Review Paper

Solar control glass

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Solar control glass serves energy conservation and, at the same time, constitutes an excellent component for the design of facades of buildings. At present, because of greater variability in exterior color and of technical advantages, coated solar control glass dominates. This paper deals with the construction, effect and application of solar control glass with the emphasis on the state of the art of solar control glass coatings, their structure, production, color, inspection and aging resistance.

Sonnenschutzscheiben

Sonnenschutzscheiben dienen der Energieeinsparung und sind gleichzeitig ein vorzügliches Bauelement für die Fassadengestaltung. Wegen der größeren Variationsmöglichkeiten bezüglich Farbe in Außenansicht und technischer Daten überwiegen heute die beschichteten Sonnenschutzscheiben. Im vorliegenden Beitrag wird auf den Aufbau, die Wirkungsweise und den Einsatz von Sonnenschutzscheiben eingegangen. Insbesondere werden der Stand der Technik der heutigen Sonnenschutzbeschichtungen, deren Strukturen, Herstellungsverfahren, Farbprobleme und Kontrollen sowie Alterungsbeständigkeit abgehandelt.

1. Introduction

Solar control glass represents one option for counteracting intensive solar irradiation in buildings. Solar irradiation may cause high heat load in the interior, the so-called greenhouse climate, impairing comfort.

The market for solar control glass started to expand during the 1960's with the advent in architecture of all-glass facades. Soon it was recognized that considerable cost in air conditioning could be saved by the introduction of solar control glass. At the same time, solar control glass offered the architect an attractive design feature. For these reasons, today solar control glass is generally used as a window material in facade constructions.

Saving energy was an issue for large-area glazing even before the first energy crisis of 1973. It was realized that when clear glass was used, a greenhouse climate could only be avoided by large energy-consuming air conditioning installations. Since, however, the kilowatts for air conditioning costs approximately four times as much as that for heating, solar control glass presented a useful way to reduce costs of energy consumed as well as of investment. For this reason solar control glass arrived on the market much before heat-insulating glazing [1]. It is well-known that the latter was only initiated by the first energy crisis. Therefore, it should be stressed that solar control glass, too, considerably contributes to energy conservation.

The efficiency of solar control glass was tested successfully in the 1960's when the railroad carriages of the German "Rheingold" express were air-conditioned. Because of the significant savings in the cost of air conditioning, solar control glass is now being applied generally to railroad carriages and busses.

Last not least, solar control glass has conquered a large market because the glass industry provided the architect with an ideal element for the design of facades offering a large palette of products with varying optical properties such as transmission, reflection, and exterior coloration. Today one may state that ultimately it was only solar control glass which made the style of glass facade acceptable in urban development. Solar control glass offers stationary solar control, in contrast to variable solar control devices. It is weather-resistant, cannot be disturbed, and needs no maintenance. These advantages contribute to the fact that solar control glass has become an essential feature of the state of the art of glazing.

While only a few types of heat-insulating glasses have prevailed and, facing a large demand, have become a mass product, solar control glass will, because of its design function, remain a custom-made product to be used individually. The literature frequently describes solar control glass as a strategy for "summer heat protection". This can lead to misunderstandings since, even in winter and in the

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transitional periods, slanted solar irradiation can cause considerable heat load in buildings. The function of solar control glass thus remains indicated for these seasons, too, therefore throughout the entire year. A series of publications on solar control glass has appeared during the past years [2 to 6]. In this paper, the present state of the art shall be reviewed.

2. Function and construction of solar control glass

The determining factor for the evaluation of solar control by panes is the total transmission of energy, the so-called g value. The g value is the sum of direct solar radiation input (τ_e) and the secondary heat release to the interior (q_i):

$$g = \tau_e + q_i \,. \tag{1}$$

τ_e is defined by

$$\tau_e = \frac{\int_0^\infty S(\lambda) \cdot T(\lambda) \cdot \mathrm{d}\lambda}{\int_0^\infty S(\lambda) \cdot \mathrm{d}\lambda} \tag{2}$$

where $S(\lambda)$ = spectral distribution of solar rays [7] and $T(\lambda)$ = spectral transmission of solar control glass.

q_i is that portion of the radiation which is absorbed by the glass, converted to heat and conveyed to the interior in the form of radiation and convection. For a two-pane insulating glass, q_i is defined – assuming equal temperature in the exterior and interior space – by the formula

$$q_i = k\left(\frac{\alpha_I + \alpha_{II}}{\alpha_a} + \frac{\alpha_{II}}{\Lambda}\right) \tag{3}$$

where k = heat transmission value (k value) [8]; α_I,α_{II} = absorption of radiation by the exterior (I) and interior (II) pane, respectively; α_a = heat transfer coefficient to the exterior [8], and Λ = heat transmission coefficient of the insulating pane.

Figure 1 shows the distribution of the incoming solar radiation in a two-pane insulating glass according to the German standard DIN 67 507 [9]. Solar control glass is characterized by a minimal g value. Since 44 % of the solar energy incident on the surface of the earth consists of the invisible infrared region, solar control glass ought to suppress the passing of the infrared portion of solar rays as much as possible. At the same time, however, light transmission (τ) of the solar control glass should be high so as to assure maximum daylight illumination of the interior. τ is defined by the formula:

