Solar material protection factor (SMPF) and solar skin protection factor (SSPF) for window panes and other glass structures in buildings

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Abstract

The two quantities solar material protection factor (SMPF) and solar skin protection factor (SSPF) are introduced in order to measure and calculate the capability of glass to protect indoor materials and human skin from degradation caused by the solar radiation. Comparison of the SMPF and SSPF values for different glass fabrications enables one to select the most appropriate glass material for the specific buildings. Numerical examples are shown with measurements and calculations carried out on various glass materials, including two electrochromic window (ECW) devices, and several two- and three-layer window pane combinations. Visibility levels at various protection degrees are also given.
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1. Introduction

Since early times when man discovered and began utilizing the glass material in their buildings, they have had efficient means to let sunlight into the buildings and at the same time be protected from harsh weather in the form of rain and wind outside. This has provided mankind with buildings where daylight and solar heat have given comfortable living and working spaces in a protected environment. With the following citation we may go back 4000–6000 years in history [1]:

Who, when he first saw the sand or ashes ... melted into a metallic form ... would have imagined that, in this shapeless lump, lay concealed so many conveniences of life? ... Yet, by some such fortuitous liquefaction was mankind taught to procure a body ... which might admit the light of the sun, and exclude the violence of the wind ...

As the use of window panes and glass structures in buildings have become more and more widespread and extensive up throughout the years, the construction design and glass-material properties have become more important. This is also strengthened by the increasing tendency of often employing rather large glass areas in today’s buildings.

Glass with material additives and different surface coatings is tailor-made and chosen in order to fulfil the various requirements for the specific buildings. The glass and window properties are selected with respect to several, often contradictory, considerations. Generally, a window is supposed to let in as much daylight as possible, give comfortable luminance conditions, give satisfactory view out of (and often into) buildings, transmit minimum heat from the interior to the exterior in order to reduce the heating demand, transmit solar radiation from the exterior to the interior in order to reduce the heating demand (i.e., in winter), shut off solar radiation by reflection, which otherwise might cause too much heating, not induce air current problems or give a poor thermal comfort and not induce unacceptable interior or exterior water condensation.
As is seen from the above, very much concern is taken regarding the energy aspects of window panes. The energy transfer in windows consists of sun radiation, thermal (infrared) radiation, thermal conduction in solids and gases and gas convection. The glass materials with surface coatings and window details are adapted to the actual building type and function, e.g., office building, hospital, family dwelling etc. The energy from the solar radiation will diminish the need for heating, but at the same time the energy costs due to cooling demands should be kept as low as possible. The measurement and calculation of quantities such as solar transmittance, solar reflectance and solar factor is important in this respect. The solar factor (SF) is the sum of the solar transmittance and the emitted infrared radiation inwards the building, i.e., the total solar energy transmission through the glazing.

One aspect with window glass panes, however, has not been emphasized in the same extent. The solar radiation is responsible for part of the degradation of the building materials, especially organic matter where the chemical bonds may be broken up by the more energetic parts of the solar spectrum, i.e., ultraviolet (UV) light. A substantial part of the UV light is blocked by the glass itself, but nevertheless a significant amount of UV light passes through the glass and into the buildings. This transmitted UV light affects both materials and living species inside the buildings. Typical examples may be fading, discoloration and degradation of books in book shelves (e.g., in libraries) and other paper materials, wall paintings and exhibits (e.g., in museums), wood materials in walls, floor, ceiling, window frames, etc., plastic materials and surface painting in various building structures and equipment, furniture and carpets. Other examples may be green plants and flowers (e.g., in family dwellings, atriums with large glass areas, greenhouses), livestock and pet animals in various buildings and human beings in situations with larger exposed skin areas (in winter gardens, indoor swimming and recreation areas with large glass facades, etc.). The desire to be able to look in and out of windows is in direct contradiction to the material and skin protection abilities, especially the material protection, as we will see later in this work. Electrochromic window (ECW) devices, which are able to control the solar radiation passage by varying the applied voltage, might also be of interest in this respect. Protection of human skin from sunlight, especially the short-wave radiation, is also interesting in other structures than buildings, e.g., in automobiles.

In order to quantify and compare the ability of different glass materials (with and without coating) to protect indoor building materials and articles, and skin of human beings, we will introduce the two quantities in this work, solar material protection factor (SMPF) and solar skin protection factor (SSPF), for window panes and other glass structures in buildings.

2. Solar radiation

The solar radiation at the earth’s surface is roughly located between 300 and 3000 nm (0.3 and 3 μm, respectively), where the visible (vis) light lies between 380 (400) and 780 nm. UV and infrared (IR) radiation are located below and above the vis region, respectively. The wavelength region between 780 and 3000 nm is called the near infrared (NIR) region. Fig. 1 depicts the solar radiation in outer space and at the earth’s surface, both with and without molecular absorption in the atmosphere.

![Fig. 1. The radiation from the sun, comparing the AM0 (outer space) and AM2 (at the earth’s surface, the sun 30° above the horizon) spectra. The AM2 spectrum is shown both with and without molecular absorption (in O₂, O₃, H₂O and CO₂). Redrawn from Fahrenbruch and Bube [2].](image-url)
The UV light is further divided into the three subregions: UV-A (315–380 nm), UV-B (280–315 nm) and UVC (100–280 nm) (wavelength borders may have small variations in the literature).

