Electrochromic Materials and their Characterization by Solar Radiation Glazing Factors for Smart Window Applications

Bjørn Petter Jelle [ab], Tao Gao [c], Yingpeng Zhen [b] and Arild Gustavsen [c]

[a] SINTEF Building and Infrastructure,
Department of Materials and Structures,
NO-7465 Trondheim, Norway.

[b] Norwegian University of Science and Technology (NTNU),
Department of Civil and Transport Engineering,
NO-7491 Trondheim, Norway.

[c] Norwegian University of Science and Technology (NTNU),
Department of Architectural Design, History and Technology,
NO-7491 Trondheim, Norway.

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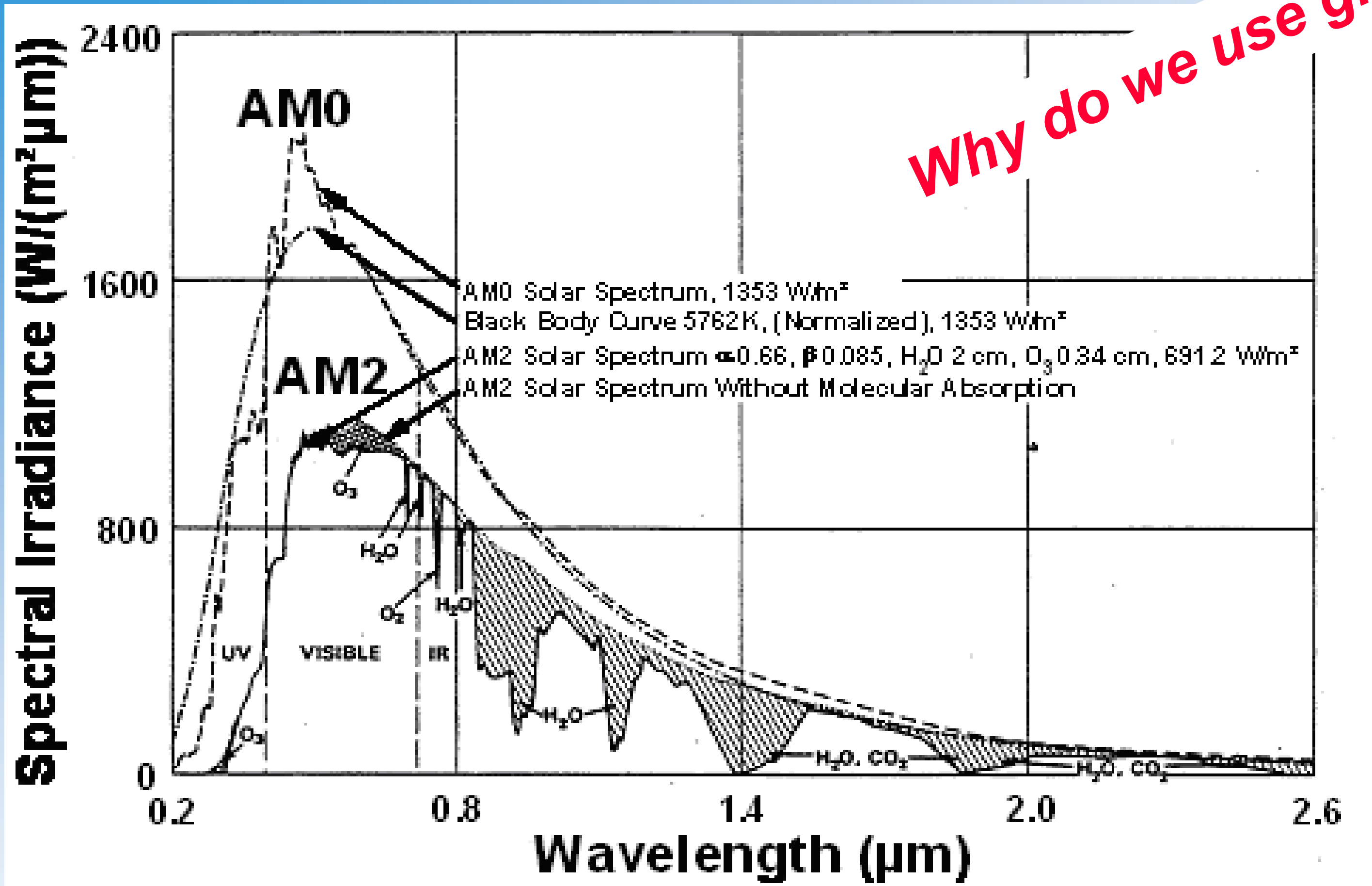
Electrochromic windows (ECWs)

- Regulates solar radiation by application of an external voltage.
- May decrease heating, cooling and electricity loads in buildings.
- Dynamic and flexible solar radiation control.
- May be characterized by a number of solar radiation glazing factors.

Glass - Solar Radiation

Why do we use glass?



- Solar Spectrum
  280-3000 nm
- Solar Ultraviolet (UV)
  280-380 nm
- Visible Light (VIS)
  380-780 nm
- Near Infrared (NIR)
  780-3000 nm

Glass

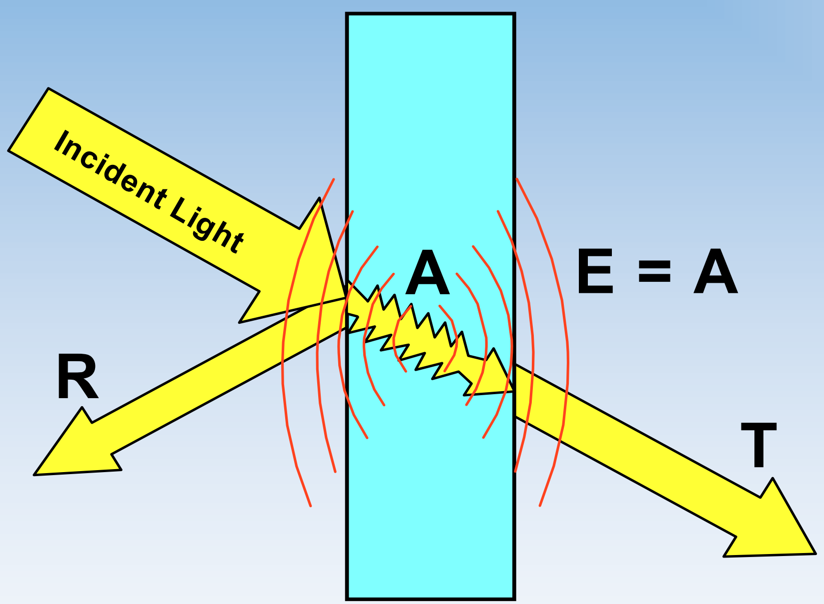
"A Marvellous Material"

- AM0 (outer space)
- AM2 (earth's surface, the sun 30º above the horizon)
- Molecular absorption (in O_2, O_3, H_2O and CO_2)
- Redrawn from: A.L. Fahrenbruch and R.H. Bube, "Fundamentals of solar cells. Photovoltaic solar energy conversion", pp. 26-31, Academic Press, 1983.

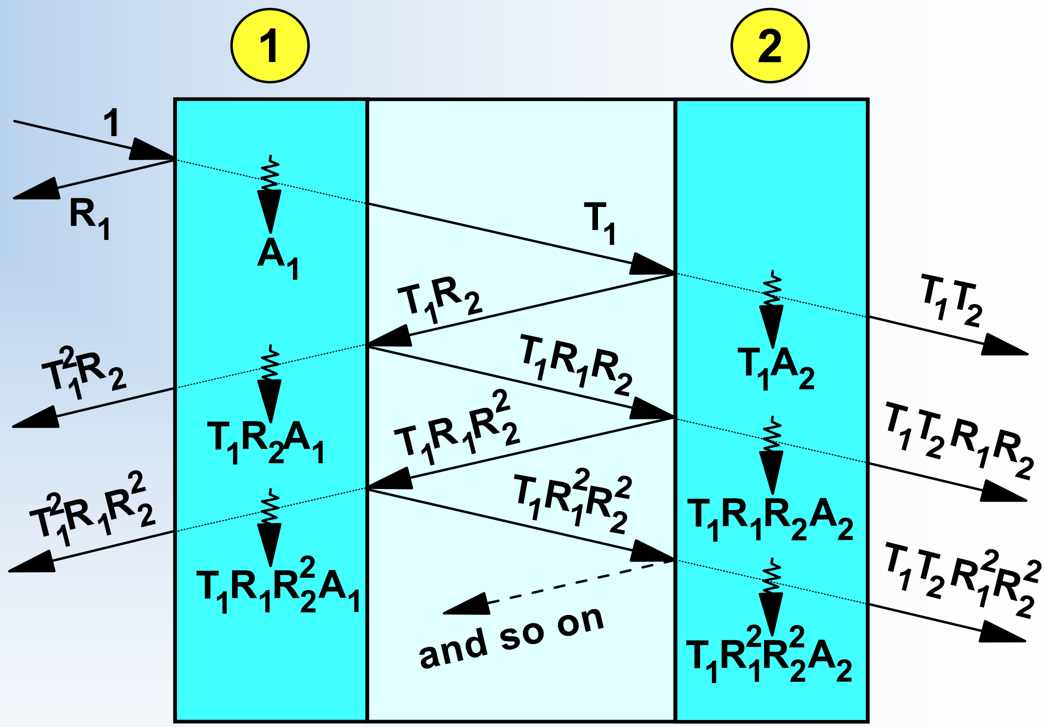
Glass – Solar Radiation – Window Panes

Solar Radiation through Window Panes and other Glass Structures

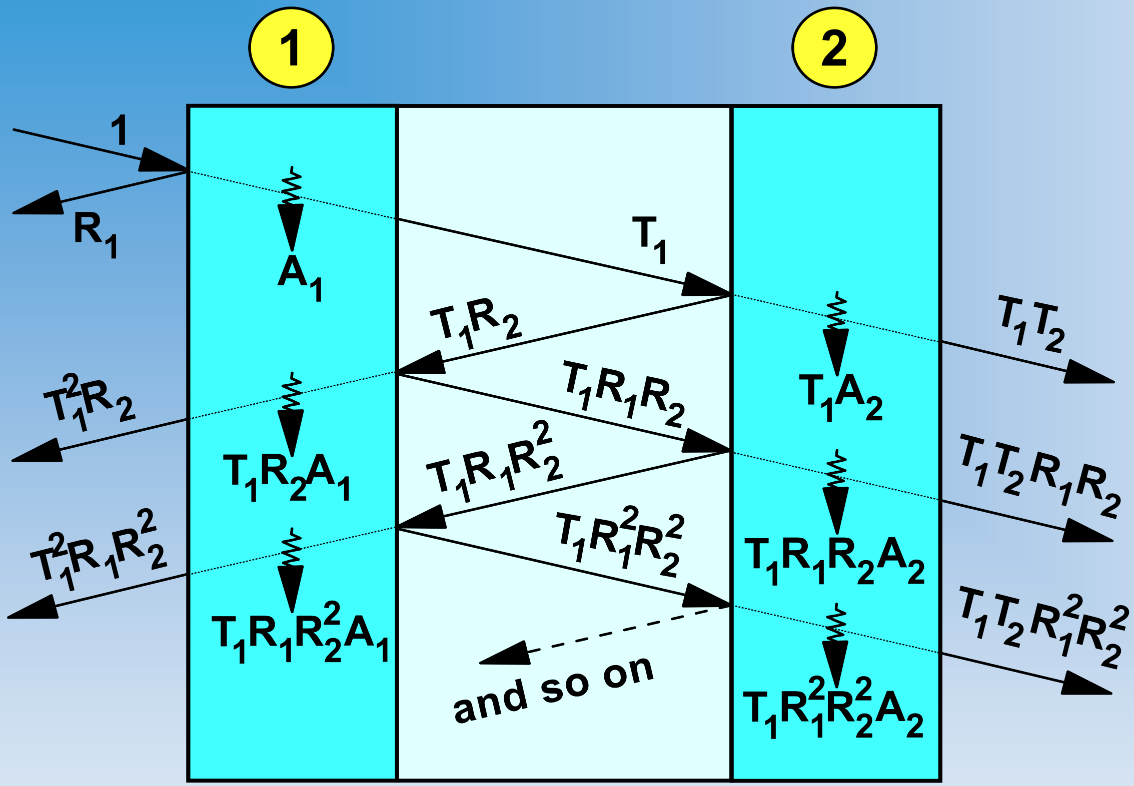
$$T(\lambda) + A(\lambda) + R(\lambda) = 1 \quad (100\ \%) \qquad \text{and} \qquad E(\lambda) = A(\lambda)$$



T + A + R = 1



Solar Radiation through Window Panes and other Glass Structures



Single Glass Pane

$$T(\lambda) = T_1$$

$$R(\lambda) = R_1$$

Two-Layer Window Pane

$$T(\lambda) = \frac{T_1 T_2}{1 - R_{1b} R_2}$$

$$R_{ext}(\lambda) = R_1 + \frac{T_1^2 R_2}{1 - R_{1b} R_2}$$

$$R_{int}(\lambda) = R_{2b} + \frac{T_2^2 R_{1b}}{1 - R_2 R_{1b}}$$

Three-Layer Window Pane

$$T(\lambda) = \frac{T_1 T_2 T_3}{[1 - R_{1b} R_2][1 - R_{2b} R_3] - T_2^2 R_{1b} R_3}$$

$$R_{ext}(\lambda) = R_1 + \frac{T_1^2 R_2 [1 - R_{2b} R_3] + T_1^2 T_2^2 R_3}{[1 - R_{1b} R_2][1 - R_{2b} R_3] - T_2^2 R_{1b} R_3}$$

$$R_{int}(\lambda) = R_{3b} + \frac{T_3^2 R_{2b} [1 - R_2 R_{1b}] + T_3^2 T_2^2 R_{1b}}{[1 - R_3 R_{2b}][1 - R_2 R_{1b}] - T_2^2 R_3 R_{1b}}$$

Solar Radiation Glazing Factors

Generally, the most important solar radiation glazing factors are:

- Ultraviolet Solar Transmittance, T_{uv}
- Visible Solar Transmittance, T_{vis}
- Solar Transmittance, T_{sol}
- Solar Material Protection Factor, SMPF
- Solar Skin Protection Factor, SSPF
- External Visible Solar Reflectance, $R_{vis,ext}$
- Internal Visible Solar Reflectance, $R_{vis,int}$
- Solar Reflectance, R_{sol}
- Solar Absorbance, A_{sol}
- Emissivity, ε
- Solar Factor, SF
- Colour Rendering Factor, CRF

A number between 0 and 1 (0 and 100 %).

