Title
OpticalConstants and Bulk Optical Properties of Soda Lime Silica Glasses for Windows

Author
Rubin, M.

Publication Date
1985

LBL-13572
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

Submitted to Solar Energy Materials

OPTICAL CONSTANTS AND BULK OPTICAL PROPERTIES OF SODA LIME SILICA GLASSES FOR WINDOWS

M. Rubin

June 1984

APPLIED SCIENCE
DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

To be published in Solar Energy Materials

LBL-13572
EEB-81-28
W-114

Optical Constants and Bulk Optical Properties of Soda Lime Silica Glasses for Windows

M. Rubin

Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley CA 94720

ABSTRACT

A comprehensive set of optical constants and a partial set of bulk optical properties are listed for clear, absorbing, and low-iron glasses used for windows. The measurements extend from the near ultraviolet to the far infrared, covering the range of interest for calculating solar and thermal radiative transfer through windows. This information is also needed to calculate the properties of thin-film coatings on glass substrates. Large variations in solar absorption are observed among these glasses, whereas the far-infrared properties are almost constant for all glass types. An important quantity, the hemispherical total emissivity, is 0.837 at 20°C, as determined from reflectance data measured with a Fourier-Transform spectrometer. Solar properties are determined from conventional transmission and reflection measurements.

June 1984

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Optical Constants and Bulk Optical Properties of Soda Lime Silica Glasses for Windows

M. Rubin

Applied Science Division

Lawrence Berkeley Laboratory

University of California

Berkeley CA 94720

Introduction

The primary purpose of this paper is to provide a set of optical constants over the solar and thermal infrared for all common window glasses. This information will interest designers of thin-film coatings on window glass substrates. We also provide some spectrally and directionally averaged bulk properties for calculating solar and thermal radiative heat transfer through windows. In any case, the optical constants can be used to calculate any desired optical property of these glasses, either individually or in combination with other materials that comprise a complex window system.

The optical properties of window glasses have been measured extensively, but the available data are contradictory and incomplete. The optical constants in particular have never been completely tabulated over the wavelength range of interest. This range covers the two important sources of radiation, the sun (0.3 to 3 μm) and local thermal sources (4 to 90 μm), including the glass itself. Some of the most widely used optical data originate before plate glass was almost completely replaced with glass produced by the modern float process. Also, there is relatively little information about glasses other than so-called clear glasses.

Glass manufacturers produce four nominally standardized varieties of glass: clear, grey, bronze, and green. Grey, bronze, and green glasses contain absorbers to reduce solar transmittance. Clear glass contains no additives other than those meant to affect the manufacturing process. However, even in clear glass, iron oxides in the raw materials produce significant absorption in the solar infrared. A fifth type of glass, produced on a regular basis by only one manufacturer, contains less iron than standard clear glass. The use of raw materials having higher purity accounts only in part for the reduced solar absorption of the product. A further reduction is achieved through the conversion of FeO to the higher oxidation state, Fe_2O_3, which absorbs principally in the ultraviolet [1].

In this paper, the experimental methods, results, and discussion are divided into two sections corresponding to the infrared and solar spectral ranges. This division follows the natural separation between the source spectra and between the fundamental optical mechanisms of the glasses.

Far-Infrared Optical Properties

The power reflection coefficient (or reflectivity), ρ, was measured at near-normal incidence from 3 to 50 μm with a Fourier-Transform spectrometer. The high signal-to-noise ratio of this instrument allows precise measurement of the small reflectivity in this spectral range. The back surfaces of the sample plates were roughened to prevent multiple reflections in the transparent region below 5 μm. Figure 1 shows the reflectance of a sample of clear float glass. The single-surface reflectivity at short wavelengths is less than 0.04 and slowly decreases with increasing wavelength. After dropping to nearly zero at 8 μm, ρ shows two major resonances centered around 9.5 and 21 μm, attributable to Si-O stretching and bending influenced by network modifiers [2]. The results for the solar-absorbing and low-iron glasses are almost identical. The principal effect of the slight chemical differences among these glasses occurs in the visible and near infrared, as shown in the following section.