3. Material and skin degradation by solar radiation

Solar radiation, particularly the high-energy part of the solar spectrum, i.e., ultraviolet light, will depend on exposure level and time, damage organic materials. Both building materials like wood, plastic and paint, and human skin, might be vulnerable to various levels of solar radiation exposure.

The photodamage in materials ranges from discoloration to loss of mechanical integrity, while human skin may experience light sun tanning or more heavily sun burning, the latter one exemplifying loss of skin integrity.

Several strategies are employed in order to protect against the solar deterioration. Organic building materials might be protected through the application of light stabilizers and/or surface treatment. Human skin may be protected by the use of sun tan lotion (sunblock) and/or various clothing.

The purpose of this work however, is to give a measure of how well building materials and human skin are protected inside buildings, where the solar radiation enters through windows and other glass structures, i.e., we want to investigate the protection level of the various window panes and glass structures. This is achieved by calculating the two quantities SMPF and SSPF based on spectrophotometric measurements. The SMPF and SSPF values for various glass materials with or without different coatings, may easily be compared in order to choose the most suitable glass material for the building in question.

The SMPF and SSPF values are thus only dependent on the glazing system’s ability to stop the solar radiation, i.e., no dependence on solar radiation levels or properties of the material or skin to be protected. However, inherently in the calculation procedures of SMPF and SSPF, there is made a basis on a specific fictitious standard of material’s or skin’s photoresistance dependence on solar radiation with wavelength and the material or skin itself. This dependence is embedded in the chosen values, which we will see later in Tables 1 and 2. Although this may not be sufficient in detailed studies of certain materials (or skin), it provides, in most cases, a practical and satisfactory way of comparing the protection properties of different glass materials.

Two identical materials behind two window panes with identical SMPF values may experience different photodeterioration. This may be due to variations in solar radiation caused by different location on earth, seasonal fluctuations, changes in ozone layer, etc. It may also be caused by the fact that the SMPF (and SSPF) value is an integrated value over part of the solar spectrum, from 300 to 600 nm (SMPF) or 400 nm (SSPF). This implies that two glass products with (nearly) identical SMPF or SSPF values may have different spectroscopic solar transmittance properties in the actual wavelength region, i.e., the first glass product may be transmitting more of the solar radiation at certain wavelengths, while in other parts of the solar spectrum the second glass product may be more sunlight transmitting.

Naturally, two different materials behind two window panes, with identical solar radiation exposure, may experience various degrees of photodamage even if the window panes have identical SMPF values, as the materials in question probably will have different photoresistance.

Solar degradation of organic materials may include chemical, physical or biological reactions resulting in bond scission of organic materials with subsequent chemical transformations. These processes may involve molecular branching and crosslinking, fragmentations of molecular main chain leading to changes in molecular weight, alterations due to splitting of low-molecular-weight species, unsaturated carbon double bonds (C= C) and oxygenated groups. The photodegradation mechanism is influenced by thermal degradation, mechanochemical degradation, physical ageing and oxidation processes.

The actual photodegradation mechanisms for different materials may be very complicated and involving several reaction steps, where oxygen and other environmental influences may be crucial for the exact reaction course. As an example, a reaction set consisting of 91 elementary reactions and 58 different species was needed to reproduce the experimentally measured kinetics for the photodegradation of a model system simulating lignin yellowing, e.g., the observed light-induced discoloration of wood materials in buildings [3]. Quantitative spectroscopy, including both UV and IR absorption measurements, in order to determine the effects of photodegradation of a polymer coating, is performed in a recent work by Croll and Skaja [4]. Furthermore, Gerlock et al. [5] apply both UV and IR spectroscopy to assess the weathering performance of different clearcoats.

Photodegradation, photooxidation and photostabilization of polymers have been summarized by Rånby and Rabek [6] in an extensive work with plenty of examples, including detailed reaction equations. Polymer photodegradation, collecting a vast number of detailed reaction mechanisms, is also treated in another comprehensive work by Rabek [7]. Furthermore, detailed photodegradation mechanisms of several polymers and polymer groups, including a large number of general reaction equations in addition to the more specific reactions, have been collected by Rabek in yet another work [8].

As an example of reaction progress during photodegradation, polyvinylchloride (PVC) may be chosen. Degradation and crosslinking processes occur during UV irradiation of PVC. In addition, hydrogen chloride (HCl) and conjugated polyenes are formed. The PVC colouration is explained by the formation of polyene structures by the following mechanism in the first step [6] (also refer
where $h^2 \approx \frac{2 \pi}{\lambda}$ sequences according to the following reaction [8]:

$$\text{CH}_2\text{CHCl} + \text{HCl} \rightarrow \text{CH}_2\text{CH} = \text{CHCl} + \text{HCl} \quad (4)$$

It is generally agreed that the shown dehydrochlorination is a “zipper” type reaction, where the yellow colouration requires a minimum of seven conjugated double bonds in a sequence [6].

Generally, the photodegradation of chlorinated polymers, e.g., PVC, results in formation of chlorinated polyene sequences according to the following reaction [8]:

$$\text{CH}_2\text{Cl} + \text{HCl} \rightarrow \text{CH}_2\text{Cl} \quad (5)$$

As wood is a commonly used building material, and thereby also exposed to photodegradation by the sun, we will, in the following, show an example of solar deterioration of cellulose.