Glass – Solar Radiation – Window Panes

Solar Radiation through Window Panes and other Glass Structures

The Solar Transmittance (T_{sol}) is given by the following expression:

$$T_{sol} = \frac{\sum_{\lambda=300nm}^{2500nm} T(\lambda) S_{\lambda} \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_{\lambda} \Delta\lambda}$$

S_{λ} = relative spectral distribution of solar radiation

$T(\lambda)$ = spectral transmittance of the glass

λ = wavelength

$\Delta\lambda$ = wavelength interval

$S_{\lambda}\Delta\lambda$ values at different wavelengths are given in a table

Solar Radiation Glazing Factor Definitions

Ultraviolet Solar Transmittance (T_{uv})

$$T_{uv} = \frac{\sum_{\lambda=300nm}^{380nm} T(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{380nm} S_\lambda \Delta\lambda}$$

Visible Solar Transmittance (T_{vis}) (Light Transmittance)

$$T_{vis} = \frac{\sum_{\lambda=380nm}^{780nm} T(\lambda) D_\lambda V(\lambda) \Delta\lambda}{\sum_{\lambda=380nm}^{780nm} D_\lambda V(\lambda) \Delta\lambda}$$

Solar Transmittance (T_{sol})

$$T_{sol} = \frac{\sum_{\lambda=300nm}^{2500nm} T(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_\lambda \Delta\lambda}$$

Solar Radiation Glazing Factor Definitions

Solar Material Protection Factor (SMPF)

$$\mathrm{SMPF} = 1 - \tau_{df} = 1 - \frac{\sum_{\lambda=300\,\mathrm{nm}}^{600\,\mathrm{nm}} T(\lambda) C_\lambda S_\lambda \Delta\lambda}{\sum_{\lambda=300\,\mathrm{nm}}^{600\,\mathrm{nm}} C_\lambda S_\lambda \Delta\lambda}$$

Solar Skin Protection Factor (SSPF)

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

B. P. Jelle, A. Gustavsen, T.-N. Nilsen and T. Jacobsen, "Solar Material Protection Factor (SMPF) and Solar Skin Protection Factor (SSPF) for Window Panes and other Glass Structures in Buildings", *Solar Energy Materials & Solar Cells*, 91, 342-354, 2007.

Solar Radiation Glazing Factor Definitions

External Visible Solar Reflectance ($R_{vis,ext}$)
(External Light Reflectance)

$$R_{vis,ext} = \frac{\sum_{\lambda=380nm}^{780nm} R_{ext}(\lambda) D_{\lambda} V(\lambda) \Delta\lambda}{\sum_{\lambda=380nm}^{780nm} D_{\lambda} V(\lambda) \Delta\lambda}$$

Internal Visible Solar Reflectance ($R_{vis,int}$)
(Internal Light Reflectance)

$$R_{vis,int} = \frac{\sum_{\lambda=380\,nm}^{780\,nm} R_{int}(\lambda) D_{\lambda} V(\lambda) \Delta\lambda}{\sum_{\lambda=380\,nm}^{780\,nm} D_{\lambda} V(\lambda) \Delta\lambda}$$

Solar Reflectance (R_{sol})

$$R_{sol} = \frac{\sum_{\lambda=300nm}^{2500nm} R_{ext}(\lambda) S_{\lambda} \Delta\lambda}{\sum_{\lambda=300nm}^{2500nm} S_{\lambda} \Delta\lambda}$$

Solar Radiation Glazing Factor Definitions

Solar Absorbance (A_{sol})

$$A_{sol} = 1 - T_{sol} - R_{sol} = 1 - \frac{\sum_{\lambda=300\text{nm}}^{2500\text{nm}} T(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300\text{nm}}^{2500\text{nm}} S_\lambda \Delta\lambda} - \frac{\sum_{\lambda=300\text{nm}}^{2500\text{nm}} R_{ext}(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300\text{nm}}^{2500\text{nm}} S_\lambda \Delta\lambda}$$

B. P. Jelle, ”Solar Radiation Glazing Factors for Window Panes, Glass Structures and Electrochromic Windows in Buildings - Measurement and Calculation”, *Solar Energy Materials and Solar Cells*, 116, 291-323, 2013.

Solar Radiation Glazing Factor Definitions

Emissivity (ε)

- **Specular IR reflectance measurements**

$$\varepsilon = c_{corr}\,\varepsilon_n = \frac{\varepsilon}{\varepsilon_n}\varepsilon_n = c_{corr}(1 - R_n) = c_{corr}\left[1 - \frac{1}{30}\sum_{i=1}^{30} R_n(\lambda_i)\right]$$

- **Heat flow meter measurements**

$$\varepsilon = \frac{2\left(q_{tot} - \frac{\kappa}{d}\Delta T\right)}{4\sigma T_m^3 \Delta T + q_{tot} - \frac{\kappa}{d}\Delta T}$$

- **Total hemispherical emissivity**

(Hemispherical reflectometer and integrating over the hemisphere)

$$\varepsilon = 2\int_0^{\pi/2} \varepsilon_t(\theta)\sin\theta\cos\theta\, d\theta$$

$$\varepsilon_t(\theta,\phi,\lambda) = 1 - \frac{\int_0^{\infty} R(\lambda)P(\lambda,T)\,d\lambda}{\int_0^{\infty} P(\lambda,T)\,d\lambda}$$

$$P(\lambda,T) = \frac{8\pi hc}{\lambda^5\left(e^{hc/(\lambda kT)} - 1\right)}$$

Solar Radiation Glazing Factor Definitions

Solar Factor (SF)
Total Solar Energy Transmittance – Solar Heat Gain Coefficient (SHGC) – g-value

$$SF = T_{sol} + q_i$$

q_i = secondary heat transfer factor towards the inside

Colour Rendering Factor (CRF)

Further details in ISO/FDIS 9050:2003(E), ISO 10292:1994(E), EN-ISO 6946:1996 and EN 410:1998 E

$$CRF = \frac{R_a}{100} = \frac{1}{800}\sum_{i=1}^{8} R_i$$

$R_i = 100 - 4.6\Delta E_i$ = specific colour rendering index

$\Delta E_i = \sqrt{(U^*_{t,i} - U^*_{r,i})^2 + (V^*_{t,i} - V^*_{r,i})^2 + (W^*_{t,i} - W^*_{r,i})^2}$ = total distortion of colour i

Solar Radiation Glazing Factor Definitions

where

λ = wavelength (nm)

$\Delta\lambda$ = wavelength interval (nm)

$T(\lambda)$ = spectral transmittance of the glass

$R_{ext}(\lambda)$ = external spectral reflectance of the glass

$R_{int}(\lambda)$ = internal spectral reflectance of the glass

R_n = average spectral reflectance calculated by summation of spectral reflectance values at 30 distinct wavelengths and divided by 30 as shown in Eq.20 above

λ_i = wavelength and λ_i values for the 30 wavelengths are given in ISO 10292:1994(E) and EN 12898:2001 E

S_λ = relative spectral distribution of ultraviolet solar radiation or solar radiation (ISO/FDIS 9050:2003(E), ISO 9845-1:1992(E))

D_λ = relative spectral distribution of illuminant D65 (ISO/FDIS 9050:2003(E), ISO 10526:1999(E))

$V(\lambda)$ = spectral luminous efficiency for photopic vision defining the standard observer for photometry (ISO/FDIS 9050:2003(E), ISO/CIE 10527:1991(E))

$S_\lambda\Delta\lambda$ values at different wavelengths for ultraviolet solar radiation or solar radiation are given in ISO/FDIS 9050:2003(E)

$D_\lambda V(\lambda)\Delta\lambda$ values at different wavelengths are given in ISO/FDIS 9050:2003(E)

τ_{df} = CIE damage factor (ISO/FDIS 9050:2003(E), CIE No 89/3:1990)

$C_\lambda = e^{-0.012\lambda}$ (λ given in nm)

$C_\lambda S_\lambda\Delta\lambda$ values at different wavelengths are given in ISO/FDIS 9050:2003(E)

F_{sd} = skin damage factor (ISO/FDIS 9050:2003(E), McKinlay and Diffey 1987)

E_λ = CIE erythemal effectiveness spectrum

$E_\lambda S_\lambda\Delta\lambda$ values at different wavelengths are given in ISO/FDIS 9050:2003(E)

q_{tot} = total heat flow density between two parallel, flat infinite isothermal surfaces (W/m^2) (EN 1946-2:1999 E, EN 1946-3:1999 E)

κ = thermal conductivity of the medium separating the two surfaces (W/(mK))

$\kappa = \kappa_{air} = 0.0242396(1 + 0.0030520\theta - 1.282 \cdot 10^{-6}\theta^2)$ (W/(mK))

(values accurate to 0.6 % between θ = 10ºC and θ = 70ºC)

(θ given in ºC) (EN 1946-2:1999 E, EN 1946-3:1999 E)

$\theta = (T_m - 273.15\ K)$ºC/K (ºC)

T_m = mean temperature of the two surfaces (K)

ΔT = temperature difference between the two surfaces (K)

d = distance between the two surfaces (m)

$\sigma = \pi^2k^4/(60\hbar^3c^2)$ = Stefan-Boltzmann's constant ≈ $5.67\cdot10^{-8}$ W/(m^{2}K^4)

$$\varepsilon_t(\theta,\phi,\lambda) = 1 - \frac{\int_0^\infty R(\lambda)P(\lambda,T)d\lambda}{\int_0^\infty P(\lambda,T)d\lambda}$$ (Surface Optics Corporation 2009)

$$P(\lambda,T) = \frac{8\pi hc}{\lambda^5(e^{hc/(\lambda kT)} - 1)}$$ = Planck's function (Surface Optics Corporation 2009)

R = hemispherical reflectance

T = temperature (K)

θ and ϕ are integrating angles over the hemisphere

h = Planck's constant ≈ $6.63\cdot10^{-34}$ Js

k = Boltzmann's constant ≈ $1.38\cdot10^{-23}$ J/K

c = velocity of light ≈ $3.00\cdot10^8$ m/s

T_{sol} = solar transmittance (Eq.13)

$A_{sol} = q_i + q_e$ (A_{sol} from Eq.19)

q_i = secondary heat transfer factor towards the inside

q_e = secondary heat transfer factor towards the outside (complete details for calculation of SF given in ISO/FDIS 9050:2003(E), with additions in ISO 10292:1994(E) and EN-ISO 6946:1996, note that ε and R_{sol} enter into q_i in Eq.22, R_{sol} from A_{sol})

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i$$ = general colour rendering index (EN 410:1998 E)

$R_i = 100 - 4.6\Delta E_i$ = specific colour rendering index

$$\Delta E_i = \sqrt{(U^*_{t,i} - U^*_{r,i})^2 + (V^*_{t,i} - V^*_{r,i})^2 + (W^*_{t,i} - W^*_{r,i})^2}$$ = total distortion of colour i

(complete details for calculation of CRF given in EN 410:1998 E)

Solar Factor (SF) for Single Glazing

$$SF = T_{sol} + q_i = T_{sol} + A_{sol} \frac{h_i}{h_e + h_i}$$

T_{sol} = solar transmittance (Eq. 13)

R_{sol} = solar reflectance (Eq. 18)

$A_{sol} = 1 - T_{sol} - R_{sol}$ = solar absorbance (Eq. 19 and Eq. 20)

$h_e = 23\ W/(m^2K)$ (Eq. 44, see applicable assumptions)

$$h_i = \left(3.6 + \frac{4.4\varepsilon}{0.837}\right) W/(m^2K)$$ (Eq. 45, see applicable assumptions)

ε = corrected emissivity of the inside surface

Solar Factor (SF) for Double Glazing

$$SF = T_{sol} + q_i = T_{sol} + \frac{\dfrac{A_{sol,1} + A_{sol,2}}{h_e} + \dfrac{A_{sol,2}}{\Lambda}}{\dfrac{1}{h_i} + \dfrac{1}{h_e} + \dfrac{1}{\Lambda}}$$

$$A_{sol,1} = \frac{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} \left\{ A_1 + \frac{A_{1b} T_1 R_2}{1 - R_{1b} R_2} \right\} S_\lambda \Delta\lambda}{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} S_\lambda \Delta\lambda}$$

$$A_{sol,2} = \frac{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} \left\{ \frac{A_2 T_1}{1 - R_{1b} R_2} \right\} S_\lambda \Delta\lambda}{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} S_\lambda \Delta\lambda}$$

Λ = thermal conductance between the outer surface of the outer (first) pane and the innermost surface of the inner (second) pane

$A_1 = 1 - T_1 - R_1$

$A_{1b} = 1 - T_1 - R_{1b}$

$A_2 = 1 - T_2 - R_2$

Solar Factor (SF) for Triple Glazing

$$SF = T_{sol} + q_i = T_{sol} + \frac{\dfrac{A_{sol,1} + A_{sol,2} + A_{sol,3}}{h_e} + \dfrac{A_{sol,2} + A_{sol,3}}{\Lambda_{12}} + \dfrac{A_{sol,3}}{\Lambda_{23}}}{\dfrac{1}{h_i} + \dfrac{1}{h_e} + \dfrac{1}{\Lambda_{12}} + \dfrac{1}{\Lambda_{23}}}$$

$$A_{sol,1} = \frac{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} \left\{ A_1 + \dfrac{T_1 A_{1b} R_2 (1 - R_{2b} R_3) + T_1 T_2^2 A_{1b} R_3}{(1 - R_{1b} R_2)(1 - R_{2b} R_3) - T_2^2 R_{1b} R_3} \right\} S_\lambda \Delta\lambda}{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} S_\lambda \Delta\lambda}$$

$$A_{sol,2} = \frac{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} \left\{ \dfrac{T_1 A_2 (1 - R_{2b} R_3) + T_1 T_2 A_{2b} R_3}{(1 - R_{1b} R_2)(1 - R_{2b} R_3) - T_2^2 R_{1b} R_3} \right\} S_\lambda \Delta\lambda}{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} S_\lambda \Delta\lambda}$$

$$A_{sol,3} = \frac{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} \left\{ \dfrac{T_1 T_2 A_3}{(1 - R_{1b} R_2)(1 - R_{2b} R_3) - T_2^2 R_{1b} R_3} \right\} S_\lambda \Delta\lambda}{\sum_{\lambda = 300\text{ nm}}^{2500\text{ nm}} S_\lambda \Delta\lambda}$$

Λ_{12} = thermal conductance between the outer surface of the outer (first) pane and the centre of the middle (second) pane

Λ_{23} = thermal conductance between the centre of the middle (second) pane and the centre of the inner (third) pane

$A_1 = 1 - T_1 - R_1$ (Eq. 71)

$A_{1b} = 1 - T_1 - R_{1b}$ (Eq. 72)

$A_2 = 1 - T_2 - R_2$ (Eq. 73)