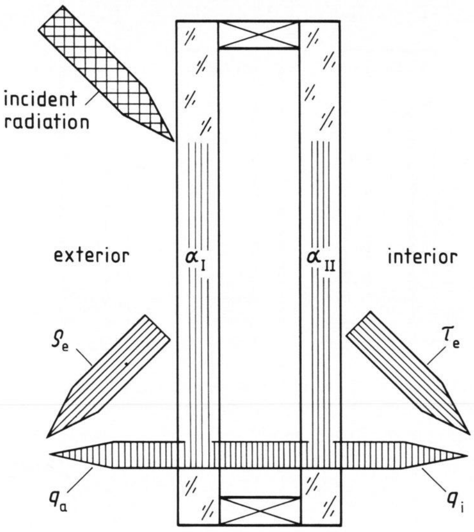


Figure 1. Distribution of the incident solar radiation (100 %) in an insulating glass according to [9]. τ_e: radiation transmittance, ϱ_e: radiation reflectivity, α_I: radiation absorbance, exterior pane, α_{II}: radiation absorbance, interior pane, q_a: secondary heat release to the exterior, q_i: secondary heat release to the interior.

$$\tau = \frac{\int_0^\infty S'(\lambda) \cdot V(\lambda) \cdot T(\lambda) \cdot \mathrm{d}\lambda}{\int_0^\infty S'(\lambda) \cdot V(\lambda) \cdot \mathrm{d}\lambda} \tag{4}$$

where $S'(\lambda)$ = spectral distribution of standard light source D 65 [10] and $V(\lambda)$ = photopic eye response function [11].

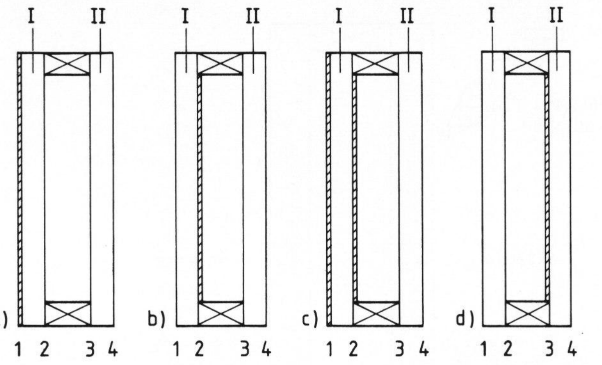
The demand for simultaneous high light transmission and suppression of the incident infrared portion of the sun rays is accounted for by the introduction of the selectivity number S [2]. S is defined by

$$S = \tau / g \,. \tag{5}$$

A solar control glass is considered particularly effective if $S > 1$. According to the formula

$$\tau_e + \varrho_e + \alpha_e = 100\ \% \tag{6}$$

solar control can be achieved by either increased reflection of solar rays (ϱ_e), increased absorption of solar rays (α_e) or by increased reflection plus absorption ($\varrho_e + \alpha_e$). All three possibilities are being realized in contemporary solar control glass, with due consideration of the fact that with increased absorption of solar radiation part of the absorbed solar energy enters the interior in the form of secondary heat release q_i. For an effective design, optical and thermal characteristics of the solar control glass must be adapted to the climatic conditions of the locations of the building. In moderate climate zones, e.g. in Northern Europe, solar control glass with g values of 20 to 50 % and at the same time a k value



Figures 2a to d. Construction of, and positions of coatings in, solar control insulating glasses; a) coating in position 1, b) coating in position 2, c) coating in positions 1 and 2, d) coating in position 3. I: exterior pane (clear or colored glass) II: interior pane (clear glass).

≤ 1.5 W/(m^2 K) have worked out. In countries within the sun belt of earth, e.g. in the south of the USA, solar control glass with *g* values of 5 to 20 % is being applied and the *k* value is relatively unimportant. The light transmission (τ) in the moderate zones will be 30 to 65, in the sun belt 5 to 30 %. The exterior reflection may, depending on the type of glass used, vary between 7 and 45 %. In many places, it has now become subject to limitations by building regulations.

On principle, the effectiveness of solar control is not dependent on the insulating glass construction, it may be realized with single panes, too. This represents a fundamental difference between solar control and heat-insulating glass. In the Federal Republic of Germany (FRG), the heat conservation law of 1982 requires, on principle, insulating glass or double glass construction to assure energy conservation. Thus, all solar control glass in the FRG now involves insulating glass. Frequently, this construction is used to provide also increased heat control so that the insulating glass construction has the dual function of solar and heat control. Today solar control glass with *k* values as low as 1.2 W/(m^2 K) is available.

Solar control is most effective if realized within or on the exterior pane. Control may be achieved by colored glass or by solar control coatings. In the case of coatings (figures 2a to d), they should best be in positions 1 and/or 2. In rare cases, marketed solar control glass involves coatings in position 3 to achieve specific color effects. This, however, does impair solar control because of increased secondary heat release (q_i). In solar control glass, insulating constructions providing increased heat conservation ($k \leq 1.5$ W/(m^2 K)) always coatings are applied with at least one heat-conserving coating. There are coatings with solar controlling and at the same time heat-conserving effect. They are placed at the position 2 or 3. Coatings with exclusively heat-conserving effect are always at the position 3 while solar control coatings (colored glasses or coatings) are installed at the exterior pane (I). These constructions are called combined solar control glasses.

At present colored glasses are marketed in shades of green, grey, bronze, and blue. Their solar control function is determined by the color of the glass matrix. Coatings may be used to modify color and brilliance (reflection) especially for viewing from the outside. This is often desirable for achieving aesthetic effects in buildings. The coloration of the glass is achieved by the addition of inorganic materials to the melt [12]. Their effect on solar irradiation is exclusively by absorption. For this reason the solar control effect of colored glasses depends on the concentration of the colorant and the thickness of the pane. Such a dependence does not hold for solar control coatings.

3. Solar control coatings

Most solar control glasses presently marketed are coated. The development of such coatings began with the introduction of solar control glass to the market at the beginning of the 1960's. Colored glasses are much older. A number of coatings and coating technologies were tried. But only a few coating structures essentially based on four coating processes have prevailed.