The phase, ψ, of the amplitude reflection coefficient at frequency ω is related to ρ through the Kramers-Krōnig formula:

$$\psi(\omega) = \frac{\omega}{\pi}\int_0^\infty \frac{\ln\rho(\omega')}{\omega'^2 - \omega^2} d\omega' . \tag{1}$$

Then the real and imaginary parts of the index of refraction, n and k, are related to ρ and ψ:

$$n = \frac{1-\rho}{1-2\sqrt{\rho}\cos\psi+\rho} \qquad k = \frac{2\sqrt{\rho}\sin\psi}{1-2\sqrt{\rho}\cos\psi+\rho} . \tag{2}$$

In theory we need ρ from λ=0 to ∞, not only in the region over which we calculate the optical constants. We can justify some extrapolation because the contribution from ρ diminishes rapidly away from the wavelength in question. This can be shown more clearly by integrating Eq. (1) by parts:

$$\psi(\omega) = \frac{1}{2\pi}\int_0^\infty \frac{d\ln\rho}{d\omega'}\ln\left|\frac{\omega'+\omega}{\omega'-\omega}\right| d\omega' . \tag{3}$$

Equation (3) also shows that regions of constant ρ do not contribute to this integral. Between 0.3 and 3.0 μm, ρ is small and varies slowly. The optical constants in this transparent region are given in the next section. At wavlengths longer than 50 μm there are no strong absorption mechanisms and the reflectivity should approach a constant value. Bagdade and Stollen [3] find n=2.6 from 100-1000 μm for a "soft" glass of similar composition. The dielectric constant of Corning 0080 soda lime glass is 6.75 at 100 MHz [4], corresponding to n=2.60. The values of k calculated from Ref. [3] indicate that absorption is barely strong enough at 200 μm to affect ρ, and that this effect decreases rapidly with increasing wavelength. Therefore we assume that ρ approaches a limiting value of 0.2 at 200 μm, and accordingly extrapolate our results from 50 μm.

Figure 2 shows the optical constants obtained by applying Eqs. (1) and (2) to data for a sample of clear float glass. Note that k becomes comparable to n in this region, and exceeds n near the reflection peaks. This feature slightly complicates calculations of optical properties because surface reflection depends on k as well as n. In principle, we can now calculate any infrared optical property, using n and k values averaged for about 20 samples (Table 1).

Strictly, heat-transfer rates should be calculated as a function of angle and wavelength, and averaged only after accounting for interactions among all elements of the window. In practice, this rigorous treatment is not necessary except where the glass (or other materials with which the glass exchanges energy) has properties that change rapidly over the peak regions of the spectral or angular weighting functions.

For the parallel-plate geometry of typical windows, only the hemispherical total emissivity appears in the simplified equations of radiative heat transfer. This quantity can be derived from the directional spectral reflectivity, $\rho(\lambda,\theta)$, which depends on both wavelength, λ, and reflected angle, θ, measured from the surface normal. Averaging over wavelength gives the directional total emissivity:

$$\epsilon(\theta,T) = \frac{\pi}{\sigma T^4}\int_0^\infty (1-\rho(\lambda,\theta))\, I(\lambda,T)\, d\lambda\,, \tag{4}$$

where σ is the Stefan-Boltzmann constant, I is the blackbody spectral intensity, and T is the surface temperature. At typical temperatures, the form of I limits the integral to the wavelength range of 4-90 μm.

Averaging over the hemisphere gives the hemispherical total emissivity:

$$\epsilon_h(T) = \frac{1}{\pi}\int \epsilon(\theta,T)\cos\theta\, d\Omega\,, \tag{5}$$

where $d\Omega=\sin\theta\, d\theta\, d\phi$ is an element of solid angle. Because $\epsilon(\theta,T)$ is isotropic (independent of ϕ),

$$\epsilon_h(T) = 2\int_0^{\pi/2} \epsilon(\theta,T)\cos\theta\,\sin\theta\, d\theta\,. \tag{6}$$

From Eqs. (4) and (6) we find that ϵ_h=0.837 at 20° and $d\epsilon/dT=1.8\times10^{-4}$ C^{-1}. Many handbooks and heat-transfer textbooks report the normal emissivity, ϵ_0, to be 0.94 at 38°. This value was measured in Germany before World War II using spectrophotometers that could not operate beyond 15 μm [5-7]. However, a blackbody at room temperature radiates almost half its energy at longer wavelengths. Because the reflectivity of soda lime glass increases from 15 to 21 μm (see Fig. 1), a spectral average performed over the entire far-infrared spectrum available with modern spectrophotometers will yield a lower total emissivity than an average that extends only to 15 μm.

In his classic papers on the emissivity of window glass at high temperatures [8,9], Gardon calculates ϵ_h=0.91 using indices of refraction and absorption coefficients measured in the near infrared [10,11]. This value is often misapplied to glasses at ambient or slightly elevated temperatures.

Linke [12] reports ϵ_h=0.825 based on calorimetric measurements of heat transfer through glass windows. Lohrengel [13,14] measured ρ at a few angles between 0 and 75° and interpolated to obtain ϵ_h=0.850 for window glass. Barnes [15] measured emissivity directly using a heated cavity emissometer at elevated temperatures. He obtained, at 100 $^{\circ}$C, ϵ_h=0.775 for fused quartz, ϵ_h=0.83 for an alumino-silicate glass, and ϵ_h=0.835 for a borosilicate glass.