$A_{2b} = 1 - T_2 - R_{2b}$

$A_3 = 1 - T_3 - R_3$

Solar Factor (SF) for Multiple Glazing

$$SF = T_{sol} + q_i$$

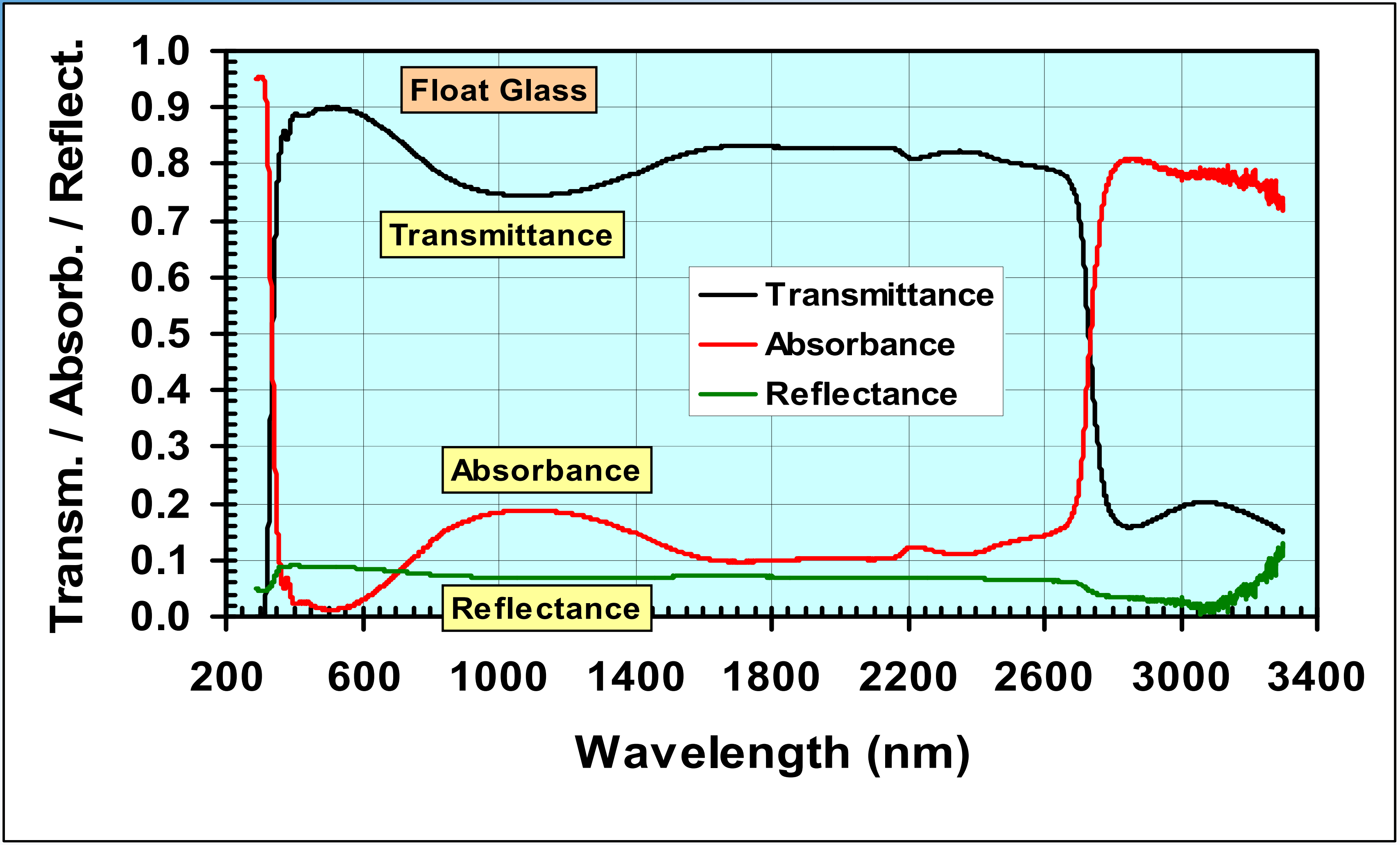
$$q_i = \frac{\dfrac{A_{sol,1} + A_{sol,2} + A_{sol,3} + \ldots + A_{sol,n}}{h_e} + \dfrac{A_{sol,2} + A_{sol,3} + \ldots + A_{sol,n}}{\Lambda_{12}} + \dfrac{A_{sol,3} + \ldots + A_{sol,n}}{\Lambda_{23}} + \dfrac{A_{sol,n}}{\Lambda_{(n-1)n}}}{\dfrac{1}{h_i} + \dfrac{1}{h_e} + \dfrac{1}{\Lambda_{12}} + \dfrac{1}{\Lambda_{23}} + \ldots + \dfrac{1}{\Lambda_{(n-1)n}}}$$

$$\frac{1}{U} = \frac{1}{h_e} + \frac{1}{\Lambda} + \frac{1}{h_i}$$

$$\Lambda = \left(\sum^{N} \frac{1}{h_s} + \sum^{M} d_m r_m \right)^{-1}$$

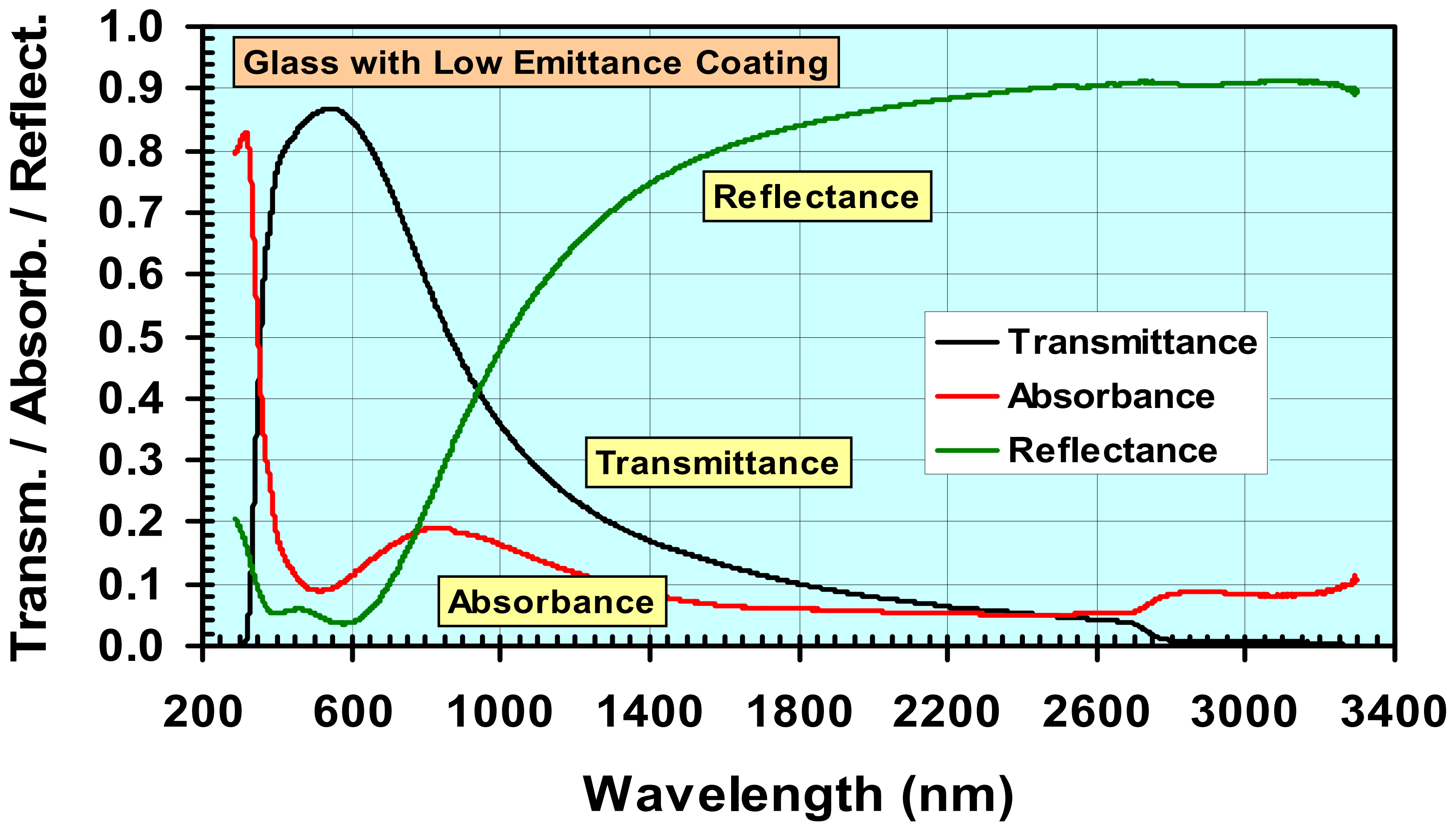
Float Glass

Solar Radiation through Window Panes and other Glass Structures



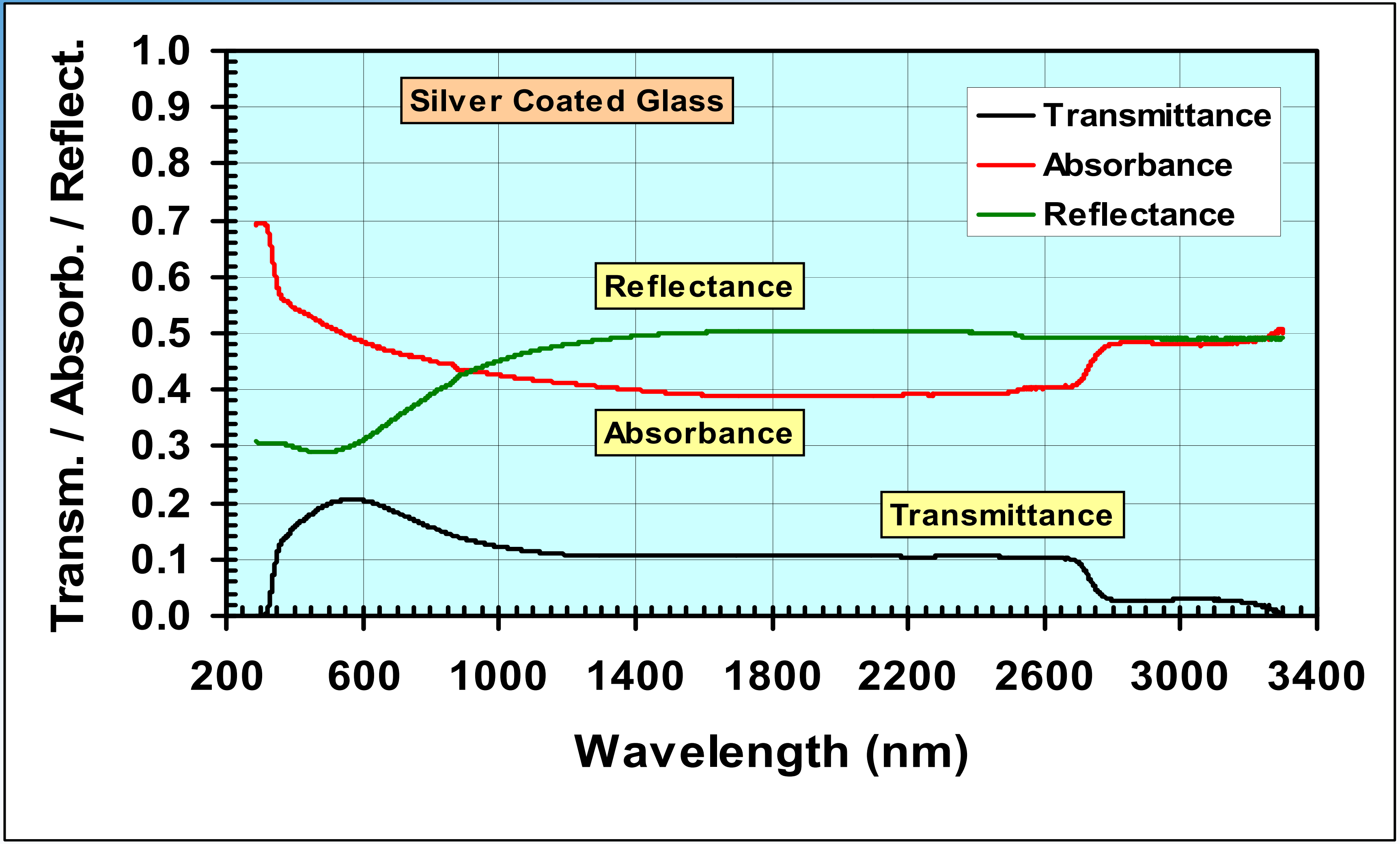
Low Emittance Coated Glass

Solar Radiation through Window Panes and other Glass Structures



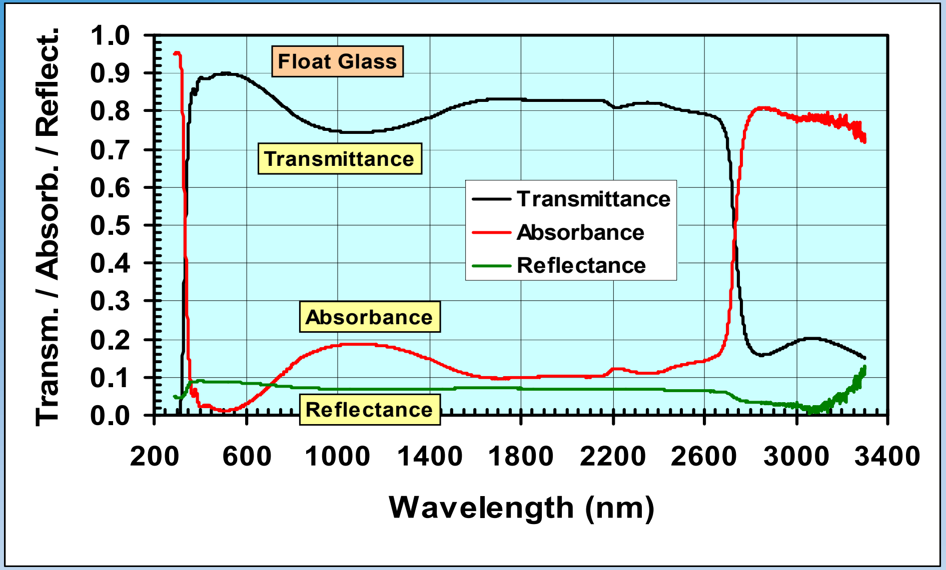
Dark Silver Coated Glass

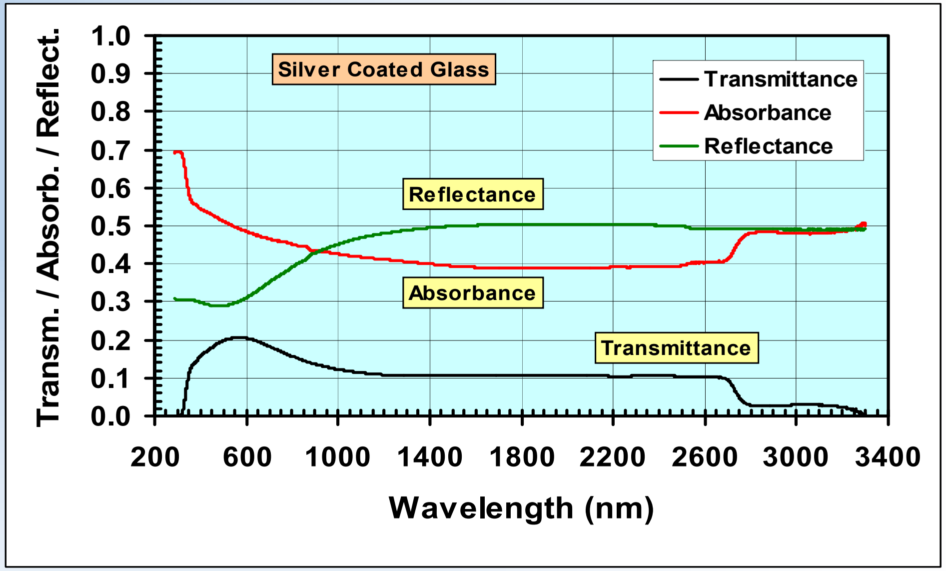
Solar Radiation through Window Panes and other Glass Structures