The actual composition of the photodegradation products depends on the cellulose type, where the following reaction mechanism for the primary processes during photodegradation of cellulose has been proposed [6] (also refer to Ref. [7]):

$$-\text{CH}_2\text{CHCl} - \text{HCl} \rightarrow -\text{CH}_2\text{CH} = \text{CHCl} \quad (6)$$

As a simplistic model for the photodegradation process, the solar radiation single photon energy need to be larger than the chemical bonding energy in the molecules or atomic lattices in order to break up the bonds. That is, a carbon–chloride (C–Cl) bonding of $5.42 \times 10^{-19} \text{ J}$ (327 kJ/mol) may be broken by UV photons of wavelength 300 nm and energy $6.63 \times 10^{-19} \text{ J}$ (4.14 eV), but not by light of wavelength 400 nm (border UV/vis) and energy $4.97 \times 10^{-19} \text{ J}$ (3.11 eV). For calculations of photon energy, recall the relationship:

$$E = h \nu = \frac{hc}{\lambda}, \quad (7)$$

where $E$ denotes the photon energy, $h$ the Planck constant ($6.63 \times 10^{-34} \text{ J} \cdot \text{s}$), $\nu$ the photon frequency, $\lambda$ the photon wavelength and $c$ the light velocity ($3.00 \times 10^8 \text{ m/s}$). The Avogadro number $N_A$ ($6.02 \times 10^{23} \text{ mol}^{-1}$) and the elementary (electron) charge $e$ ($1.60 \times 10^{-19} \text{ C}$) may be applied in various of these calculations. Reorganization of Eq. (7) yields

$$\lambda_{\text{threshold}} = \frac{hc}{E_{\text{threshold}}}, \quad (8)$$

where $\lambda_{\text{threshold}}$ and $E_{\text{threshold}}$ denote the threshold photon wavelength and energy, where wavelengths below and energies above, will break the actual chemical bond, respectively, e.g., 367 nm and 327 kJ/mol for C–Cl.

The exact composition and structure of the various materials on an atomic level will determine the exact photon energy required to break up the bonds, e.g., one or more hydrogen atoms bonded to the same carbon atom as the chloride atom in the example above, may increase the bonding energy, i.e., CH$_2$–Cl (343 kJ/mol) has a larger bonding energy than C–Cl (327 kJ/mol). Impurities in the materials may also be responsible for absorption of light at higher wavelengths.

At last it should be commented that in some cases it is actual desirable to have polymers and other materials, which will deteriorate after some specified time, i.e., materials with controlled lifetimes, in order to reduce the waste problem and improve the environment. This is obviously in direct contradiction to the usual desired long-time endurable plastics and building materials; and proper care must be taken to ensure the best choice of materials and protection system. Generally speaking on a global basis, these opposing forces involve a complex and multifaceted system with a vast number of considerations to be carried out. The SMPF and SSPF values for window panes and other glass structures in buildings may be very helpful in some of these considerations.

4. Experimental

To illustrate various transmittance, absorbance and reflectance levels in the solar spectrum, one float glass, one glass with a low-emittance coating, one dark silver-coated glass, several two- and three-layer window pane combinations, and two ECW devices, were selected as examples. Based on these measurements the SMPF and the
SSPF were calculated. In addition, in order to quantify the visibility at the various protection levels, the visible solar transmittance ($T_{vis}$) was calculated.

A Cary 5 UV-vis-NIR spectrophotometer, with an absolute reflectance accessory (VW principle), was used to measure the transmittance and reflectance of these glass samples in the UV, vis and NIR regions, from 290 to 3300 nm. The absorbance was calculated from the following relationship:

$$T(\lambda) + A(\lambda) + R(\lambda) = 1 \quad (100\%),$$  \hspace{1cm} (9)

where $T$, $A$, $R$ and $\lambda$ denote the transmittance, absorbance, reflectance and wavelength of the solar radiation, respectively. Eq. (9) expresses the total energy conservation in the light beam. For a body in thermodynamic equilibrium with its surroundings the energy absorbed in the material must be equal to the emitted energy.

5. Calculation method and definition of solar protection factors

This chapter contains the calculation method employed in order to determine the two quantities SMPF and SSPF. In order to quantify the visibility levels at the various protection levels, the $T_{vis}$ is also defined in this chapter.

5.1. Solar material protection factor (SMPF)

The SMPF is given by the following expression:

$$SMPF = 1 - \frac{\sum_{\lambda = 300}^{600} T(\lambda)C_{\lambda}S_{\lambda}\Delta\lambda}{\sum_{\lambda = 300}^{600} C_{\lambda}S_{\lambda}\Delta\lambda},$$  \hspace{1cm} (10)

where $C_{\lambda}$ is the CIE damage factor [9,10]; $C_{\lambda} = e^{-0.012\lambda}$ ($\lambda$ given in nm); $S_{\lambda}$ the relative spectral distribution of solar radiation [9,11]; $T(\lambda)$ the spectral transmittance of the glass; $\lambda$ the wavelength; $\Delta\lambda$ the wavelength interval; $C_{\lambda}S_{\lambda}\Delta\lambda$ values at different wavelengths are given in Table 1 [9].