Yellott [5] reported ϵ_0 = 0.896 for window glass based on reflectivity measurements to 50 μm. For an opaque dielectric, there is a unique correspondence between ϵ_0 and ϵ_h, from which Yellott obtains ϵ_h = 0.842. Isard [16] shows indirectly that deviations from ideal behavior near the molecular resonances in the far infrared do not seriously affect this correspondence.

Using the Kramers-Krönig technique, Bagley [17] derived the optical constants of a special high-purity glass that was similar in composition to window glass. From these optical constants, Hsieh [18] calculates ϵ_h=0.835 at 20° C, correctly assuming that the differences in composition and preparation would not lead to serious errors in averaged properties. We duplicated Bagleys glass composition and verified this assumption experimentally.

Using the methods of [19] we estimate the effect of variations in ϵ on the overall coefficient of heat transfer, U (including convection). Using the incorrect handbook value of 0.936 produces an increase in U of 10-12% for double- and triple-glass. The variation will be less for windows having infrared-reflecting coatings.

In a limited number of samples of weathered glass we observed variations in ϵ_h of a few percent, producing less than 1% variations in U. This effect is supressed because the most variation ocurs on the outside surface, where strong wind-forced convection tends to short-circuit radiative heat transfer.

Solar Optical Properties

These glasses are partially transparent throughout the near-ultraviolet, visible, and near-infrared regions that compose the solar spectrum (0.3-3 μm). The transmittance and reflectance of these glasses vary much more in the solar spectrum than in the far-infrared because of the FeO in the raw materials or added to control color and melting. Other absorbers are added to produce the bronze, grey, and blue-green glasses. Also, within each nominal color and thickness there are variations that affect the transmittance and absorptance.

Although the transmission of some of these glasses falls below 0.25, the absorption coefficient never becomes high enough to affect the surface reflectance. However, the total reflectance may decrease by half because less second-surface reflectance can penetrate the plate. The real part of the index of refraction, therefore, does not vary greatly among glasses that have the same matrix composition. For soda lime glasses of similar composition to window glasses, the reported variation in n does not exceed 1% for any λ. This corresponds to a 5% variation in r, which can be ignored for this application. Therefore, we can use n as determined for a "light crown" glass of similar composition to window glasses [20]. A simplifed form of the dispersion equation proposed by Herzberger [21] fits these data to the third decimal place over the entire solar spectrum:

$$n = 1.5130 - 0.003169\lambda^2 + \frac{0.003962}{\lambda^2}. \quad (7)$$

To determine k we measure the normal transmittance, τ_0, of each type of glass. The relationship between τ_0 and k, counting multiple reflections, is

$$\tau_0(d) = \frac{(1-\rho)^2 e^{-\alpha d}}{1-\rho^2 e^{-2\alpha d}}, \quad (8)$$

where d is the thickness of the plate, and the absorption coefficient $\alpha = 4\pi k/\lambda$. This expression can be solved as a quadratic in the exponential factor:

$$k = \frac{\lambda}{2\pi d} \ln\left[\frac{\sqrt{(1-\rho)^4 + 4\rho^2\tau_0^2} - (1-\rho)^2}{2\rho^2\tau_0}\right]. \quad (9)$$

Figure 3 shows the transmittances for representative samples of each type of glass, and Table 2 gives the calculated values of k.

The visible and solar-average quantities can be evaluated by expressions analogous to Eqs. (4) and (6). For solar averages the AM2 standard of solar spectral irradiance given by Lind, Pettit, and Masterson [22] replaces the blackbody weighting function. Over the visible subset of this spectrum the weighting function is the product of the solar irradiance and the luminous efficacy of the eye, which we approximate by a Gaussian of the form:

$$V(\lambda) = \exp(-278.5(\lambda - 0.559)^2). \quad (10)$$

Transmittance is the primary quantity of interest for calculating both direct solar heat gain and daylight illuminance. It is absorptance, however, that most directly determines secondary solar heat gain, while reflectance relates to secondary redistribution of daylight. From the optical constants of Table 2, we calculate some of these optical properties using the methods of Ref. [23]. Tables 3 and 4 list the solar transmittance and absorptance as a function of d and θ. Similarly, Tables 5 and 6 list the visible transmittance and reflectance.

Much of the published data on the solar properties of glass are incorrect, outdated, or not in useful form. Hsieh [18] provided the first complete tabulation of $n(\lambda)$ and $k(\lambda)$ for clear glass. The spectrally averaged properties derived from these data agree closely with our data; however, the k values are slightly higher than ours in the visible and lower in the near infrared. Manufacturers' product literature usually provides accurate tables of total normal transmittance, and less often reflectance and absorptance and the corresponding hemispherical quantities. The normal-incidence values in Tables 3 through 6 can thus be used for comparisons with existing data. However, if a single value must be used to quantitatively characterize a glazing material, the normal-incidence value is not the best choice. The hemispherical quantities, besides applying to diffuse light, also correspond coincidentally to the directional properties at typical angles of incidence for vertical windows. The variation of the solar optical properties with sun angle, included in Tables 3 through 6, should be accounted for in detailed calculations.