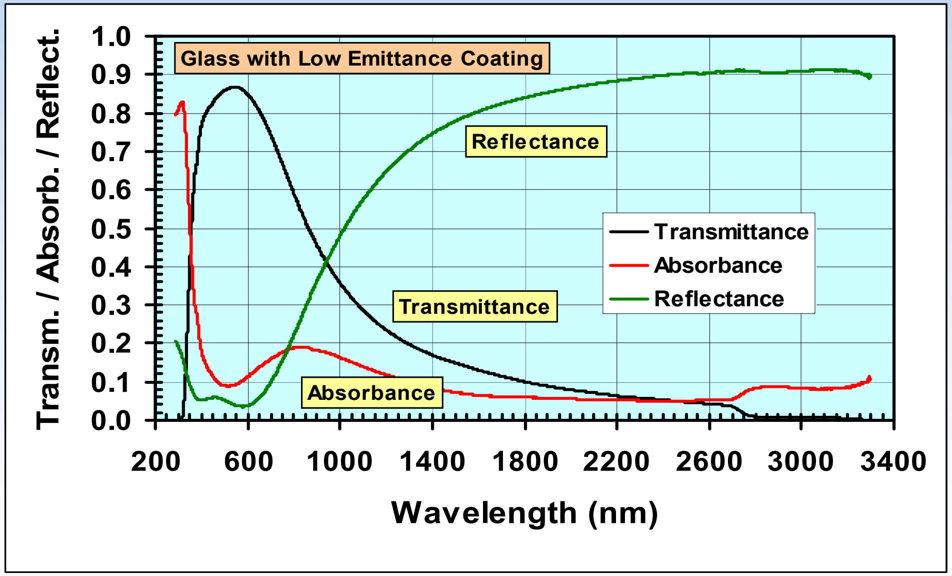


Float – Low Emittance – Dark Silver

Solar Radiation through Window Panes and other Glass Structures







Solar Radiation Glazing Factors for Miscellaneous Glass

(Float – Low Emittance – Dark Silver)

Glass Configuration	n	T_{uv}	T_{vis}	T_{sol}	SMPF	SSPF	$R_{vis,ext}$	$R_{vis,int}$	R_{sol}	A_{sol}	ε	SF	CRF
Float Glass G	1	0.65	0.89	0.83	0.20	0.81	0.09	0.09	0.08	0.10	0.836	0.85	0.99
Low Emittance Glass LE/G	1	0.41	0.86	0.59	0.32	0.89	0.04	0.04	0.27	0.14	0.836	0.62	0.98
Dark Silver Glass S/G	1	0.10	0.20	0.16	0.85	0.97	0.30	0.30	0.38	0.47	0.836	0.28	0.97

Solar Radiation Glazing Factors for Miscellaneous Glass

Solar Radiation through Window Panes and other Glass Structures

Glass Configuration	n	T_{uv}	T_{vis}	T_{sol}	SMPF	SSPF	$R_{vis,ext}$	$R_{vis,int}$	R_{sol}	A_{sol}	ε	SF	CRF
Float Glass G	1	0.65	0.89	0.83	0.20	0.81	0.09	0.09	0.08	0.10	0.836	0.85	0.99
Low Emittance Glass LE/G	1	0.41	0.86	0.59	0.32	0.89	0.04	0.04	0.27	0.14	0.836	0.62	0.98
Dark Silver Glass S/G	1	0.10	0.20	0.16	0.85	0.97	0.30	0.30	0.38	0.47	0.836	0.28	0.97
Float/Float G/A/G	2	0.50	0.80	0.69	0.31	0.87	0.16	0.04	0.13	0.17	0.836	0.76	0.97
Float/LowE G/A/LE/G	2	0.32	0.77	0.50	0.41	0.92	0.12	0.03	0.26	0.24	0.836	0.60	0.96
Float/Silver G/A/S/G	2	0.08	0.19	0.14	0.87	0.98	0.33	0.00	0.34	0.52	0.836	0.42	0.97
LowE/LowE G/LE/A/LE/G	2	0.22	0.74	0.43	0.48	0.94	0.09	0.01	0.26	0.31	0.836	0.52	0.95
LowE/Float G/LE/A/G	2	0.32	0.77	0.50	0.41	0.92	0.12	0.02	0.24	0.25	0.836	0.55	0.96
Silver/Float G/S/A/G	2	0.08	0.19	0.14	0.87	0.98	0.26	0.15	0.24	0.62	0.836	0.21	0.97
Silver/LowE G/S/A/LE/G	2	0.05	0.18	0.11	0.88	0.99	0.26	0.04	0.24	0.65	0.836	0.18	0.96
Silver/Silver G/S/A/S/G	2	0.01	0.05	0.03	0.97	1.00	0.27	0.00	0.25	0.72	0.836	0.16	0.95
Float/Float/Float G/A/G/A/G	3	0.40	0.73	0.59	0.40	0.90	0.21	0.17	0.17	0.24	0.836	0.68	0.96
Float/Float/LowE G/A/G/A/LE/G	3	0.26	0.69	0.44	0.48	0.93	0.18	0.10	0.25	0.31	0.836	0.55	0.95
Float/LowE/LowE G/A/LE/G/A/LE/G	3	0.18	0.66	0.37	0.54	0.95	0.15	0.09	0.29	0.34	0.836	0.50	0.94

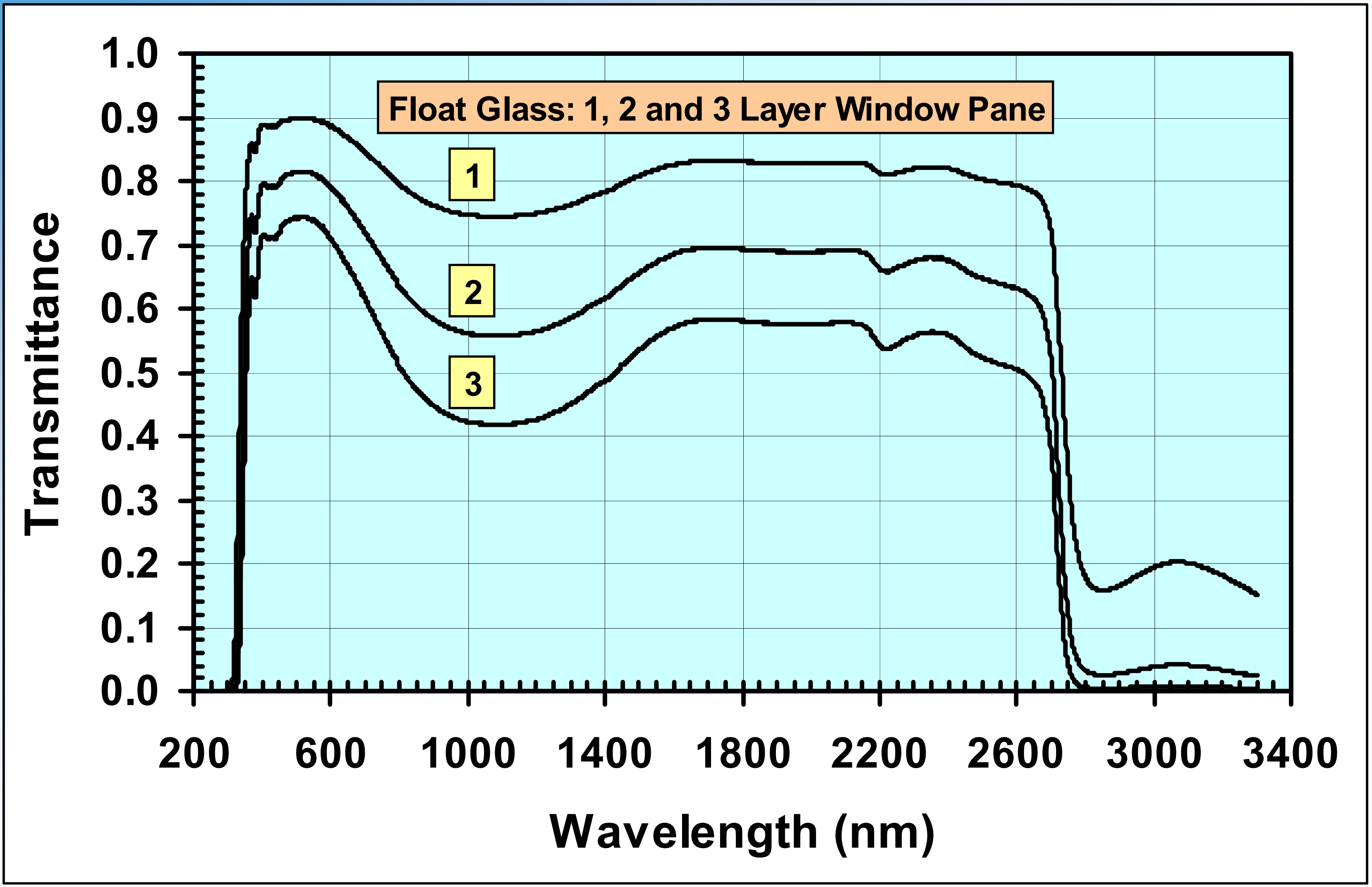
Solar Radiation Glazing Factors for Miscellaneous Glass

Solar Radiation through Window Panes and other Glass Structures

Glass Configuration	n	T_{uv}	T_{vis}	T_{sol}	SMPF	SSPF	$R_{vis,ext}$	$R_{vis,int}$	R_{sol}	A_{sol}	ε	SF	CRF
Float Glass G	1	0.65	0.89	0.83	0.20	0.81	0.09	0.09	0.08	0.10	0.836	0.85	0.99
Low Emittance Glass LE/G	1	0.41	0.86	0.59	0.32	0.89	0.04	0.04	0.27	0.14	0.836	0.62	0.98
Dark Silver Glass S/G	1	0.10	0.20	0.16	0.85	0.97	0.30	0.30	0.38	0.47	0.836	0.28	0.97
Float/Float G/A/G	2	0.50	0.80	0.69	0.31	0.87	0.16	0.04	0.13	0.17	0.836	0.76	0.97
Float/LowE G/A/LE/G	2	0.32	0.77	0.50	0.41	0.92	0.12	0.03	0.26	0.24	0.836	0.60	0.96
Float/Silver G/A/S/G	2	0.08	0.19	0.14	0.87	0.98	0.33	0.00	0.34	0.52	0.836	0.42	0.97
LowE/LowE G/LE/A/LE/G	2	0.22	0.74	0.43	0.48	0.94	0.09	0.01	0.26	0.31	0.836	0.52	0.95
LowE/Float G/LE/A/G	2	0.32	0.77	0.50	0.41	0.92	0.12	0.02	0.24	0.25	0.836	0.55	0.96
Silver/Float G/S/A/G	2	0.08	0.19	0.14	0.87	0.98	0.26	0.15	0.24	0.62	0.836	0.21	0.97
Silver/LowE G/S/A/LE/G	2	0.05	0.18	0.11	0.88	0.99	0.26	0.04	0.24	0.65	0.836	0.18	0.96
Silver/Silver G/S/A/S/G	2	0.01	0.05	0.03	0.97	1.00	0.27	0.00	0.25	0.72	0.836	0.16	0.95
Float/Float/Float G/A/G/A/G	3	0.40	0.73	0.59	0.40	0.90	0.21	0.17	0.17	0.24	0.836	0.68	0.96
Float/Float/LowE G/A/G/A/LE/G	3	0.26	0.69	0.44	0.48	0.93	0.18	0.10	0.25	0.31	0.836	0.55	0.95
Float/LowE/LowE G/A/LE/G/A/LE/G	3	0.18	0.66	0.37	0.54	0.95	0.15	0.09	0.29	0.34	0.836	0.50	0.94
LowE/LowE/LowE G/LE/A/LE/G/A/LE/G	3	0.12	0.63	0.33	0.59	0.97	0.11	0.08	0.28	0.39	0.836	0.45	0.93
Silver/Float/Float G/S/A/G/A/G	3	0.06	0.17	0.12	0.88	0.98	0.26	0.26	0.24	0.64	0.836	0.18	0.96
Silver/Float/LowE G/S/A/G/A/LE/G	3	0.04	0.16	0.09	0.89	0.99	0.26	0.15	0.24	0.66	0.836	0.15	0.95
Silver/LowE/LowE G/S/A/LE/G/A/LE/G	3	0.03	0.15	0.08	0.91	0.99	0.26	0.14	0.25	0.67	0.836	0.14	0.94
Silver/Silver/Silver G/S/A/S/G/A/S/G	3	0.00	0.01	0.01	0.99	1.00	0.27	0.26	0.25	0.74	0.836	0.11	0.93

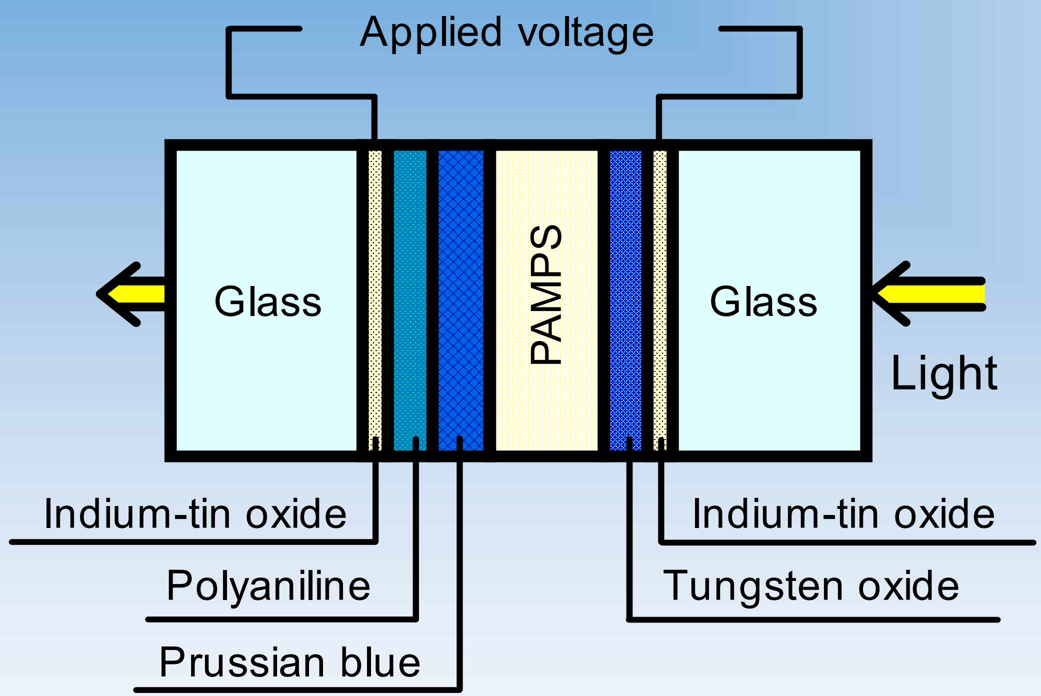
Float Glass – Number of Window Panes

Solar Radiation through Window Panes and other Glass Structures

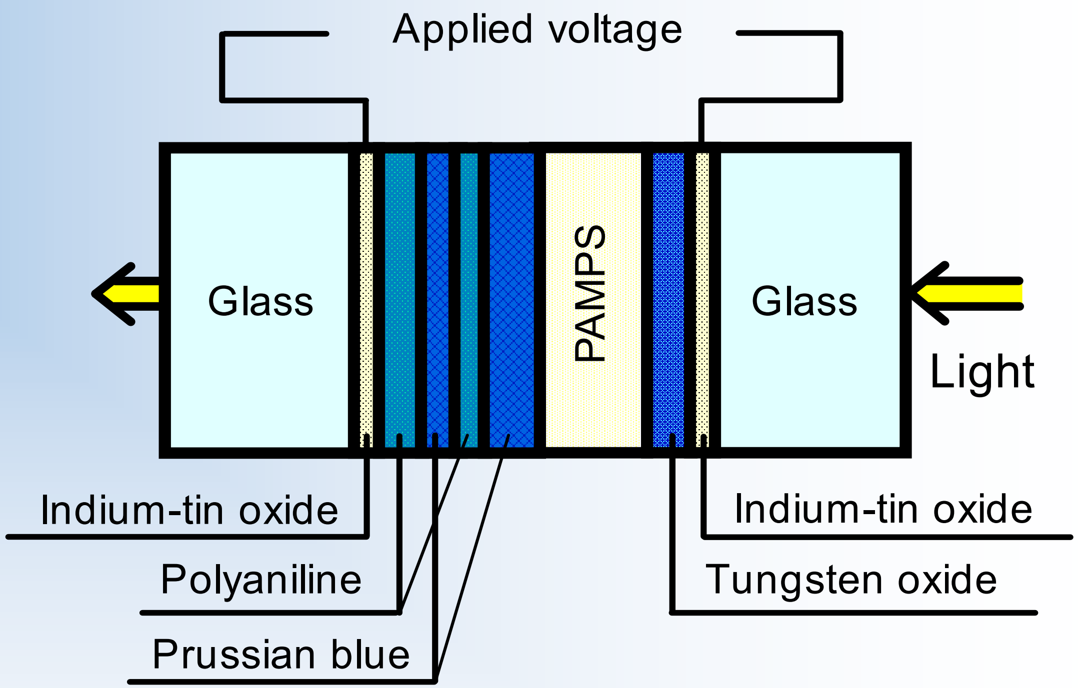


Smart Windows

Electrochromic Window Configurations



Window configuration ECW1



Window configuration ECW2 (PANI-PB multilayer)