The SMPF value will thus be a number between 0 and 1, similar to and consistent with related values like solar transmittance, emissivity, solar factor, etc. A low number indicates a low material protection, whereas a high number represents a high degree of material protection. In common usage the SMPF values may often be chosen in percentage, i.e., between 0% and 100%.

One should notice that the wavelength region for the calculation of SMPF recently has been extended from the earlier 500 nm upper limit till today’s value of 600 nm [9], demonstrating an increased awareness that a much larger part of the visible solar spectrum also contributes to the degradation of materials (Earlier a Krochmann damage factor for materials was calculated, with integration between 300 and 500 nm [12]).

It should further be noted that some of the short-wavelength part of the UV solar spectrum is not covered in the calculation of SMPF, and in future versions of ISO/FDIS 9050:2003(E) [9] the wavelength range may favourably be extended to cover an even larger part of the UV and vis solar radiation, e.g., from 290 to 600 nm.

5.2. Solar skin protection factor (SSPF)

The SSPF is given by the following expression:

$$SSPF = 1 - F_{sd} = 1 - \frac{\sum_{\lambda = 300}^{400} T(\lambda)E_{\lambda}S_{\lambda}\Delta\lambda}{\sum_{\lambda = 300}^{400} E_{\lambda}S_{\lambda}\Delta\lambda},$$  \hspace{1cm} (11)

where $F_{sd}$ is the skin damage factor [9,13]; $E_{\lambda}$ the CIE erythemal effectiveness spectrum; $S_{\lambda}$ the relative spectral distribution of solar radiation [9,11]; $T(\lambda)$ the spectral transmittance of the glass; $\lambda$ the wavelength; $\Delta\lambda$ the wavelength interval; $E_{\lambda}S_{\lambda}\Delta\lambda$ values at different wavelengths are given in Table 2 [9].

The SSPF value will thus be a number between 0 and 1, similar to and consistent with related values like solar transmittance, emissivity, solar factor, etc. A low number indicates a low skin protection, whereas a high number represents a high degree of skin protection. In common usage the SSPF values may often be chosen in percentage, i.e., between 0% and 100%.

The calculation of the SSPF extends over the UV spectrum (at earth’s surface) and the low-wavelength part of the vis spectrum, which may contribute to the solar radiation damage of the human skin. It may be noted that earlier there existed another definition of a skin protection factor, denoted SPF [12], with the following correlation.
between the different terms: \( \text{SSPF} = 1 - (1/\text{SPF}) = 1 - \text{F}_{\text{sd}} = (\text{SPF} - 1)/\text{SPF} \).

It should further be noted that some of the short-wavelength part of the UV solar spectrum is not covered in the calculation of SSPF, and in future versions of ISO/FDIS 9050:2003(E) [9] the wavelength range may favourably be extended to cover an even larger part of the UV and vis solar radiation, e.g. from 290 to 400 nm.

### 5.3. Visible solar transmittance

The visible solar transmittance \( (T_{\text{vis}}) \), often denoted light transmittance, is given by the following expression [9]:

\[
T_{\text{vis}} = \frac{\int_{380 \text{ nm}}^{780 \text{ nm}} T(\lambda) D_\lambda V(\lambda) \Delta \lambda}{\int_{380 \text{ nm}}^{780 \text{ nm}} D_\lambda V(\lambda) \Delta \lambda},
\]

where \( D_\lambda \) is the relative spectral distribution of illuminant D65 [9,14]; \( V(\lambda) \) the spectral luminous efficiency for photopic vision defining the standard observer; for photometry [9,15]; \( T(\lambda) \) the spectral transmittance of the glass; \( \lambda \) the wavelength; \( \Delta \lambda \) the wavelength interval; \( D_\lambda V(\lambda) \Delta \lambda \) values at different wavelengths are given in Table 3 [9].

The \( T_{\text{vis}} \) value will thus be a number between 0 and 1, calculated in the visible part of the solar spectrum, i.e., 380–780 nm. A low number indicates a low transmission of vis light, whereas a high number represents a high vis light transmission. In common usage the \( T_{\text{vis}} \) values may often be chosen in percentage, i.e., between 0% and 100%.

### 5.4. Generally about SMPF, SSPF and \( T_{\text{vis}} \)

Generally, one should note that both SMPF and SSPF are protection factors. The word “protection” promotes positive associations, while “damage” in CIE damage factor and in skin damage factor, may give negative associations. It may be easier and better for a potential window customer to look for a window with the highest protection factor, and not the lowest damage factor, and which would probably sell far more windows also (!).

The SMPF, SSPF and \( T_{\text{vis}} \) quantities may readily be calculated by application of simple computer programs. However, with today’s sophisticated data collection tools in computers and instruments, there should be no reason for not applying even higher resolutions, i.e., narrower (wavelength) data intervals, in future versions of Tables 1–3. In order to simplify the programming of the calculation procedures, there should be chosen one wavelength interval for the whole table. For easy implementation of the table values in calculation procedures, there may be given a reference in the standard (ISO/FDIS 9050:2003(E) [9]) to an internet web site where the table values may be downloaded as ASCII files.