Solar control coatings now in use have, among others, the following features:

a) reproducible production of color as viewed from the outside,

b) controllability of color,

c) aging resistance,

d) economical application to large (up to (3.20 × 6.00) m^2) panes.

It is remarkable that relatively simple coating structures have been accepted, sometimes subordinating solar control to aesthetic effect.

For the satisfaction of the desires of architects, a broad palette of colors has become available, with a grading of technical values. It must be stated, however, that at least in Europe, solar control glass predominantly offers an outside view of neutral or blue color. Golden, grey and bronze are rarer, and green is found only occasionally.

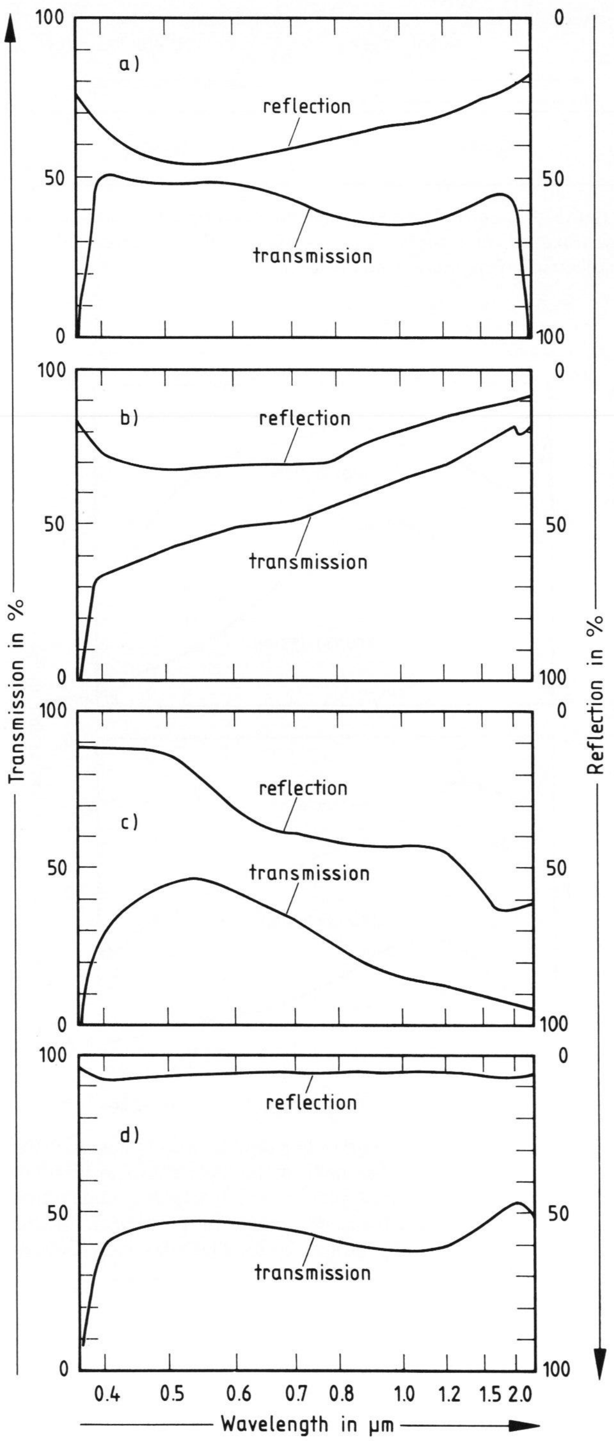
3.1. Structure of coatings

Essentially the following basic structure can be found in today's solar control coatings:

3.1.1. Single dielectric coatings

They are single metal-oxide coatings. The coating materials include titanium oxide, palladium-doped titanium oxide, and mixed oxides of iron, cobalt and nickel. The solar control effect of these coatings is achieved by increased reflection (titanium oxide) or increased reflection plus absorption (other oxides). In the first case, one deals with absorption-free dielectric coatings with refractive index $n = 2.3$ to 2.5 and absorption index k close to zero in the visible range; in the second case one deals with absorbing dielectric coatings with the refractive index $n \approx 2.6$ and the absorption index $k = 0.2$ to 0.5 in the visible range. The optical thickness $(n \cdot d)$ of the titanium oxide coating is $\lambda/4$ at the wavelength 550 nm; the thickness of the other coatings is less than 60 nm, varying from product to product depending on the desired solar control effect.

No single metal-oxide coatings are selective for solar rays nor do they have any heat conservation effect. Viewed from the outside they look neutral and can be produced to uniform color appearance. At present they are applied both to clear and colored glass. Of course, when coatings are applied to colored glass the glass will influence the color viewed from the outside. Single metal-oxide coatings are predominantly applied to position 1 and/or 2 of the insulating glass construction (figures 2a to c). Figures 3a and b show typical spectral curves for solar control glasses with single metal-oxide coatings.



Figures 3a to d. Spectral curves for a) absorption-free dielectric single metal-oxide coatings (TiO_2) in positions 1 and 2 in an insulating glass (Calorex AO, Schott Glaswerke, Mainz (FRG)); b) an absorbing dielectric single metal-oxide coating in position 1 of a 6 mm thick single pane (Antelio-clear, St. Gobain, Neuilly-sur-Seine (France)); c) a single gold coating in position 2 of an insulating glass (Ipasol bronce 45/29, Interpane, Lauenförde (FRG)); d) a single-metal (Cr, Fe, Al base) coating in position 2 of an insulating glass (Infrastop grey 47/51, Flachglas AG, Gelsenkirchen (FRG)).