Smart Windows

Electrochromic Materials and Chemical Reactions

PANI, PB and WO_3

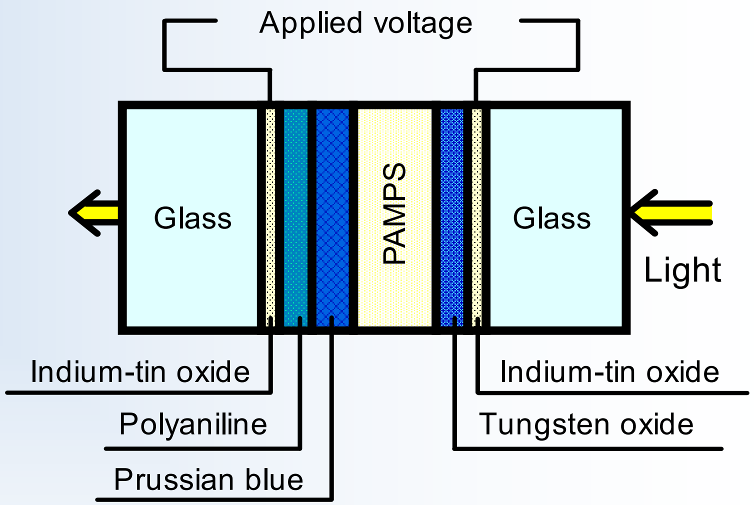
(transparent)

$$WO_3 + (PANI)(yH^+A^-) + (x\text{-}y)K_2Fe^{II}[Fe(CN)_6] + (x\text{-}y)H^+$$

$$\leftrightarrow$$

$$H_xWO_3 + (PANI^{y+})(A^-)_y + (x\text{-}y)KFe^{III}[Fe(CN)_6] + (x\text{-}y)K^+$$

(blue)



$y = x \Rightarrow$

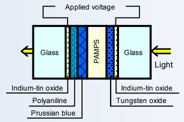
PANI and WO_3

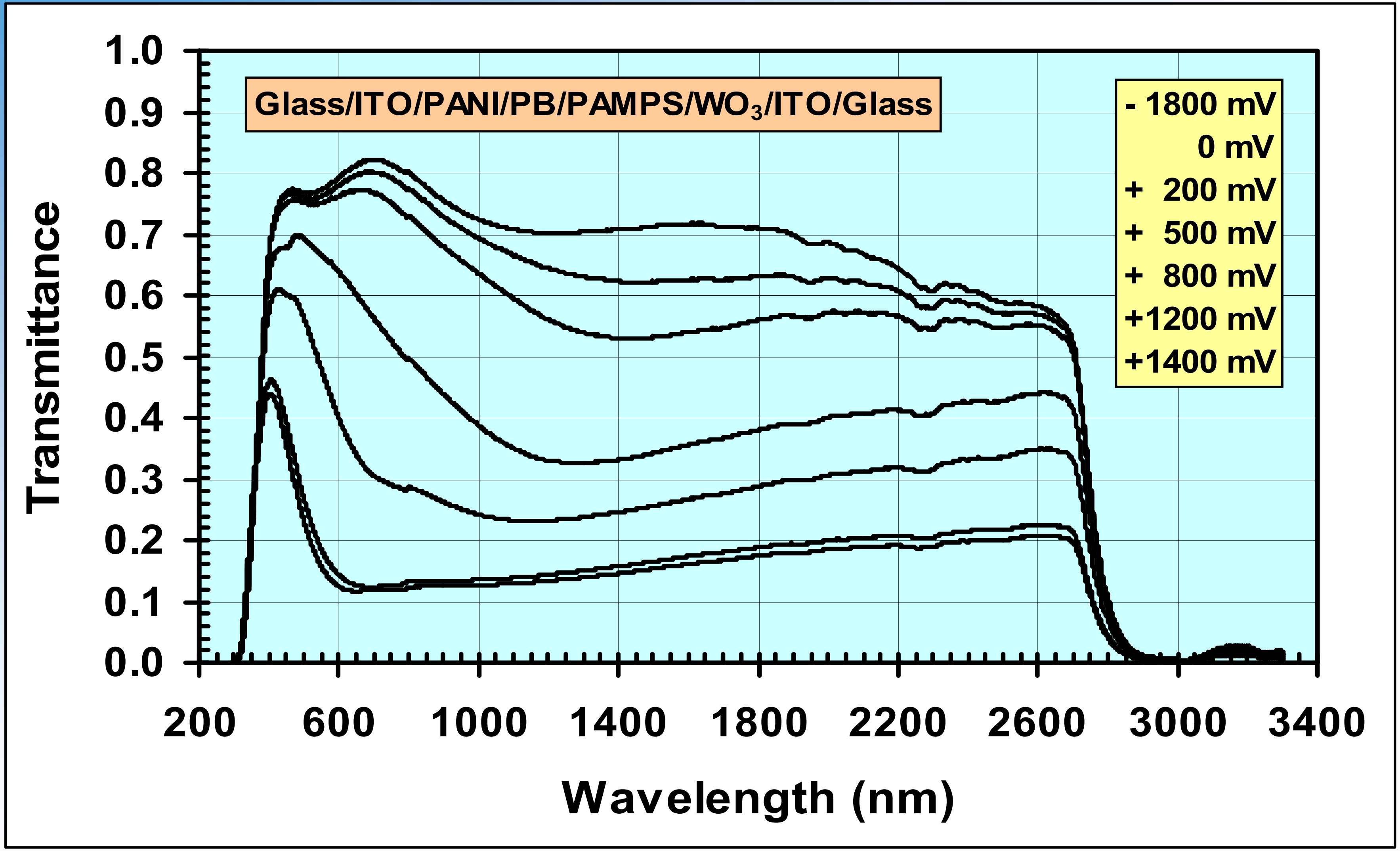
$$WO_3 + (PANI)(xH^+A^-) \leftrightarrow H_xWO_3 + (PANI^{x+})(A^-)_x$$

(transparent) (blue)

Spectroscopical Data for Electrochromic Windows

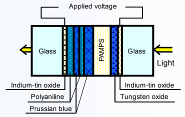
Window configuration ECW1

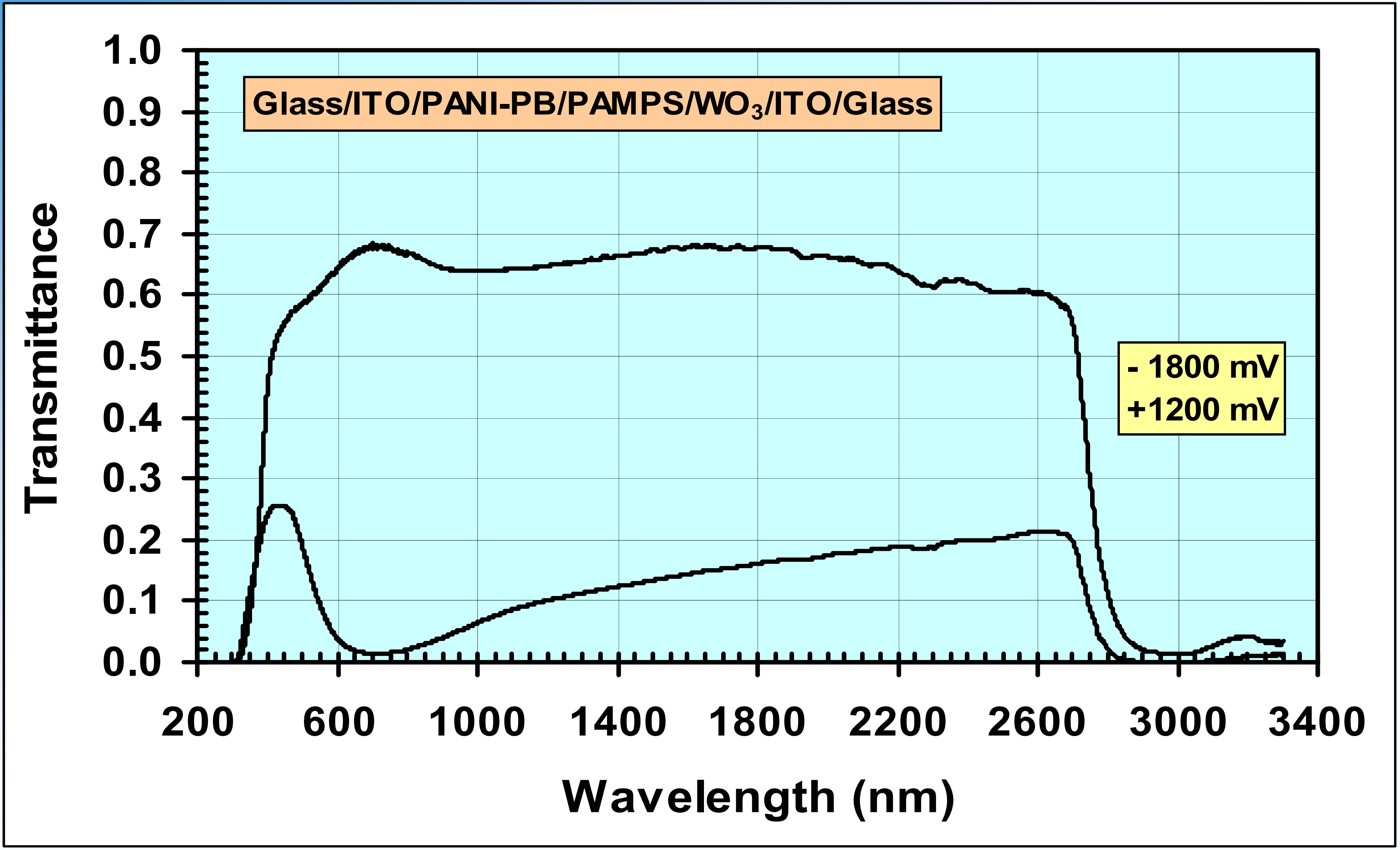




Spectroscopical Data for Electrochromic Windows

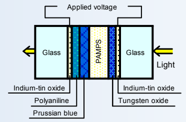
Window configuration ECW2 (PANI-PB multilayer)