### 6. Glass measurements and calculation examples

In the following, spectrophotometric measurements along with calculations of the SMPF and SSPF, will be shown for one float glass, one glass with a low-emittance coating, one dark silver-coated glass, several two- and three-layer window pane combinations, and two ECW devices at various coloration levels. The visible solar transmittance \( T_{\text{vis}} \) values for each glass or window configuration are also calculated in order to compare the visibility with the various material and skin protection levels. The absorbance spectra depicted in the following sections comply with the absorbance definition in Eq. (9), a number between 0 and 1, i.e., the absorbance is not written
on the often used/measured logarithmic scale called optical density.

6.1. Spectroscopical data for float glass and low-emittance glass

The transmittance, absorbance and reflectance in the whole solar spectrum were measured for one float glass and one glass with low-emittance coating, depicted in Figs. 2 and 3, respectively. The measured wavelength range is from 290 to 3300 nm. The upper border of 3300 nm represents the spectrophotometer’s long-wave limit, while below 290 nm the absorption in glass becomes very large. The most noticeable difference is the large reflectance values, and thereby small transmittance values, in the near IR region for the glass with the low-emittance coating. By taking a closer look at the UV and vis regions (Figs. 4 and 5) it is observed that the low-emittance glass is absorbing more light at these lower wavelengths than the float glass, i.e., the transmittance is lower for the low-emittance glass than the float glass in the UV–vis regions (in addition to the NIR region referred above).

The drop in transmittance at around 1000 nm, with a corresponding absorbance peak, as seen in Fig. 2, is due to a certain impurity amount of ferric oxide (Fe₂O₃) in the glass. The sharp transmittance cutoffs located around 400 and 2700 nm are due to the large absorption in glass into the UV and IR regions, respectively, see Figs. 2 and 3. The sharp transmittance cutoff, with corresponding absorbance increase, at around 2700 nm, is also observed in Fig. 3 for the low-emittance glass, but much smaller in value since the largest part of the incoming light in this wavelength region is reflected from the low-emittance coating (the coating surface is facing the incident light beam in the spectrophotometer).

6.2. Spectroscopical data for dark silver coated glass

The transmittance, absorbance and reflectance in the whole solar spectrum were measured for one dark silver-coated glass, which is depicted in Fig. 6. In addition, the UV and vis regions are shown in Fig. 7. The transmittance is found to be rather low, between 0.1 to 0.2, in almost the whole UV–vis–NIR regions. Both the reflectance and
absorbance are quite high in the whole UV–vis–NIR regions, with the absorbance dominating in the UV–vis regions (0.45–0.7) while still retaining a substantial reflectance (0.3–0.4), which gives rise to the dark absorbing and reflecting colour. As will be seen later (Table 4), this coating will result in high SMPF and SSPF values, i.e., high material and skin protection.

6.3. Spectroscopical data for electrochromic windows

Electrochromic windows (ECWs) are able to control the colour of the window, thereby also the solar radiation throughput, by varying the applied electrical potential. A schematic drawing of one ECW is shown in Fig. 8, constructed in a sandwich form from the electrochromic

![Fig. 8. Schematic drawing of the electrochromic window (ECW) configuration based on the electrochromic materials polyaniline (PANI), prussian blue (PB) and tungsten oxide (WO₃). From Jelle et al. [16].](image)

Table 4

<table>
<thead>
<tr>
<th>Window pane type</th>
<th>Configuration</th>
<th>$T_{vis}$</th>
<th>SMPF</th>
<th>SSPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single float glass</td>
<td>G</td>
<td>0.89</td>
<td>0.20</td>
<td>0.81</td>
</tr>
<tr>
<td>Single low-emittance glass</td>
<td>G/LE</td>
<td>0.86</td>
<td>0.32</td>
<td>0.89</td>
</tr>
<tr>
<td>Single low-emittance glass</td>
<td>LE/G</td>
<td>0.86</td>
<td>0.32</td>
<td>0.89</td>
</tr>
<tr>
<td>Single dark silver-coated glass</td>
<td>G/S</td>
<td>0.20</td>
<td>0.85</td>
<td>0.97</td>
</tr>
<tr>
<td>Single dark silver-coated glass</td>
<td>S/G</td>
<td>0.16</td>
<td>0.85</td>
<td>0.97</td>
</tr>
<tr>
<td>Two-layer 1 (float/float)</td>
<td>G/A/G</td>
<td>0.80</td>
<td>0.31</td>
<td>0.87</td>
</tr>
<tr>
<td>Two-layer 2 (float/low E)</td>
<td>G/A/LE/G</td>
<td>0.77</td>
<td>0.41</td>
<td>0.92</td>
</tr>
<tr>
<td>Two-layer 3 (float/silver)</td>
<td>G/A/S/G</td>
<td>0.19</td>
<td>0.87</td>
<td>0.98</td>
</tr>
<tr>
<td>Two-layer 4 (silver/float)</td>
<td>G/S/A/G</td>
<td>0.19</td>
<td>0.87</td>
<td>0.98</td>
</tr>
<tr>
<td>Two-layer 5 (silver/low E)</td>
<td>G/S/A/LE/G</td>
<td>0.18</td>
<td>0.88</td>
<td>0.99</td>
</tr>
<tr>
<td>Three-layer 1 (float/float/float)</td>
<td>G/A/G/A/G</td>
<td>0.73</td>
<td>0.40</td>
<td>0.90</td>
</tr>
<tr>
<td>Three-layer 2 (float/float/low E)</td>
<td>G/A/G/A/LE/G</td>
<td>0.69</td>
<td>0.48</td>
<td>0.93</td>
</tr>
<tr>
<td>Three-layer 3 (float/low E/low E)</td>
<td>G/A/LE/G/A/LE/G</td>
<td>0.66</td>
<td>0.54</td>
<td>0.95</td>
</tr>
<tr>
<td>Three-layer 4 (silver/low E/low E)</td>
<td>G/S/A/LE/G/A/LE/G</td>
<td>0.15</td>
<td>0.91</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Corresponding transmittance curves are depicted in Figs. 2–7. The following configuration denotations are employed: $G =$ glass, LE = low-emittance coating, $S =$ dark silver coating, $A =$ air cavity.
materials polyaniline (PANI), prussian blue (PB) and tungsten oxide (WO₃), transparent conducting glass plates with an indium–tin oxide (indium oxide doped with tin, In₂O₃(Sn), ITO, typical surface resistivity of 90 Ω/□) coating and the solid state polymer electrolyte poly(2-acrylamido–2-methyl–propane–sulphonic acid) (PAMPS) as an ionic conductor. Both the PANI, PB and WO₃ coating thicknesses are less than 1 μm, while the PAMPS layer thickness is about 0.1 mm. Applying a positive potential to the PANI/PB electrode, both PANI, PB and WO₃ turn to a blue colour, while the window is bleached (made almost transparent) by reversing the polarity of the electrodes. Only a small charge density of about 3 mC/cm², corresponding to a low-energy consumption of about 5 mWh/m², is required for either the colouring or the bleaching process [16].

