer
C     PR        =  boundary layer reflection, parallel E-vector ¦
C     SR        =  boundary layer reflection, vertical E-vector ¦
C     PT        =  transmission, parallel E-vector              ¦ for
C     ST        =  transmission, vertical E-vector              ¦ single panes
C     PA        =  layer absorption, parallel E-vector          ¦ each
C     SA        =  layer absorption, vertical E-vector          ¦
C
```

```
C     Output :
C     --------
C
C     GR        =  total reflection (system)
C     GT        =  total transmission (system)
C     GA        =  layer absorption (system)
C
      REAL    PR(2,4),SR(2,4),PT(2,4),ST(2,4),PA(2,4),SA(2,4)
      REAL    GR(2),GT(2),GA(2,3)
C
C     Reflection
C     ----------
C
      GR(I)=0.5*(PR(I,1)+TAT**2*PR(I,3)*PT(I,1)**2/
     &       (1-TAT**2*PR(I,1)*PR(I,2))+SR(I,1)+TAT**2*SR(I,3)
     &       *ST(I,1)**2/(1-TAT**2*SR(I,1)*SR(I,3)))
C
C     Transmission
C     ------------
C
      GT(I)=0.5*(TAT*PT(I,1)*PT(I,3)/(1-TAT**2*PR(I,1)*PR(I,3))
     &       +TAT*ST(I,1)*ST(I,3)/(1-TAT**2*SR(I,1)*SR(I,3)))
C
C     Layer absorption
C     ----------------
C
C
C     1st glazing
C     ...........
C
      GA(I,1)=0.5*(PA(I,1)+PA(I,1)*TAT**2*PR(I,3)*PT(I,1)/
     &         (1-TAT**2*PR(I,1)*PR(I,3))+SA(I,1)+SA(I,1)*TAT**2
     &         *SR(I,3)*ST(I,1)/(1-TAT**2*SR(I,1)*SR(I,3)))
C
C     Intermediate layer
C     ..................
C
      GA(I,2)=0.5*((1-TAT)*PT(I,1)+(1-TAT)*PR(I,3)*TAT*PT(I,1)*
     &       ((1+PR(I,1)*TAT)/(1-PR(I,1)*PR(I,3)*TAT**2))+
     &       (1-TAT)*ST(I,1)+(1-TAT)*SR(I,3)*TAT*ST(I,1)*
     &       ((1+SR(I,1)*TAT)/(1-SR(I,1)*SR(I,3)*TAT**2)))
C
C     2nd glazing
C     ...........
C
      GA(I,3)=0.5*(PA(I,3)*TAT*PT(I,1)/(1-TAT**2*PR(I,1)
     &         *PR(I,3))+SA(I,3)*TAT*ST(I,1)/(1-TAT**2*SR(I,1)
     &         *SR(I,3)))
C
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

APPENDIX B

Reilly, S; Selkowitz, S :

Switchable Window Modelling

Function for Thermochromic Windows

Lawrence Berkeley Laboratory

Berkeley, California, USA.

EXAMPLE OF FUNCTION FOR THERMOCHROMIC WINDOW

```
      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
```

EXAMPLE OF FUNCTION FOR THERMOCHROMIC WINDOW

```
      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
```