3.1.2. Single-metal coatings

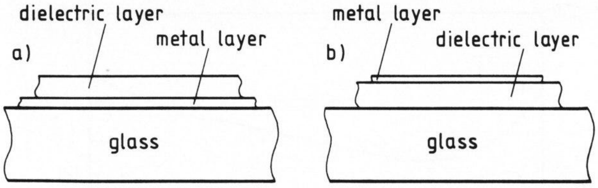
These coatings consist of gold, nickel chrome, stainless steel or alloys resembling stainless steel. Due to the particular electron structure of gold the gold coatings have a selective effect on solar rays, i.e. solar control is achieved by increased reflection and absorption in the visible range as well as by high reflection in the infrared. Because of the high reflection in the infrared gold coatings are heat conserving at the same time. Transmission in the visible range decreases with increasing thickness of the gold coating.

Coatings of nickel chrome or stainless steel are not selective, their solar control is based predominantly on absorption in the overall spectral range. They do not have any heat-conservation effect. With these coatings the transmission also decreases with increasing thickness of the coating.

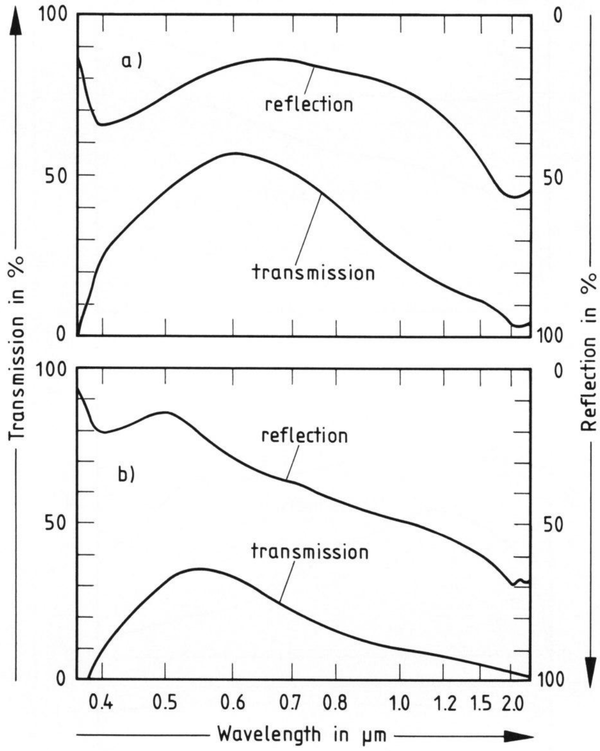
Viewed from the outside the gold layers have the typical golden hue, the other metal coatings look metallic neutral. All single-metal coatings can be produced to uniform color appearance. They are mainly applied to clear glass and to position 2 of the insulating glass construction. Figures 3c and d show typical spectral curves of solar control panes with single-metal coatings.

3.1.3. Multiple layer systems

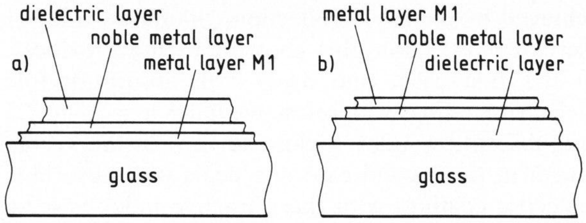
The optical properties (transmission, reflection, color) of metal coatings are varied mostly by interference effect in combination with dielectric layers essentially free of absorption. The metals used are gold, sometimes silver or copper, nickel chrome



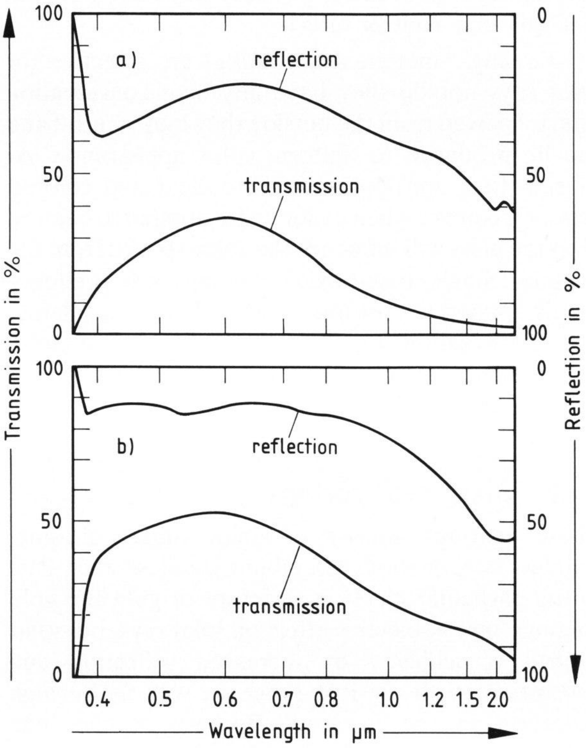
Figures 4a and b. Coating arrangements on glass in double-layer systems, a) first metal layer, second dielectric layer, b) first dielectric layer, second metal layer.



Figures 5a and b. Spectral curves of a double-layer system with the coating arrangements a) glass/noble metal/dielectric in position 2 of the insulating glass (Ipasol blue 53/38, Interpane, Lauenförde (FRG)); b) glass/dielectric/noble metal in position 2 of the insulating glass (Infrastop bronze 36/26, Flachglas AG, Gelsenkirchen (FRG)).



Figures 6a and b. Coating arrangements in triple-layer systems with two adjoining metal layers; a) first metal layer M1, second noble-metal layer, third dielectric layer; b) first dielectric layer, second noble-metal layer, third metal layer M1.