A high transmission regulation and solar modulation have been achieved with this type of ECW (solar regulation 53% here, typically ~50% of the total solar energy), which is depicted in Fig. 9 (whole solar spectrum) and Fig. 10 (UV–vis regions). The inclusion of PB in PANI enhances the colouration (wavelength dependent absorption), while the adhesion of PB is improved by PANI, i.e., in this respect there exists a symbiotic relationship between PANI and PB [8]. Transmittance curves for a second ECW of the same construction, though with PANI-PB multilayers and a very dark colour in the coloured state, are shown in Figs. 11 and 12 (solar regulation 49%) [17]. In addition to their evident potential benefits and savings in solar energy control, the ECWs may also be employed in order to achieve the desired protection of materials and human skin inside buildings during direct sunlight. That is, the dynamic characteristics of ECWs allow diffuse daylight through the window panes in the required amount in order to obtain a satisfactory room illumination, whereas at direct sunlight exposure, the SMPF and SSPF values for the window panes may be increased to a sufficient high-protection level.

![Fig. 9. Transmittance versus wavelength in the whole solar spectrum measured for an electrochromic window (ECW) at different applied potentials. The total solar energy regulation is 53%. Highest colouration level is at +1400 mV. Redrawn from Jelle et al. [16].](image1)

![Fig. 10. Transmittance versus wavelength in the UV and vis regions measured for an electrochromic window (ECW) at different applied potentials. Highest colouration level is at +1400 mV. Redrawn from Jelle et al. [16].](image2)

![Fig. 11. Transmittance versus wavelength in the whole solar spectrum measured for a second electrochromic window (ECW 2, PANI–PB multilayer) at different applied potentials. The total solar energy regulation is 49%. Highest colouration level is at +1200 mV. Redrawn from Jelle et al. [17].](image3)

![Fig. 12. Transmittance versus wavelength in the UV and vis regions measured for a second electrochromic window (ECW 2, PANI–PB multilayer) at different applied potentials. Highest colouration level is at +1200 mV. Redrawn from Jelle et al. [17].](image4)
6.4. SMPF and SSPF for float glass, low-emittance glass, dark silver-coated glass and several two- and three-layer window pane configurations

In Table 4, there is given calculated SMPF and SSPF values for one float glass, one low-emittance glass, one dark silver-coated glass and several two- and three-layer window pane combinations. The glass with the low-emittance coating has SMPF and SSPF values of 0.32 and 0.89, respectively, which gives better protection than the float glass with SMPF and SSPF values of 0.20 and 0.81, respectively. The decrease in visibility expressed by the $T_{\text{vis}}$ value from 0.89 (float glass) to 0.86 (low-emittance glass) is rather small. The silver-coated glass has SMPF and SSPF values of 0.85 and 0.97, respectively, which gives a far better material protection than both the float glass and the low-emittance glass. However, the low $T_{\text{vis}}$ value of 0.20 for the silver-coated glass implies a large reduction in visibility compared with the float glass or the low-emittance glass.

Naturally, the two-layer window panes give an even better protection compared with their single pane counterparts, with SMPF values of 0.31, 0.41 and 0.87, and with SSPF values of 0.87, 0.92 and 0.98, for float/float, float/low E and float/silver, respectively. Note that the SMPF is as high as 0.87 for the two-layer window pane consisting of one float glass and one silver-coated glass. The three-layer window panes give to some extent even better material protection (i.e., higher SMPF) than their two-layer window pane counterparts.

Comparing the relatively low SMPF (with silver-coated glass as an exception) and relatively high SSPF values, gives evident reasons for the everyday observation that some materials like books in book shelves become discoloured, whereas we human beings usually do not get tanned or sunburnt behind glass inside buildings.