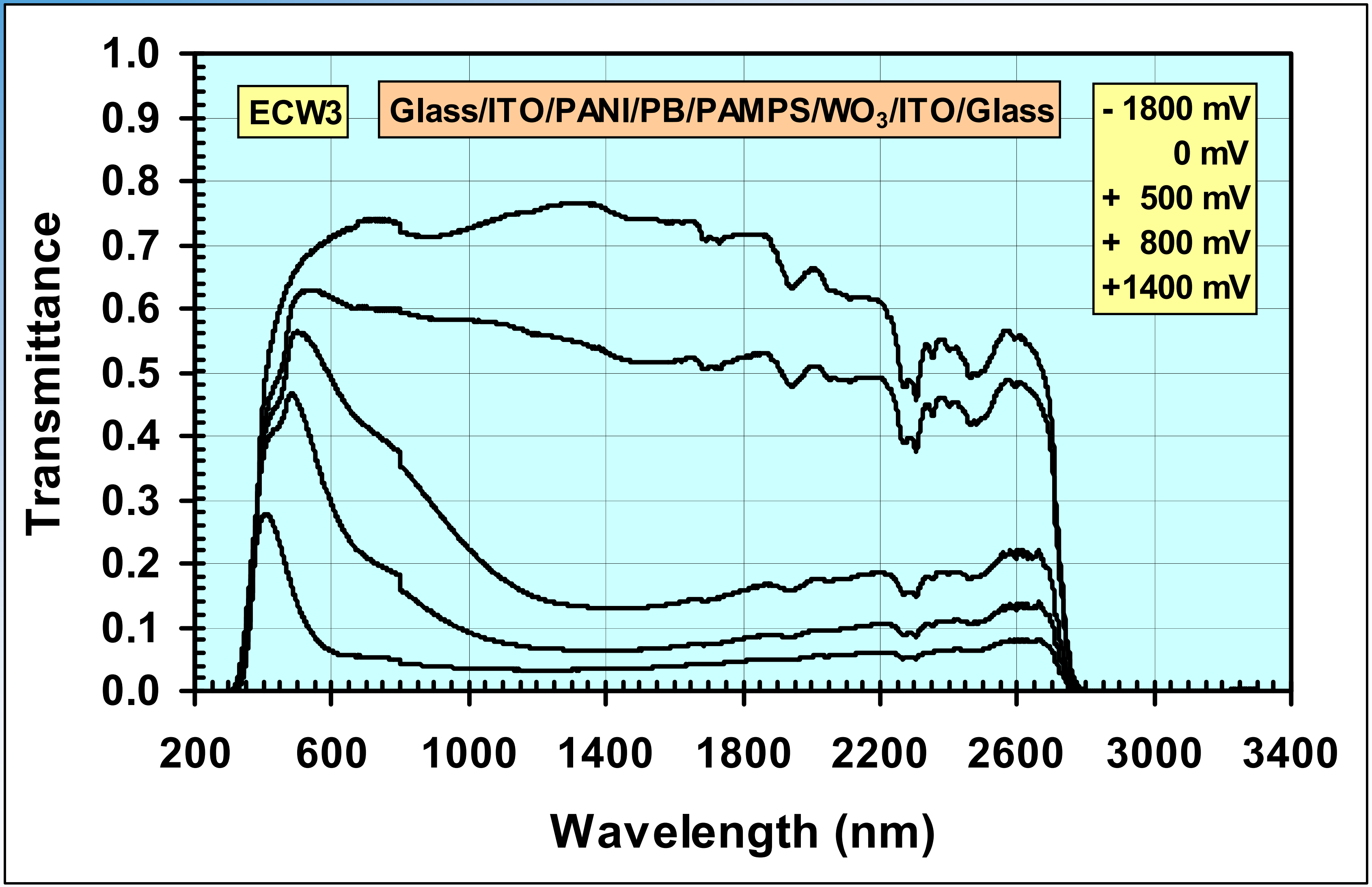




Spectroscopical Data for Electrochromic Windows

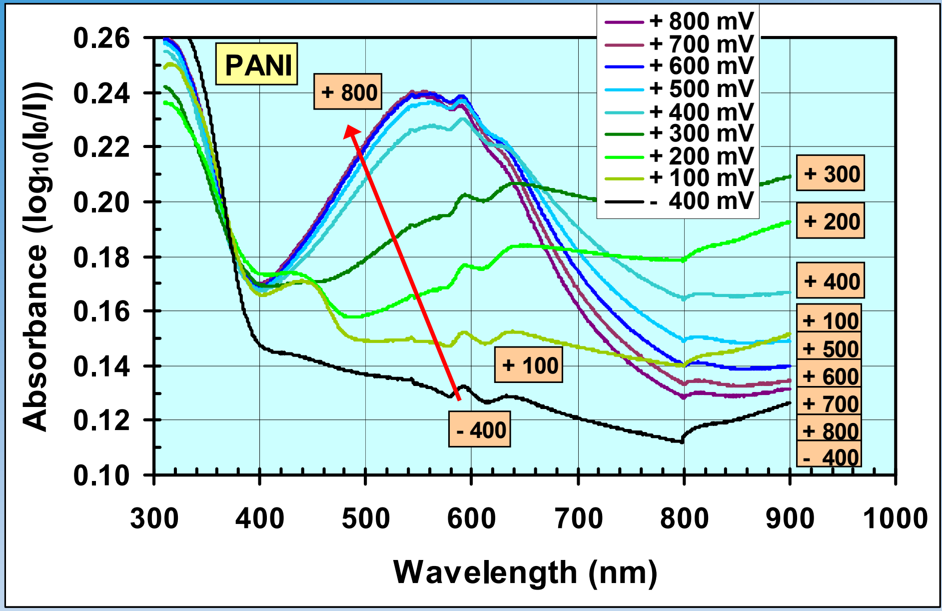
Window configuration ECW3

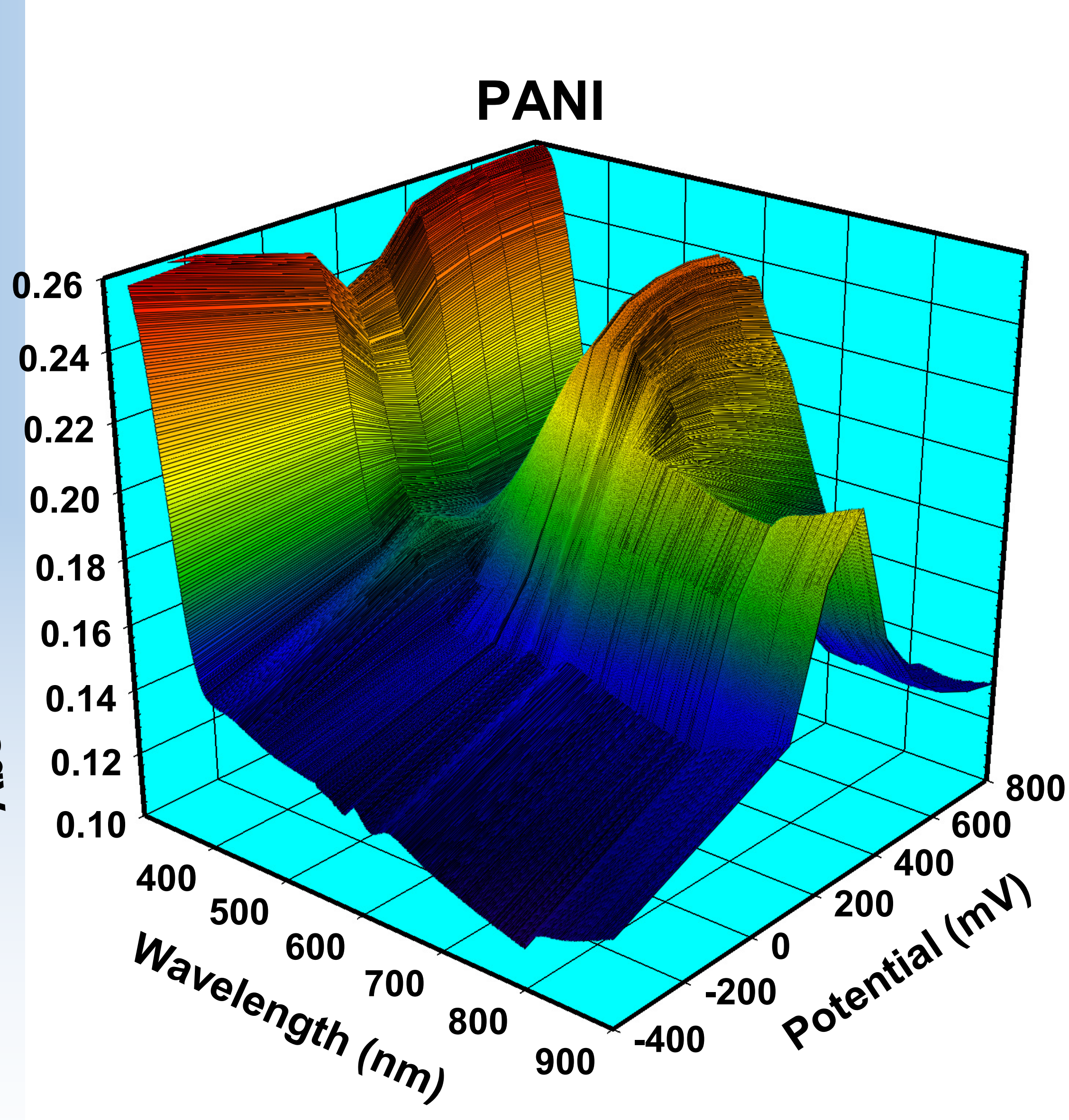




Spectral Changes in Polyaniline (PANI)

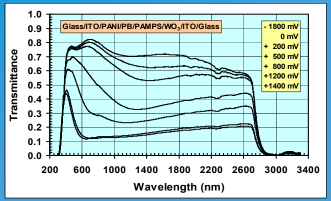
Transparent – Yellow – Green – Blue – Violet



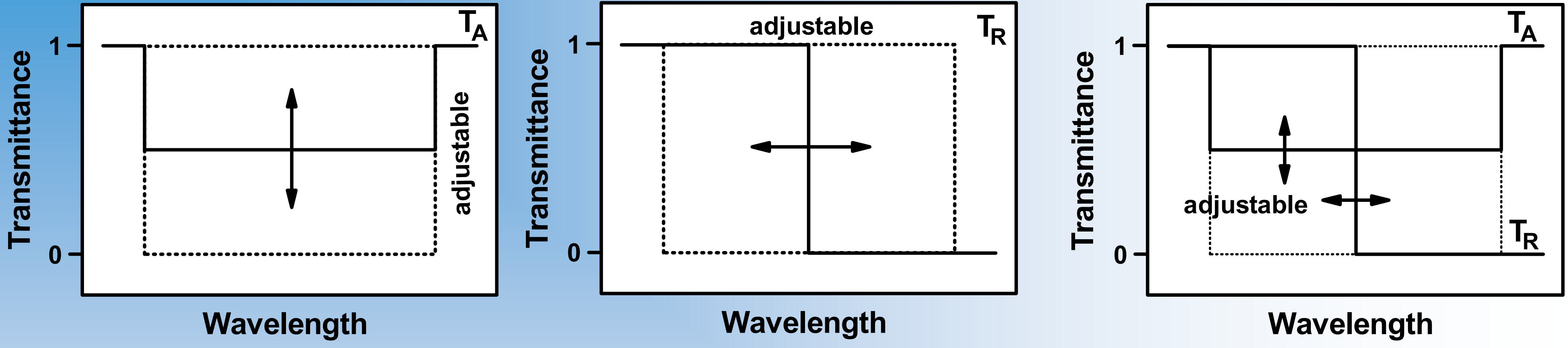


PANI may exhibit many colours

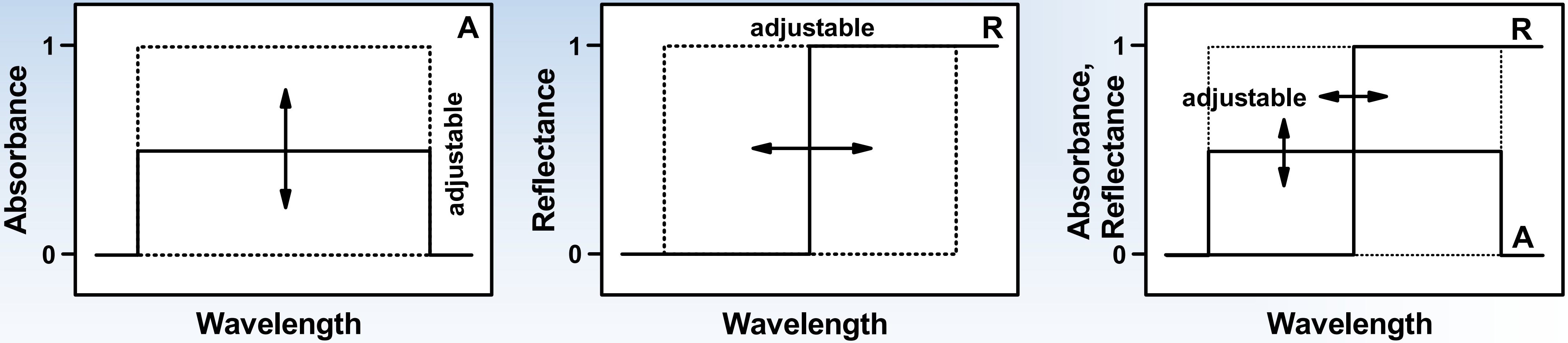
- **PANI doping:**
- Redox processes
- Proton doping



Solar Radiation Modulation by ECWs



Absorbance (A) Regulating **Reflectance (R) Regulating** **Combined A and R Regulating**



$$\lambda_p = 2\pi c / \omega_p = (2\pi c/q_e)(m_e \varepsilon_0 / n_e)^{1/2}$$

Solar Radiation Glazing Factors for Electrochromic Windows

Glass Configuration	n	T_{uv}	T_{vis}	T_{sol}	SMPF	SSPF	$R_{vis,ext}$	$R_{vis,int}$	R_{sol}	A_{sol}	ε	SF	CRF
ECW1 (-1800 mV)	1	0.23	0.78	0.74	0.43	0.93	0.09	0.09	0.08	0.18	0.836	0.79	0.98
ECW1 (0 mV)	1	0.23	0.77	0.72	0.43	0.93	0.09	0.09	0.08	0.21	0.836	0.77	0.98
ECW1 (+200 mV)	1	0.24	0.75	0.68	0.44	0.93	0.09	0.09	0.08	0.24	0.836	0.74	0.99
ECW1 (+500 mV)	1	0.25	0.66	0.52	0.48	0.93	0.09	0.09	0.08	0.40	0.836	0.62	0.95
ECW1 (+800 mV)	1	0.26	0.47	0.36	0.54	0.92	0.09	0.09	0.08	0.56	0.836	0.51	0.82
ECW1 (+1200 mV)	1	0.24	0.19	0.19	0.68	0.93	0.09	0.09	0.08	0.73	0.836	0.38	0.68
ECW1 (+1400 mV)	1	0.23	0.17	0.17	0.71	0.93	0.09	0.09	0.08	0.75	0.836	0.37	0.68
ECW2 (-1800 mV)	1	0.10	0.62	0.61	0.61	0.97	0.09	0.09	0.08	0.31	0.836	0.69	0.95
ECW2 (+1200 mV)	1	0.12	0.10	0.10	0.82	0.97	0.09	0.09	0.08	0.82	0.836	0.31	0.31
ECW3 (-1800 mV)	1	0.08	0.69	0.67	0.59	0.97	0.09	0.09	0.08	0.25	0.836	0.74	0.96
ECW3 (+1400 mV)	1	0.12	0.09	0.08	0.83	0.97	0.09	0.09	0.08	0.84	0.836	0.30	0.59

Solar Radiation Glazing Factors for Electrochromic Windows

Glass Configuration	n	T_{uv}	T_{vis}	T_{sol}	SMPF	SSPF	$R_{vis,ext}$	$R_{vis,int}$	R_{sol}	A_{sol}	ε	SF	CRF
ECW1 (-1800 mV)	1	0.23	0.78	0.74	0.43	0.93	0.09	0.09	0.08	0.18	0.836	0.79	0.98
ECW1 (0 mV)	1	0.23	0.77	0.72	0.43	0.93	0.09	0.09	0.08	0.21	0.836	0.77	0.98
ECW1 (+200 mV)	1	0.24	0.75	0.68	0.44	0.93	0.09	0.09	0.08	0.24	0.836	0.74	0.99
ECW1 (+500 mV)	1	0.25	0.66	0.52	0.48	0.93	0.09	0.09	0.08	0.40	0.836	0.62	0.95
ECW1 (+800 mV)	1	0.26	0.47	0.36	0.54	0.92	0.09	0.09	0.08	0.56	0.836	0.51	0.82
ECW1 (+1200 mV)	1	0.24	0.19	0.19	0.68	0.93	0.09	0.09	0.08	0.73	0.836	0.38	0.68
ECW1 (+1400 mV)	1	0.23	0.17	0.17	0.71	0.93	0.09	0.09	0.08	0.75	0.836	0.37	0.68
ECW2 (-1800 mV)	1	0.10	0.62	0.61	0.61	0.97	0.09	0.09	0.08	0.31	0.836	0.69	0.95
ECW2 (+1200 mV)	1	0.12	0.10	0.10	0.82	0.97	0.09	0.09	0.08	0.82	0.836	0.31	0.31
ECW3 (-1800 mV)	1	0.08	0.69	0.67	0.59	0.97	0.09	0.09	0.08	0.25	0.836	0.74	0.96
ECW3 (+1400 mV)	1	0.12	0.09	0.08	0.83	0.97	0.09	0.09	0.08	0.84	0.836	0.30	0.59
EC1/Float (-) EC1T/A/G	2	0.18	0.70	0.62	0.50	0.95	0.14	0.04	0.12	0.26	0.836	0.67	0.99
EC1/Float (+) EC1C/A/G	2	0.18	0.15	0.15	0.75	0.95	0.09	0.04	0.08	0.77	0.836	0.25	0.67
EC1/LowE (-) EC1T/A/LE/G	2	0.12	0.67	0.45	0.55	0.97	0.11	0.03	0.23	0.32	0.836	0.55	0.99
EC1/LowE (+) EC1C/A/LE/G	2	0.12	0.14	0.11	0.78	0.97	0.09	0.03	0.09	0.80	0.836	0.19	0.68
EC1/Float/Float (-) EC1T/A/G/A/G	3	0.15	0.63	0.53	0.55	0.96	0.18	0.17	0.15	0.32	0.836	0.60	0.99
EC1/Float/Float (+) EC1C/A/G/A/G	3	0.14	0.14	0.13	0.78	0.96	0.09	0.17	0.08	0.79	0.836	0.20	0.67
EC1/Float/LowE (-) EC1T/A/G/A/LE/G	3	0.10	0.60	0.39	0.60	0.97	0.16	0.10	0.22	0.39	0.836	0.50	0.98
EC1/Float/LowE (+) EC1C/A/G/A/LE/G	3	0.10	0.13	0.10	0.81	0.97	0.09	0.10	0.09	0.82	0.836	0.16	0.67
EC1/LowE/LowE (-) EC1T/A/LE/G/A/LE/G	3	0.07	0.58	0.33	0.64	0.98	0.13	0.09	0.25	0.41	0.836	0.45	0.97
EC1/LowE/LowE (+) EC1C/A/LE/G/A/LE/G	3	0.07	0.12	0.08	0.83	0.98	0.09	0.09	0.09	0.83	0.836	0.14	0.67
EC2/LowE/LowE (-) EC2T/A/LE/G/A/LE/G	3	0.03	0.46	0.26	0.74	0.99	0.11	0.09	0.22	0.52	0.836	0.37	0.96
EC2/LowE/LowE (+) EC2C/A/LE/G/A/LE/G	3	0.03	0.07	0.04	0.89	0.99	0.09	0.09	0.08	0.87	0.836	0.10	0.30