Figures 7a and b. Spectral curves for a triple-layer system with the coating arrangement in position 2 of the insulating glass, a) glass/metal M1/nobe metal/dielectric (Infrastop Auresin 39/28, Flachglas AG, Gelsenkirchen (FRG)); b) glass/dielectric/noble metal/metal M1 (Infrastop neutral 51/39, Flachglas AG, Gelsenkirchen (FRG)).

or stainless steel. The coatings are applied to clear or colored glass, almost exclusively on position 2, in rare cases on position 3 of the insulating glass.

Coatings based on gold, silver or copper are selective also in combination with dielectric layers discussed here and are simultaneously heat conserving. The solar control effect corresponds with that of the single-gold coatings described in section 3.1.2.

An important group of these coating structures is represented by the double-layer systems with structures shown in figures 4a and b based on gold, nickel chrome or stainless steel. Materials chosen for the dielectric layers are zinc sulfide, titanium oxide, tin oxide and bismuth oxide. By means of these coating structures a series of interference colors, especially neutral, blue or bronze in exterior view, can be produced by varying the thickness of the individual layers. Figures 5a and b show typical spectral curves of solar control glasses with such coating structures.

To neutralize color in exterior and interior views, metal or metal-alloy coatings based essentially on iron, nickel and chrome are sometimes added to coatings based on gold and silver. Figures 6a and b show the coating structures used with the additional metal layer M1. In the structure of figure 6a the additional layer M1 neutralizes the typical green or blue transmission color of thick gold or silver coatings; in the structure of figure 6b it can weaken the reflection and color as viewed from the outside. Figures 7a and b show typical spectral curves of solar control glasses with these structures.

On the market are also found several solar control coatings in which a gold layer is imbedded in dielectric layers based on zinc sulfide and bismuth oxide, respectively, or a copper layer in protective dielectric layers based on silicon oxide (figure 8).

Such structures were first proposed by Holland and Siddall [13] and are – next to single-gold coatings – among the earliest solar control coatings. The dielectric layers act as anti-reflection films on the noble-metal coatings. For a constant thickness of the gold layer, increasing thickness of the dielectric layers produces the hues of yellow, violet, blue and green. For increasing thicknesses of the metal layer the same hue requires an increase in the thickness of the dielectric layers. It should be noted that a significant portion of heat-conserving coatings [1] has the same coating structure. However, in that case the metal layer is always silver and the thicknesses of the individual layers are chosen to attain minimum reflection of the visible light and, at the same time, an emissivity of $\varepsilon \leq 0.1$. Solar control coatings consisting of noble-metal layers imbedded in dielectric layers are very color-sensitive. Figure 9 shows the typical spectral curves of a solar control glass with this coating structure.

The multiple layer systems discussed here are of interest for the reason that with the same coating process a variation of the coating structure and the thickness of the individual layers provides a color palette of solar control glass with some grading of technical values (τ, g, k). But the deposition of these systems on large areas calls for considerable know-how.

Both for single-metal and multiple layer systems sometimes very thin adhesion or getter layers are inserted. But, because they are so thin, they have no significant influence on the optical properties. The need for such auxiliary layers depends on the coating material, the coating process and the processing of the coated glass.

3.2. Theoretical interpretation of the optical properties

Berning [5] has calculated the optical properties of a series of solar control coatings and, in addition, the function of heat-conservation coatings. These calculations are based on the Maxwell and the consistency equations for the spread of electromagnetic waves in matter. For such calculations the optical constants (refractive index $n(\lambda)$ and absorption index $k(\lambda)$) as well as the thickness of the single coatings must be known.

A frequently used method of calculation is based on the quadrupole theory of electrical engineering which describes the connection between currents and potentials on the input and output sides of the components of a network. Each quadrupole is represented by a matrix. Because of the analogous structure of the description of the spread of electromagnetic waves in layer systems, the quadrupole theory may be applied to them. Now every layer is described by a matrix which transforms the electric and the magnetic field in the proper phase from the front to the rear of the layer, and vice versa. The properties of a multiple layer system are obtained from the product of all matrices.

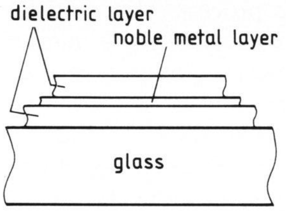


Figure 8. Coating arrangement in a triple-layer system with the noble-metal coating imbedded in dielectric layers.

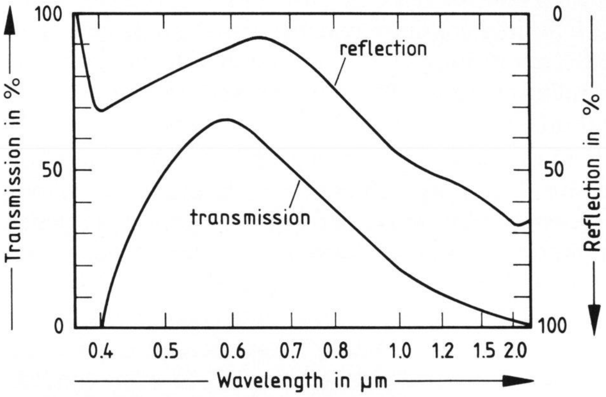


Figure 9. Spectral curves for a triple-layer system with the coating arrangement glass/dielectric/noble metal/dielectric in position 2 of the insulating glass (Infrastop Auresin 66/44, Flachglas AG, Gelsenkirchen (FRG)).