It should be mentioned that with the earlier upper wavelength limit of 500 nm (compared with 600 nm today) in calculation of SMPF, the previous material protection values are apparently larger, 0.34, 0.52 and 0.89 for the single float glass, the low-emittance glass and the silver-coated glass, respectively. That is, a much larger part of the vis sunlight is thought today to contribute to the solar deterioration of materials.

It is clear that materials inside buildings are far better protected with the two- or three-layer window pane with one silver-coated surface than with the float or low-emittance coating alternatives, i.e., SMPF value of 0.87 versus 0.31 and 0.41 for the two-layer window pane alternatives, respectively (Table 4). By designing and choosing the appropriate window glass or glass structure, all considerations have to be taken into account, e.g. SMPF and SSPF values, energy aspects, daylight, visual appearance, etc.

In Fig. 13, the SMPF and SSPF values have been plotted versus the visible solar transmittance for the different glass configurations given in Table 4. Such a plot may offer a convenient visualization and help during the determination of a building’s solar protection and visibility requirements for window panes and other glass structures. Note the large difference between glass configurations with and without the silver coating, both in SMPF values and especially in visibility levels.

6.5. SMPF and SSPF for electrochromic windows

Table 5 gives the SMPF and SSPF for different colouration levels, i.e., at different applied electrical potentials. In addition, the visibility through the ECWs is given as the visible solar transmission ($T_{\text{vis}}$). Highest colouration level is at $+1400$ mV (ECW) and $+1200$ mV (ECW 2, PANI-PB multilayer)
different colouration levels in a second electrochromic window (ECW 2, PANI–PB multilayer). The SMPF varies from 0.61 in the transparent state to 0.82 in the (dark blue) coloured state. The SSPF for ECW 2 has only small changes around 0.97.

In addition, the visibility through the ECWs is given as the $T_{\text{vis}}$ in Table 5. Increasing SMPF values lead to decreasing $T_{\text{vis}}$ values, e.g., an increase in SMPF from 0.43 (ECW, $-1800$ mV) to 0.71 (ECW, $+1400$ mV) results in a decrease in $T_{\text{vis}}$ from 0.78 to 0.17, respectively.

In Fig. 14, the SMPF and SSPF values have been plotted vs. the visible solar transmittance for the different ECW glass configurations given in Table 5. Such a plot may offer a convenient visualization and help during the determination of a building’s solar protection and visibility requirements for window panes and other glass structures. Note the large difference between the various ECW colouration states, both in SMPF values and especially in visibility levels.

It should be noted that the above referred ECWs were constructed in order to achieve the highest possible solar energy regulation, with no thought of SMPF and SSPF values. Direct investigation in this area may therefore improve the SMPF and SSPF regulation in ECWs substantially.

Although still at the experimentally laboratory stage, the ECWs may in the future contribute to elegant, flexible glazing systems with dynamical control of the solar radiation influx, both with regard to energy aspects and protection of materials and skin of human beings inside buildings.

### 6.6. SMPF and SSPF for electrochromic windows in selected two- and three-layer window pane configurations

SMPF, SSPF and $T_{\text{vis}}$ values for selected two- and three-layer window pane configurations, with an ECW device as the outermost glass pane, are given in Table 6. The ECW device is chosen as the outermost glass pane in order to be able to regulate as much as possible of the solar radiation.

Reflectance values of the ECW have not been measured, but as the (absorbing) electrochromic coatings are located between two glass plates, the reflectance values will be close to the values for float glass, and these are hence employed in the current calculations. The corresponding transmittance curves are depicted in Figs. 2–7 and 9–12. The following configuration denotations are employed: G = glass, LE = low-emittance coating, S = dark silver coating, A = air cavity, EC = electrochromic coating device between two glass plates, EC2 = electrochromic coating device between two glass plates (PANI-PB multilayer), T or C behind EC and EC2 denote transparent or coloured state, respectively.