Solar Radiation Glazing Factor Modulation for Electrochromic Windows

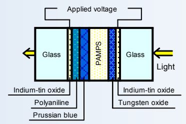
Glass Configuration	n	ΔT_{uv}	ΔT_{vis}	ΔT_{sol}	$\Delta SMPF$	$\Delta SSPF$	$\Delta R_{vis,ext}$	$\Delta R_{vis,int}$	ΔR_{sol}	ΔA_{sol}	ε	ΔSF	ΔCRF
ECW1 (-1800 mV) ECW1 (+1400 mV)	1	0.00	0.61	0.57	-0.28	0.00	0.00	0.00	0.00	-0.57	-	0.42	0.30
ECW2 (-1800 mV) ECW2 (+1200 mV)	1	-0.02	0.52	0.51	-0.21	0.00	0.00	0.00	0.00	-0.51	-	0.38	0.64
ECW3 (-1800 mV) ECW3 (+1400 mV)	1	-0.04	0.60	0.59	-0.24	0.00	0.00	0.00	0.00	-0.59	-	0.44	0.37
EC1/Float (-) EC1T/A/G EC1/Float (+) EC1C/A/G	2	0.00	0.55	0.47	-0.25	0.00	0.05	0.00	0.04	-0.51	-	0.42	0.32
EC1/LowE (-) EC1T/A/LE/G EC1/LowE (+) EC1C/A/LE/G	2	0.00	0.53	0.34	-0.23	0.00	0.02	0.00	0.14	-0.48	-	0.36	0.31

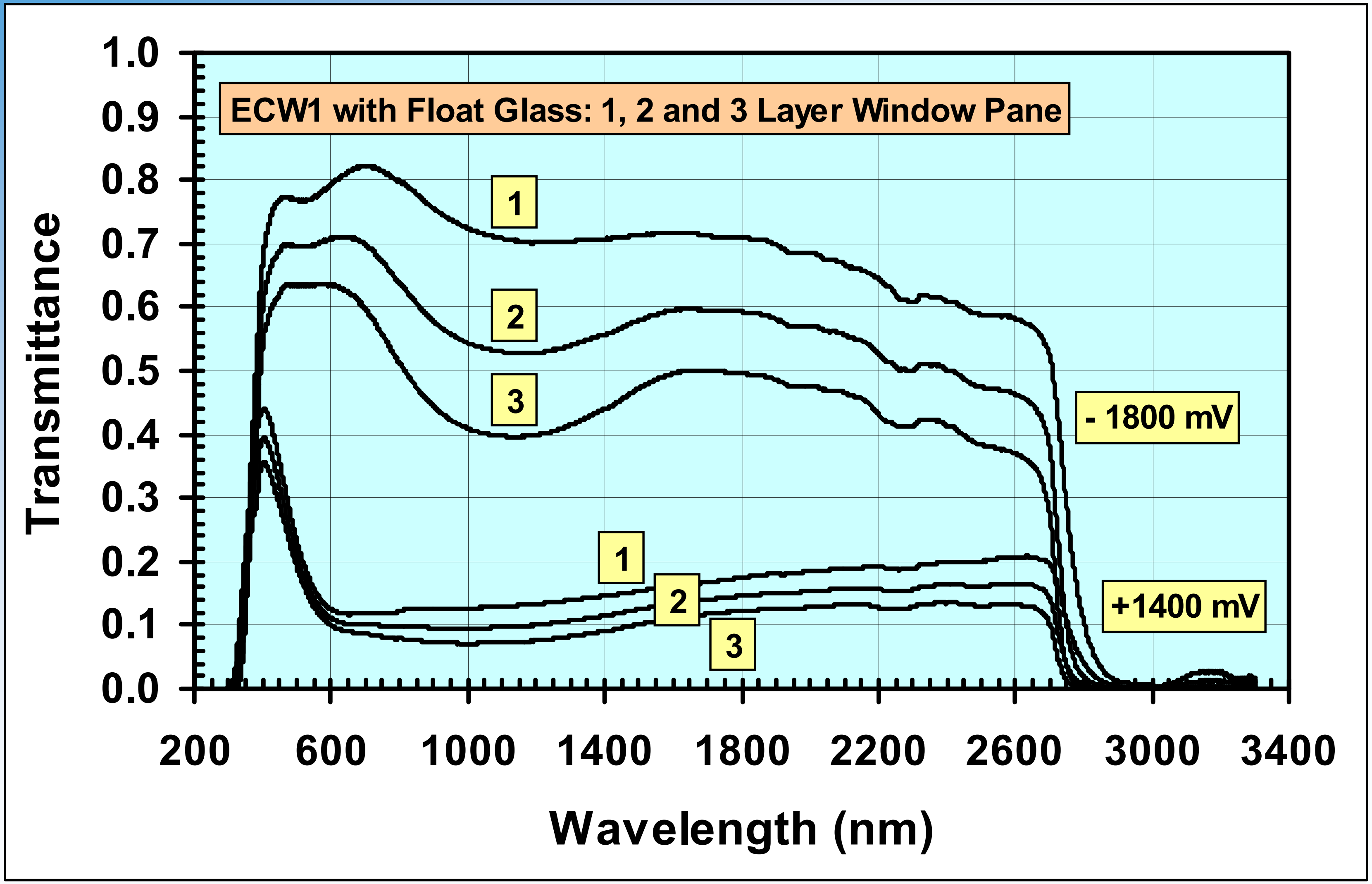
Solar Radiation Glazing Factor Modulation for Electrochromic Windows

Glass Configuration	n	ΔT_{uv}	ΔT_{vis}	ΔT_{sol}	ΔSMPF	ΔSSPF	$\Delta R_{vis,ext}$	$\Delta R_{vis,int}$	ΔR_{sol}	ΔA_{sol}	ε	ΔSF	ΔCRF
ECW1 (-1800 mV) ECW1 (+1400 mV)	1	0.00	0.61	0.57	-0.28	0.00	0.00	0.00	0.00	-0.57	-	0.42	0.30
ECW2 (-1800 mV) ECW2 (+1200 mV)	1	-0.02	0.52	0.51	-0.21	0.00	0.00	0.00	0.00	-0.51	-	0.38	0.64
ECW3 (-1800 mV) ECW3 (+1400 mV)	1	-0.04	0.60	0.59	-0.24	0.00	0.00	0.00	0.00	-0.59	-	0.44	0.37
EC1/Float (-) EC1T/A/G EC1/Float (+) EC1C/A/G	2	0.00	0.55	0.47	-0.25	0.00	0.05	0.00	0.04	-0.51	-	0.42	0.32
EC1/LowE (-) EC1T/A/LE/G EC1/LowE (+) EC1C/A/LE/G	2	0.00	0.53	0.34	-0.23	0.00	0.02	0.00	0.14	-0.48	-	0.36	0.31
EC1/Float/Float (-) EC1T/A/G/A/G EC1/Float/Float (+) EC1C/A/G/A/G	3	0.01	0.49	0.40	-0.23	0.00	0.09	0.00	0.07	-0.47	-	0.40	0.32
EC1/Float/LowE (-) EC1T/A/G/A/LE/G EC1/Float/LowE (+) EC1C/A/G/A/LE/G	3	0.00	0.47	0.29	-0.21	0.00	0.07	0.00	0.13	-0.43	-	0.34	0.31
EC1/LowE/LowE (-) EC1T/A/LE/G/A/LE/G EC1/LowE/LowE (+) EC1C/A/LE/G/A/LE/G	3	0.00	0.46	0.25	-0.19	0.00	0.04	0.00	0.16	-0.42	-	0.31	0.30
EC2/LowE/LowE (-) EC2T/A/LE/G/A/LE/G EC2/LowE/LowE (+) EC2C/A/LE/G/A/LE/G	3	0.00	0.39	0.22	-0.15	0.00	0.02	0.00	0.14	-0.35	-	0.27	0.66

ECW1 with Float Glass – Number of Window Panes

Window configuration ECW1





Solar Radiation Glazing Factors

Article addressing the solar radiation glazing factors

Solar Energy Materials & Solar Cells 116 (2013) 291–323

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Review

Solar radiation glazing factors for window panes, glass structures and electrochromic windows in buildings—Measurement and calculation

CrossMark

Bjørn Petter Jelle [a,b,*]

[a] SINTEF Building and Infrastructure, Department of Materials and Structures, NO-7465 Trondheim, Norway
[b] Norwegian University of Science and Technology (NTNU), Department of Civil and Transport Engineering, NO-7491 Trondheim, Norway

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Absorbance
Emissivity
Colour rendering factor

A B S T R A C T

Window panes, glass structures and electrochromic windows in buildings may be characterised by a number of solar radiation glazing factors, i.e. ultraviolet solar transmittance, visible solar transmittance, solar transmittance, solar material protection factor, solar skin protection factor, external visible solar reflectance, internal visible solar reflectance, solar reflectance, solar absorbance, emissivity, solar factor and colour rendering factor. Comparison of these solar quantities for different glass fabrications enables one to evaluate and thus select the most appropriate glass material or system for the specific buildings and applications. Measurements and calculations were carried out on various glass materials, including three electrochromic window devices, and several two-layer and three-layer window pane configurations.

Properties, Requirements and Possibilities
Smart Windows – A State-of-the-Art Review

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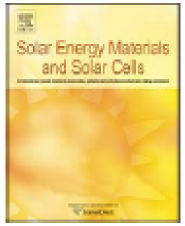

Review

Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review

Ruben Baetens [a,b], Bjørn Petter Jelle [a,c,*], Arild Gustavsen [d]

[a] *Department of Building Materials and Structures, SINTEF Building and Infrastructure, NO-7465 Trondheim, Norway*
[b] *Department of Civil Engineering, Catholic University of Leuven (KUL), B-3001 Heverlee, Belgium*
[c] *Department of Civil and Transport Engineering, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway*
[d] *Department of Architectural Design, History and Technology, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway*

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Liquid crystal window
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Electrophoretic window
Daylight control
Solar energy control

A B S T R A C T

A survey on prototype and currently commercial dynamic tintable smart windows has been carried out. The technologies of electrochromic, gasochromic, liquid crystal and electrophoretic or suspended-particle devices were examined and compared for dynamic daylight and solar energy control in buildings. Presently, state-of-the art commercial electrochromic windows seem most promising to reduce cooling loads, heating loads and lighting energy in buildings, where they have been found most reliable and able to modulate the transmittance up to 68% of the total solar spectrum. Their efficiency has already been proven in hot Californian climates, but more research is necessary to validate the products for colder climates, and to improve furthermore the commercial products in order to control the indoor climate in a more energy efficient way by reducing both heating and cooling loads.

Fenestration of Today and Tomorrow: A State-of-the-Art Review and Future Research Opportunities

From Today…

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Review

Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities

Bjørn Petter Jelle[a,b,*], Andrew Hynd[a,c], Arild Gustavsen[d], Dariush Arasteh[e], Howdy Goudey[e], Robert Hart[e]

[a] SINTEF Building and Infrastructure, Department of Materials and Structures, NO-7465 Trondheim, Norway
[b] Norwegian University of Science and Technology (NTNU), Department of Civil and Transport Engineering, NO-7491 Trondheim, Norway
[c] University of Strathclyde, Civil Engineering Department, Glasgow G4 0NG, Scotland
[d] Norwegian University of Science and Technology (NTNU), Department of Architectural Design, History and Technology, NO-7491 Trondheim, Norway
[e] Lawrence Berkeley National Laboratory (LBNL), Windows and Daylighting Group, Berkeley, CA 94720-8134, USA

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ABSTRACT

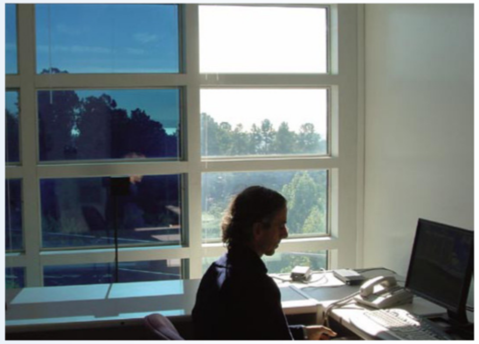
Fenestration of today is continuously being developed into the fenestration of tomorrow, hence offering a steadily increase of daylight and solar energy utilization and control, and at the same time providing a necessary climate screen with a satisfactory thermal comfort. Within this work a state-of-the-art market review of the best performing fenestration products has been carried out, along with an overview of possible future research opportunities for the fenestration industry. The focus of the market review was low thermal transmittance (*U*-value). The lowest centre-of-glass U_g-values found was 0.28 and 0.30 W/m^2 K, which was from a suspended coating glazing product and an aerogel glazing product, respectively. However, the majority of high performance products found were triple glazed. The lowest frame *U*-value was 0.61 W/m^2 K. Vacuum glazing, smart windows, solar cell glazing, window frames, self-cleaning glazing, low-emissivity coatings and spacers were also reviewed, thus also representing possibilities for controlling and harvesting the solar radiation energy. Currently, vacuum glazing, new spacer materials and solutions, electrochromic windows and aerogel glazing seem to have the largest potential for improving the thermal performance and daylight and solar properties in fenestration products. Aerogel glazing has the lowest potential *U*-values, ~0.1 W/m^2 K, but requires further work to improve the visible transmittance. Electrochromic vaccum glazing and evacuated aerogel glazing are two vacuum-related solutions, which have a large potential. There may also be opportunities for completely new material innovations, which could revolutionize the fenestration industry.