The so-obtained connections may be presented elegantly in the complex "admittance plane" ("admittance" = relation of magnetic to electrical field) since – if the optical constants of the various coatings are known – a graphic permits the direct reading of the reflection or transmission behavior of a system of layers and their dependence on thicknesses [14]. The calculation of the optical properties of solar control coatings as well as the possibilities for the analysis of coatings by means of the admittance method is presented in detail in [15].

3.3. Coating processes

The solar control coatings described in section 3.1. are applied today by pyrolysis, dipping, and spraying as well as by vacuum processes such as thermal vapor deposition and cathode sputtering. Essentially all metal-oxide single coatings are applied by pyrolysis, the single-metal and the multiple coatings by vacuum processes. All processes listed here can be applied for coating of flat glass of sizes up to $(3.20 \times 6.00)\ \mathrm{m}^2$ and are described in [16].

Cathode sputtering is the process most used for solar control coatings. During recent years magnetron sputtering is prevailing because of greater coating possibilities. Pyrolytic spraying is only used by float glass manufacturers in combination with the float glass process. Dipping and thermal deposition is only used by a few companies, the pioneers in solar control. Because of the building-related manufacture of solar control glass, the installation of coating plants with limited coating capacities may be indicated, e.g. batch operations. It is important that the design of the installation (e.g., the number and arrangement of cathodes) determines the feasible structures.

In the past, attempts have been made to produce identical coating structures with different coating processes. All these attempts – especially when applied to complex systems – have failed. This happened because it is not possible to produce identical coatings with equal optical constants (n and k) by different coating processes, e.g. thermal deposition and cathode sputtering, or even conventional and magnetron sputtering. Multiple layer systems produced by different processes thus can provide only approximately equal transmission and reflection, thus only rarely the same color in exterior view. In the case of color-sensitive multiple layer systems, it is often difficult to obtain coatings of equal color even by the identical process in different installations, since it is rarely feasible to maintain identical process parameters in large coating installations.

3.4. Color problems

Since solar control glass is applied by architects as a design element in the construction of a facade, its color in transmission as well as external view is of great importance. As far as the color of objects viewed through the glasses, solar control glass as presently produced in Europe offers mostly good to very good color rendering according to the German standard DIN 6169 [17], i.e. they are essentially neutral in transmission ($R_a \geq 81$). And there are hardly any problems as to variation in transmission within one pane or between panes. This is the result of the maturity of final inspection which has been achieved by now and of the lesser sensitivity of the human eye to fluctuations in brightness.

Uniformity and reproducibility of color as viewed from the outside remains the biggest problem of the development and production of solar control coatings. Today it is not yet possible to make a general statement on acceptable color tolerances for solar control glass. Fortunately, acceptable empirical tolerances are available. Generally, it may be stated that the following measures will alleviate problems of the color viewed from the exterior:

a) Single coating or layer systems should be chosen which are relatively insensitive to color variations as viewed from the outside due to minor variations in optical constants or thicknesses. This postulate is connected with the high sensitivity of the human eye for color differences. (The color as seen from the inside is generally of small concern since it becomes only noticeable in the evening or at night when it is not observed or is covered by shades or curtains.)

b) The optical constants (n, k) and the thicknesses of the coatings must be maintained as exactly as possible. This requires the strict maintenance of process parameters. In certain layer systems, thickness variations by a few atomic layers may cause observable color differences.

c) Final inspection of coated panes must be efficient (see section 3.5.).

As indicated in sections 3.1.1. and 3.1.2., single coatings are insensitive as to causing color differences seen from the outside; in the case of metal oxides because the optical thickness is $\leq \lambda/4$ so that no color effects occur and because additionally the absorbing metal oxides have their own inherent color. The insensitivity of the single-metal coatings as to color as seen from the outside as well as in looking through from the inside is also due to their inherent color by absorption.

But coating structures with metal and dielectric layers are critical in regard to the color variations seen from the outside. For systems highly reflecting in the visible color variations are affected by the angle of observation in addition to the effect of variations in optical constants and thicknesses of the individual layers. Such color variations due to variations in angle of observation are caused by changes in interference conditions due to different path lengths of rays in the dielectric layers. Hence they are unavoidable in multiple dielectric layer systems.

Experience has demonstrated that the color sensitivity of the multiple layer systems treated here increases with increasing thickness of the dielectric layers. For this reason green interference colors requiring larger thicknesses are, on principle, very color-sensitive. To this add that the human eye has a very great sensitivity for color differences in the green color range, thus being affected by quite small variations in thickness. This holds also for layer structures with bronze interference colors. For these reasons it is by far less critical to produce in exterior view green or bronze solar control glasses with the respective colored glasses and with single metal-oxide coatings in order to increase the often desired brilliance. Because of their high absorption in the near infrared ($\lambda = 1100$ nm) solar control glasses based on green glass have a selectivity number $S > 1$.

Blue interference colors realized with layer systems are less color-sensitive because of the lesser thickness of the dielectric layers. In addition, the human eye is less sensitive to color differences in this color range. But here, too, experience has shown that the sensitivity decreases with decreasing thickness of the metal coating since the dielectric layers then are thinner, too.

It should also be stated that the color sensitivity of the multiple layer systems treated here is alleviated if the transmission is as high (reflection as low) as possible and if the space behind the glazing is furnished, i.e. inhabited. The untrained eye then is known to concentrate on the furnishing and not on the color of the glazing, i.e. the eye is detracted from the latter. Such coatings can only be obtained with high anti-reflection multiple layer systems on the basis of gold or silver coatings. The color sensitivity of the multiple layer systems treated here is also reduced by applying the coating on position 3 and covering it by a clear or colored external glass pane. However, as stated in section 2., this design increases the *g* value, i.e. impairs solar control.