<table>
<thead>
<tr>
<th>Window pane type (mV)</th>
<th>Configuration</th>
<th>$T_{\text{vis}}$</th>
<th>SMPF</th>
<th>SSPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-layer A (EC/float) ($-1800$)</td>
<td>ECT/A/G</td>
<td>0.70</td>
<td>0.50</td>
<td>0.95</td>
</tr>
<tr>
<td>Two-layer A (EC/float) ($+1400$)</td>
<td>ECC/A/G</td>
<td>0.15</td>
<td>0.75</td>
<td>0.95</td>
</tr>
<tr>
<td>Two-layer B (EC/low E) ($-1800$)</td>
<td>ECT/A/LE/G</td>
<td>0.67</td>
<td>0.55</td>
<td>0.97</td>
</tr>
<tr>
<td>Two-layer B (EC/low E) ($+1400$)</td>
<td>ECC/A/LE/G</td>
<td>0.14</td>
<td>0.78</td>
<td>0.97</td>
</tr>
<tr>
<td>Two-layer C (EC/silver) ($-1800$)</td>
<td>ECT/A/S/G</td>
<td>0.16</td>
<td>0.90</td>
<td>0.99</td>
</tr>
<tr>
<td>Two-layer C (EC/silver) ($+1400$)</td>
<td>ECC/A/S/G</td>
<td>0.03</td>
<td>0.95</td>
<td>0.99</td>
</tr>
<tr>
<td>Three-layer A (EC/float/float) ($-1800$)</td>
<td>ECT/A/G/A/G</td>
<td>0.63</td>
<td>0.55</td>
<td>0.96</td>
</tr>
<tr>
<td>Three-layer A (EC/float/float) ($+1400$)</td>
<td>ECC/A/G/A/G</td>
<td>0.14</td>
<td>0.78</td>
<td>0.96</td>
</tr>
<tr>
<td>Three-layer B (EC/float/low E) ($-1800$)</td>
<td>ECT/A/G/A/LE/G</td>
<td>0.60</td>
<td>0.60</td>
<td>0.97</td>
</tr>
<tr>
<td>Three-layer B (EC/float/low E) ($+1400$)</td>
<td>ECC/A/G/A/LE/G</td>
<td>0.13</td>
<td>0.81</td>
<td>0.97</td>
</tr>
<tr>
<td>Three-layer C (EC/low E/low E) ($-1800$)</td>
<td>ECT/A/LE/G/A/LE/G</td>
<td>0.58</td>
<td>0.64</td>
<td>0.98</td>
</tr>
<tr>
<td>Three-layer C (EC/low E/low E) ($+1400$)</td>
<td>ECC/A/LE/G/A/LE/G</td>
<td>0.12</td>
<td>0.83</td>
<td>0.98</td>
</tr>
<tr>
<td>Three-layer D (EC/silver/low E) ($-1800$)</td>
<td>ECT/A/S/G/A/LE/G</td>
<td>0.14</td>
<td>0.92</td>
<td>1.00</td>
</tr>
<tr>
<td>Three-layer D (EC/silver/low E) ($+1400$)</td>
<td>ECC/A/S/G/A/LE/G</td>
<td>0.03</td>
<td>0.96</td>
<td>1.00</td>
</tr>
<tr>
<td>Three-layer E (EC/low E/low E) ($-1800$)</td>
<td>EC2T/A/S/G/A/LE/G</td>
<td>0.11</td>
<td>0.94</td>
<td>1.00</td>
</tr>
<tr>
<td>Three-layer E (EC/low E/low E) ($+1200$)</td>
<td>EC2C/A/S/G/A/LE/G</td>
<td>0.02</td>
<td>0.98</td>
<td>1.00</td>
</tr>
</tbody>
</table>
used in the current calculations. Note that the actual electrochromic coatings employed here, are mainly solar radiation absorbing materials and not reflecting materials, i.e., the small reflectance values are neglected in these calculations.

As we have no ECWs with the silver coating deposited onto the innermost glass side of the ECW device, the silver coated glass is placed as the innermost glass for the two-layer window pane configuration and as the middle glass for the three-layer window pane configuration, in the calculations given in Table 6.

For all the different ECW pane configurations calculated in Table 6, the SSPF values show only small variations between 0.95 and 1.00.

The ECW construction allows one to regulate the SMPF values between a wide range of values for the float and low-emittance glass configurations, e.g., the SMPF for the two-layer A configuration (ECT/A/G and ECC/A/G in Table 6) increases from 0.50 to 0.75 as the electrochromic coatings change from the transparent to the coloured state. Such a 50% increase in SMPF will greatly reduce the solar material deterioration, although an exact quantification of the protection enhancement will among other factors be dependent on the actual material and solar wavelength distribution through the window pane.

The ECW construction also allows one to regulate the $T_{vis}$ values between a wide range of values for the float and low-emittance glass configurations, e.g., the $T_{vis}$ value decreases from 0.70 (transparent state) to 0.15 (coloured state) for the two-layer A configuration (ECT/A/G and ECC/A/G in Table 6).

Due to the low transmittance (high reflectance and high absorbance) in the window panes with silver-coated glass, there is less variation in SMPF for the transparent and coloured ECW states, than for the ECW configurations with float or low-emittance glass, e.g., SMPF increases from 0.90 (transparent state) to 0.95 (coloured state) for the two-layer C configuration (ECT/A/S/G and ECC/A/S/G in Table 6). The $T_{vis}$ value, however, has a somewhat larger relative variation, although low, from 0.16 (transparent) to 0.03 (coloured) for the same two-layer C configuration.

Note the very high SMPF of 0.94 and 0.98 and corresponding low $T_{vis}$ of 0.11 and 0.02 for the three-layer E configuration (EC2T/A/S/G/A/LE/G and EC2C/A/S/G/A/LE/G in Table 6) in the transparent and coloured state, respectively.

In Fig. 15, the SMPF and SSPF values have been plotted versus the visible solar transmittance for the different ECW two- and three-layer window pane configurations given in Table 6. Such a plot may offer a convenient visualization and help during the determination of a building’s solar protection and visibility requirements for window panes and other glass structures. Note the large difference between the various ECW colouration states, both in SMPF values and especially in visibility levels. Also note the large difference between glass configurations with and without the silver coating, both in SMPF values and especially in visibility levels.

7. Conclusions

The two quantities solar material protection factor and solar skin protection factor, abbreviated SMPF and SSPF, respectively, have been introduced for window panes and other glass structures in buildings. These two factors give the protection degree for materials and human skin behind glass of various types. The SMPF and SSPF values for different glass fabrications, together with the quantified visibility levels, may readily be compared in order to choose the most appropriate glass material for the building in question.

Acknowledgements

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References