To Tomorrow…

Commercial Electrochromic Windows

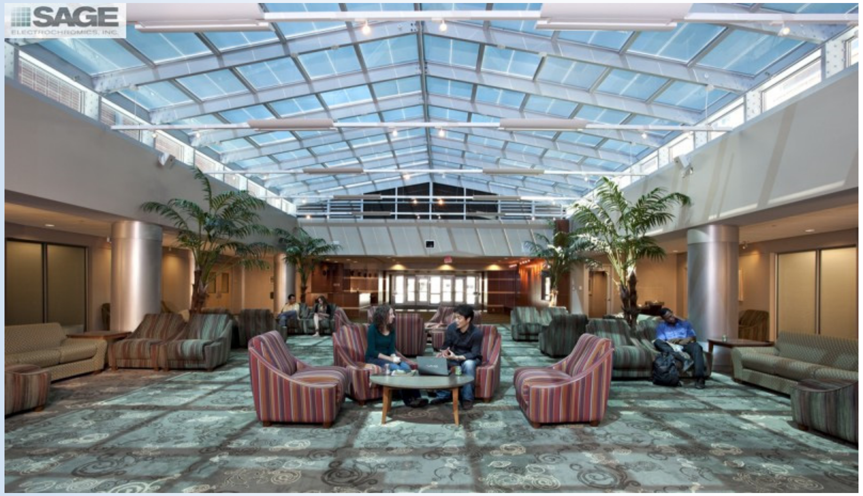
Some Company Examples:

- SAGE Electrochromics (USA)
- EControl-Glas (Germany)
- GESIMAT (Germany)
- ChromoGenics (Sweden)



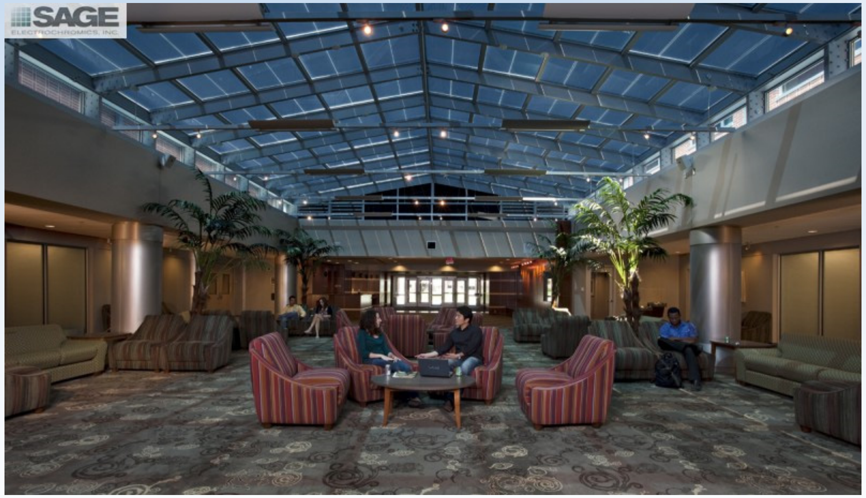
Commercial Electrochromic Windows

Transparent



Intermediate

Dark



Commercial Electrochromic Windows

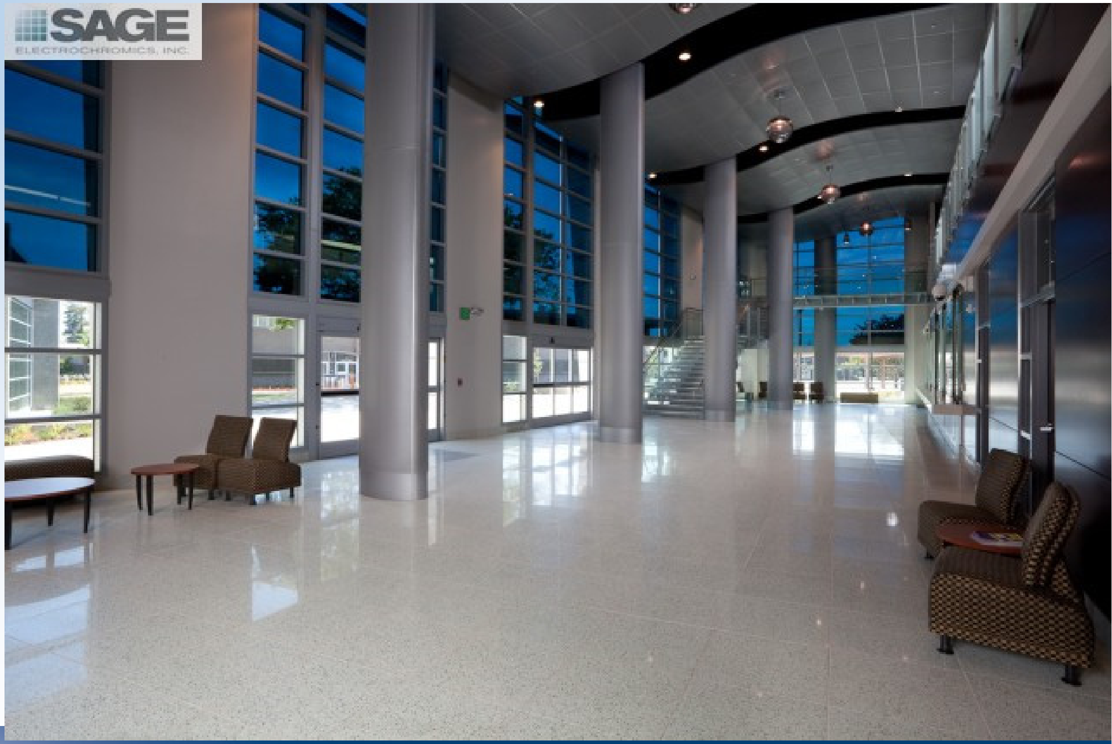
Coloured

Transparent

Commercial Electrochromic Windows

Transparent

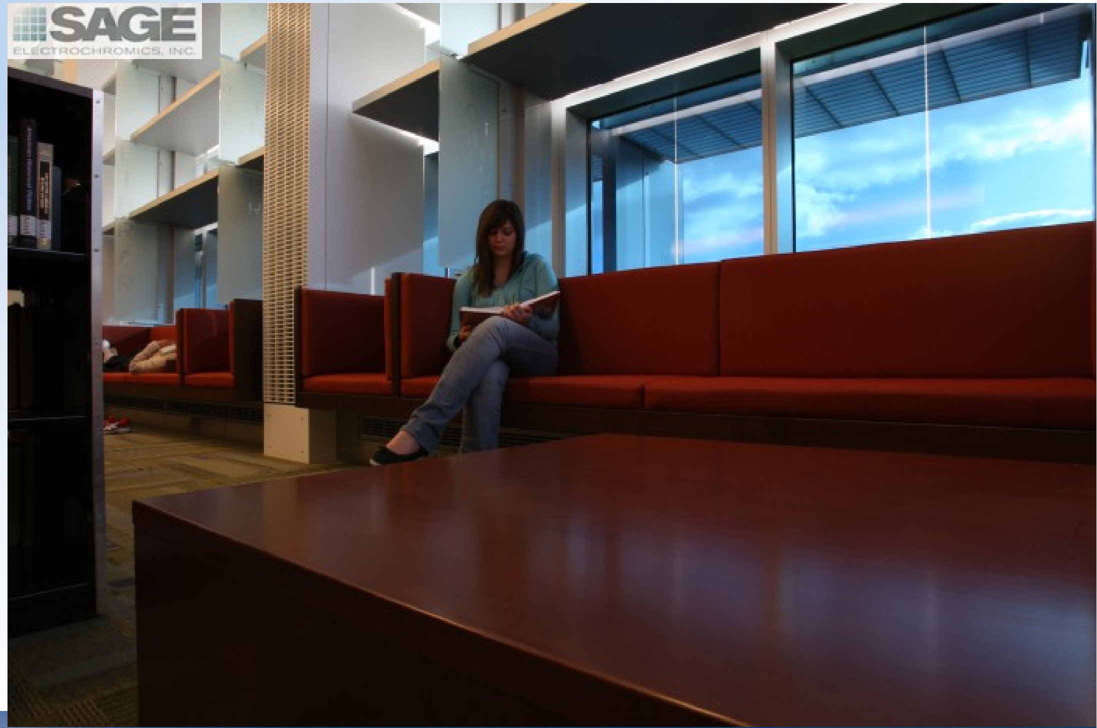
Coloured



Commercial Electrochromic Windows

Transparent

Coloured



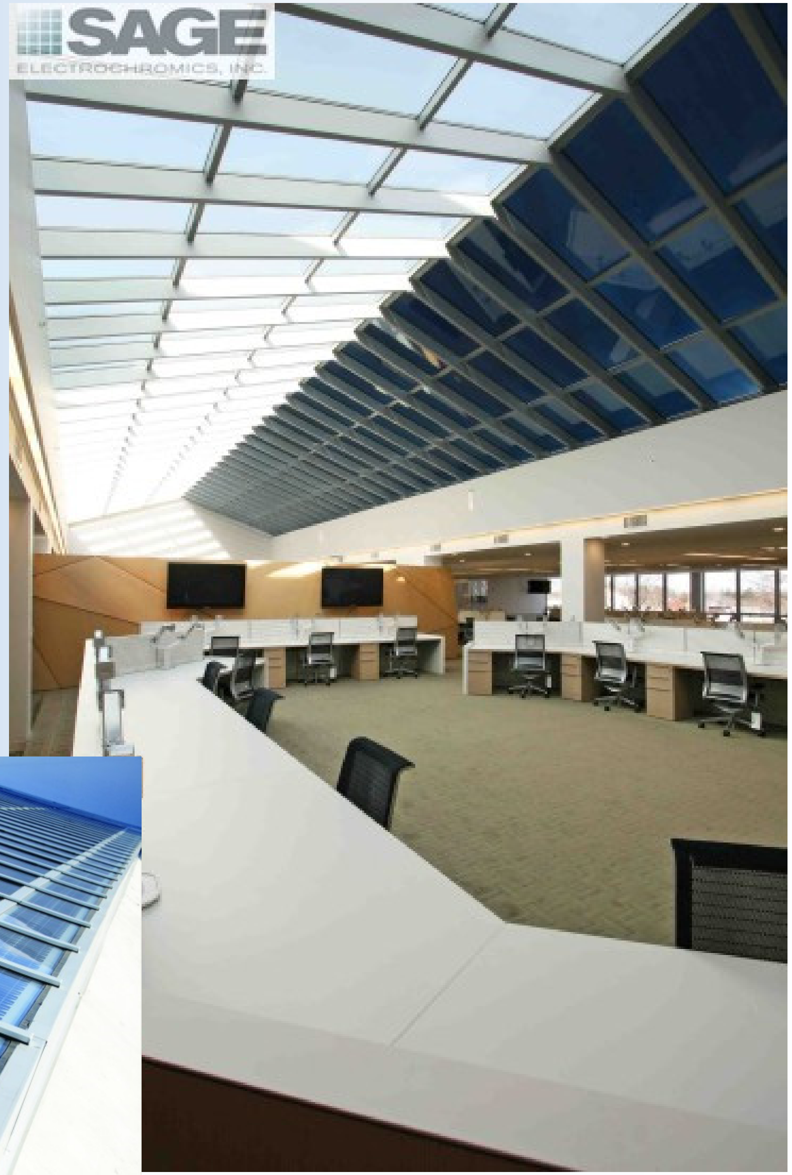
Commercial Electrochromic Windows

Transparent

Coloured

Commercial Electrochromic Windows

Area Control



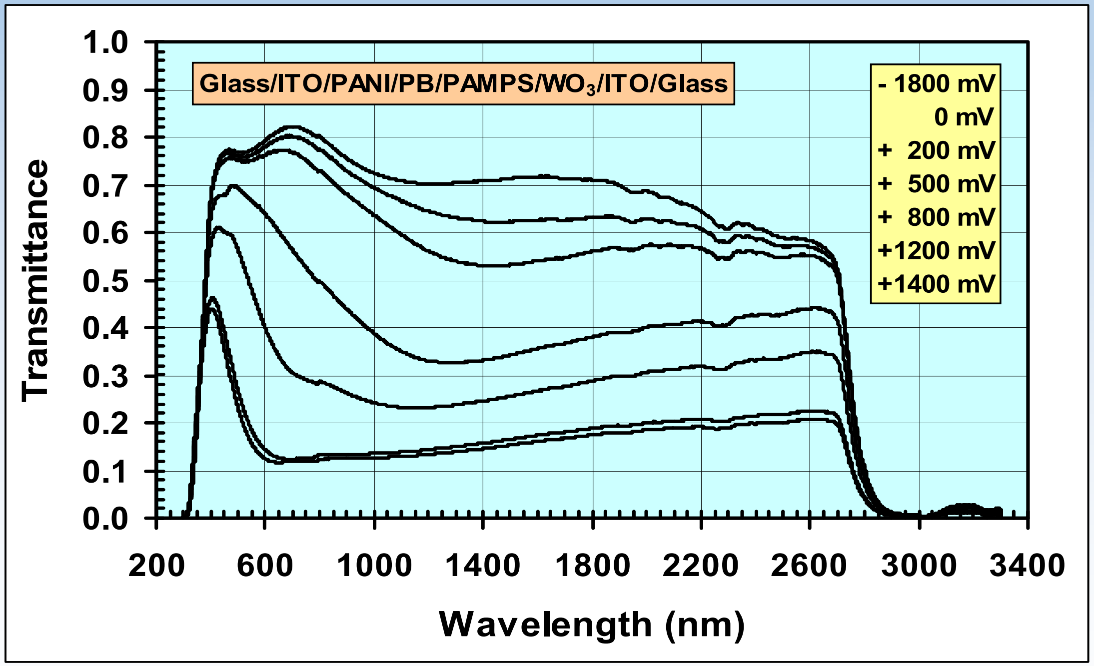
Commercial Electrochromic Windows

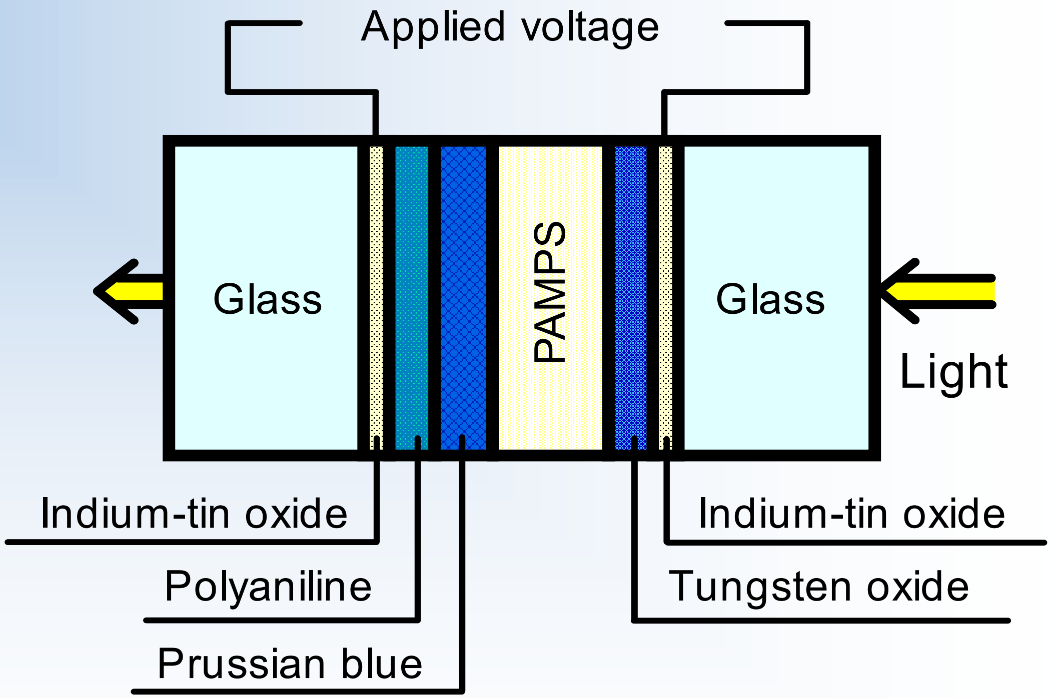
Coloured

Transparent

Conclusions – Electrochromic Windows

- Enable a dynamic control of the solar radiation radiation throughput in windows.
- May readily be characterized by solar radiation glazing factors.





Solar radiation… dynamically controlled by electrochromic windows… and characterized by solar radiation glazing factors…