It also should be noted that when conceiving coated solar control glazing, the selection of the color palette must be considered carefully. Test coatings for special objects or the inclusion of less saleable products can involve high cost in the future when supplementing deliveries may necessitate the coating of single panes.

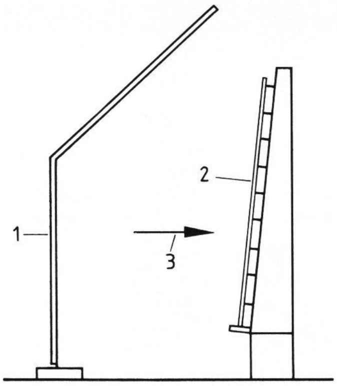


Figure 10. Schematic of visual final inspection device for solar control coatings. 1: diffuse white luminous wall, 2: pane subject to inspection on conveyor, 3: direction of observation by inspector.

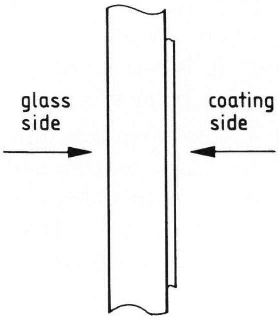


Figure 11. Definition of viewing side for coated solar control glass.

3.5. Inspection of coatings

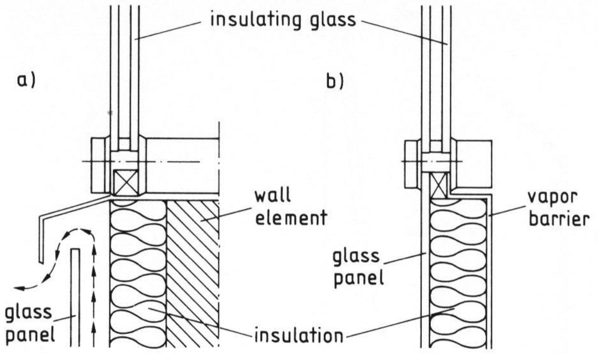
As to inspection of coated solar control glass, one has to distinguish factory inspection, i.e. inspection after or even during deposition, and inspection on the mounted condition in the facade. Factory inspection generally comprises the examination of transmission and color as well as of coating defects (point, stripe and area defects) and of abrasion resistance.

Transmission is measured and registered by photometers at characteristic wavelengths for each coating (e.g. at $\lambda = 550$ and 2000 nm in the case of gold) or in a characteristic wavelength range at some points of the coated sheets or along some lines while the glass passes the photometric installation. Experience shows that generally this inspection is sufficient also for assessing the color in transmission. For judging the color, i.e. hue and reflection (brilliance) of the coated glazing when viewed from the outside, visual inspection of the entire pane in front of a white wall (figure 10) is sufficient for color-insensitive single dielectric and single-metal coatings. If transmission values are maintained in these single coatings, experience has shown that the color in external view is also maintained.

But for color-sensitive multiple layer systems, the measurement of transmission is no longer sufficient for the evaluation of the color as seen from the outside. In the past, inspection was carried out by comparing with limiting color samples. But this is a quite subjective method and for large areas it becomes difficult because of color shifts with angle of observation. For this reason it is now recommended to supplement visual inspection of color-sensitive multiple layer systems by measuring the color by means of a colorimeter at some points or along some lines of the coated glazing. Colorimeters available today permit exact determination of hue and reflection without touching the surface. Evaluation by means of the CIELab coordinates according to the German standard DIN 5033 [18] has been proven advantageous. Inspection for point, line or limited area color deviations is still carried out visually.

Especially in the case of solar control glazing coated with multiple layer systems, the color viewed from the air or glass side can be quite different (figure 11). On principle, it is recommended for final inspection to inspect color under ultimate observation in its built-in condition. For the case of coating in position 2 of an insulating arrangement, it should be from the glass side, in the case of coating in positions 1 and 3 from the coating side. Visual inspection of the entire glazing from the glass side might be quite difficult for some coating processes. In that case, the reliability of the inspection from the coating side as well as the feasibility of an economically justifiable inspection of such coatings should be investigated.

The inspection for abrasion resistance is performed with suitable methods. It is important particularly for the assessment of storage and transpor-



Figures 12a and b. Schematics of a cold (figure a) and a warm (figure b) facade.

tation behavior especially of vacuum-coated sheets before assembly of the insulating glass. In many cases the coating is tested by manual abrasion with a cloth and subsequent visual inspection. While this is certainly a subjective method, it is sufficient for judging storage and transportation behaviors.

The inspection of the built-in glazing judges only the visual color impression of the single glazing and the entire facade. It is important, particularly for solar control glazing coated with multiple layer systems, to keep the distance of the observation from the facade sufficiently large (at least 100 m) and to keep all glazings in one plane so as to minimize the influence of the angle of observation. Experience has shown that open and closed windows, especially coated with multiple layer systems, show different colors to the outside view. A covered sky is much more critical than a cloudless sky for judging the color uniformity because of diffuse illumination. It may be stated generally that the environment, such as location of the building, surrounding buildings, landscaping, sky light, all decisively influence visual inspection of a facade.

3.6. Aging resistance

Depending on the location of the coating in the insulating glass, different requirements of aging resistance exist. If the coating is applied at position 2 or 3 the coating must be resistant to solar irradiation, high temperature (maximum depending on the absorption of the glass) and reaction with components of the edge sealing. If the coating is applied at position 1, it must be, in addition, resistant to the environment (H_2O, CO_2, SO_2, etc.) and to mechanical damage (abrasion, adhesion).

Single coatings based on metal oxides are chemically resistant to the environment and, because of the pyrolytic deposition process also mechanically stable enough to permit application to all positions including position 1.

All coatings produced by vacuum processes can as a rule only be applied at positions 2 and 3 because they are often lacking chemical resistance and their mechanical resistance cannot be warranted. Experience has shown that all coatings based on gold, nickel chrome, stainless steel or similar alloys are stable at all temperatures occurring in glazing of buildings, as well as under solar irradiation. This does not hold for all silver and copper coatings. Silver and copper coatings are not aging-resistant even in the protected positions 2 and 3; they gradually oxidize. However, it has become possible to imbed silver and copper coatings in dielectric layers preventing their oxidation. In the case of silver, this has been achieved by means of titanium oxide, tin oxide, and manganese-doped bismuth oxide layers [19]. Copper coatings can be made aging-resistant by imbedding in silicon-oxide layers [20]. Generally, the danger of oxidation of silver and copper coatings is smaller the larger the difference in the binding energy of oxygen is in the imbedding metal oxides.

At the start of the introduction of coated solar control glasses in the 1960's, sometimes serious problems regarding aging resistance arose. Today, however, it can be stated that all reliable producers of solar control coatings are aware of the problematics and can warrant sufficient aging resistance of their products.

4. All-glass facade design with solar control glass

All-glass facade constructions are carried out either as cold or warm facades. The cold facade (figure 12a) is a two-shell construction of non-transparent spandrels. The outer shell consists of glass, serves the architectural design and, in addition, procures protection of the facade against weather influences. The inner shell, separated from the outer one by a spacing of at least 30 cm for back airing, represents the wall proper. It is the supporting element, the closing to the exterior and, at the same time, provides the thermal insulation. The non-transparent spandrels of the warm facade (figure 12b) consist of a glass sheet with insulation attached to its back side and a room-side vapor barrier. This panel is fastened on the supporting construction of the facade. It assumes all functions of a wall including architectural design.

The glass sheets of the spandrels consist either of enameled single panes or of insulating glass. To provide color matching in the first case, the pane may moreover be coated at the outside by a solar control coating based on metal oxides; in the second case it usually consists of insulating glass coated with the same solar control coating as that of the window. In all cases the panes of the spandrels must be thermal-shock resistant. The mounting of the windows and spandrels in the construction of the facade and the related standards and building codes for the Federal Republic of Germany are not treated here and are referred to in [21].

All important producers of solar control glass today have computer programs which are able to determine the energetically most favorable solar control glass from their program considering optical and thermal data, the climatological data of the proposed location and the design of the building. It then behooves the architect to choose from this determination the product most suitable for the facade design as to color. There are no German standards for the installation of solar control glass in air-conditioned buildings; the standard DIN 4108 [8] just expresses recommendations.

An all-glass facade of uniform color – as frequently desired by architects – cannot always be achieved with solar control glass. On the one hand, it is often not possible to realize spandrel glasses with the same coatings as those of the windows. In this case single enameled panes have to be applied whose color effect can only be adapted to that of the windows. On the other hand, one has to account for the fact that in Europe light transmissions of more than 30 % are usual. At that level of transmission it it impossible to achieve a color match between window and spandrel even for identical coatings and identical construction. This is because the different backgrounds of windows and spandrels significantly affect the color impression of the exterior. For this reason the matching of window and spandrel can only be approximated. An absolute match, even for equal coatings of window and spandrel can only be achieved when the light transmission is below 30 %. To avoid misunderstanding, it is advisable for the architect to consult the producers of solar control glass as to the possibilities of color design for all-glass facades.

Increasing demands on glazing include – besides the function of solar control and heat conservation – the additional functions of acoustic control and fire and burglary protection. Today all these functions can be realized in one glazing system by adequate insulating glass construction. Such glazings are called multifunction insulating glasses and are offered by all important producers of insulating glasses.

5. Summary

Solar control glass permits a significant reduction of the cost of air conditioning in a building, thus saving energy. In addition, solar control glass because of the available color palette represents an excellent element of facade design. Compared to other methods of solar control, solar control glass has the advantage of weathering resistance, of lacking susceptibility to disturbance, and of needing no service.

In the moderate climatic zones of earth, solar control glass is constructed predominantly in the form of insulating glass, with a maximum efficiency provided by solar control on the exterior pane. Solar control is determined by a minimal *g* value. In addition, solar control glass should permit good daylight illumination of the interior space. This can only be adhered to if the ratio of light transmission to *g* value, the selectivity number *S*, is larger than 1.

Solar control may be achieved by colored glass and solar control coatings. Compared to colored glass, coatings allow the realization of a larger palette of exterior colors as well as the tuning to climatological values and the construction and location of the building. This is why coated solar control glass is now being used predominantly.

Since the design function of solar control glass is very important, the development and production of solar control coatings require much attention to the uniformity and reproducibility of the color as seen from the outside. Relatively simple coatings have become acceptable. In deposition, optical constants and thicknesses must be controlled closely. This implies an efficient final inspection of the coating and the exact maintenance of process parameters during the coating process. Solar control coatings today are predominantly produced by cathode sputtering and pyrolytic spraying. Because of the building-related manufacture, batch plants for the coating process are indicated.

All-glass facades with solar control glass are produced as cold or warm facades. A serious problem is the color match between window glazing and the rest of the facade as often desired by architects. A complete match can only be achieved with panes whose light transmission is less than 30 %. Otherwise the color of the facade has to be adapted to that of the glazing. For the evaluation of the color of the solar control glass in a facade, the background is of great importance. The location of the building and surrounding land use and/or landscaping, sky light and angle of observation all decisively influence visual inspection of a facade glazed with solar control glass.

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