Conclusion

Although measurable variations in optical properties exist within manufacturing tolerances, the optical data in this paper are self-consistent and broadly representative of most window glasses presently manufactured in the U.S. We can now compare plastics and more exotic coated and uncoated glazings to this most common and enduring material.

Acknowledgement

This work was supported by the Assistant Secretary for Conservation and

Renewable Energy, Office of Building Energy Research and Development, Buildings Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

We also thank D.S. Balik of General Glass International Corp., P.G.T. Owens of Pilkington Flat Glass Ltd., A.R. Shaw of Libbey-Owens-Ford Company, A.J. Thimons of PPG Industries, Inc., and J.I. Yellott of Yellott Engineering Associates, Inc. for their assistance.

References

1. J.K. Goodyear and V.L. Lindberg, Solar Energy Mater. **3** (1980) 57.
2. T.A. Sidorov, J. Appl. Spectrosc. **7** (1967) 258.
3. W. Bagdade and R. Stolen, J. Phys. Chem. Sol. **29** (1968) 2001.
4. CRC Handbook of Chemistry and Physics, Chemical Rubber Co. (1977) p.E-56.
5. J. Yellott, ASHRAE Trans. **69** (1963) 418.
6. E. Schmidt, Gesundheits Ingenieur **20** (1927) 1.
7. E. Schmidt and E. Eckert, Forsch. Gebeite Ingenieurwesen **6** (1935).
8. R. Gardon, J. Am. Ceramic Soc. **39** (1956) 278.
9. R. Gardon, J. Am. Ceramic Soc. **44** (1961) 305.
10. N. Neuroth, Glastech. Ber. **25** (1952) 242.
11. N. Neuroth, Glastech. Ber. **26** (1953) 66.
12. W. Linke, Kaltetechnik **8** (1956) 378.
13. J. Lohrengel, Glastechnische Berichte **43** (1970) 493.
14. J. Lohrengel and C. Tingwaldt, Optik **31** (1970) 404.
15. B.T. Barnes, W.T. Forsythe, and E.Q. Adams, J. Opt. Soc. Am. **37** (1947) 804.
16. J.O. Isard, Infrared Phys. **20** (1980) 249.

17. B.G. Bagley et al., J. Non-Cryst. Sol. **22** (1976) 423.

18. C.K. Hsieh and K.C. Su, Solar Energy **22** (1979) 37.

19. M. Rubin, J. Energy Res. **6** (1982) 341.

20. G.W. Cleek and J.J. Villa, J. Opt. Soc. Am. **49** (1959) 1090.

21. M. Herzberger, J. Opt. Soc. Am. **32** (1942) 70.

22. M.A. Lind, R.B. Pettit, and K.D. Masterson, Solar Energy Eng. **102** (1980) 34.

23. M. Rubin, J. Energy Res. **6** (1982) 123.

Table 1. Optical constants of window glass in the far infrared

λ(μm)	n	k	λ(μm)	n	k	λ(μm)	n	k
5.0	1.397	0.003	12.0	1.733	0.222	22.0	1.931	1.216
6.0	1.323	0.005	12.5	1.612	0.244	23.0	2.196	0.988
7.0	1.152	0.008	13.0	1.606	0.306	24.0	2.263	0.746
8.0	0.939	0.028	13.5	1.615	0.304	25.0	2.223	0.582
8.2	0.822	0.061	14.0	1.615	0.280	27.0	2.139	0.462
8.4	0.624	0.216	14.5	1.558	0.269	30.0	2.035	0.381
8.5	0.613	0.354	15.0	1.554	0.299	35.0	1.960	0.421
8.7	0.684	0.543	15.5	1.546	0.288	40.0	1.969	0.487
9.0	0.736	0.759	16.0	1.511	0.278	45.0	2.033	0.538
9.2	0.812	0.938	16.5	1.468	0.288	50.0	2.099	0.545
9.4	0.971	1.123	17.0	1.433	0.309	60.0	2.199	0.536
9.5	1.085	1.187	17.5	1.401	0.322	70.0	2.274	0.515
9.6	1.209	1.232	18.0	1.328	0.329	80.0	2.333	0.493
9.8	1.479	1.240	18.5	1.216	0.382	90.0	2.384	0.470
10.0	1.707	1.123	19.0	1.108	0.521	100.0	2.426	0.445
10.5	1.956	0.809	19.5	1.069	0.760	150.0	2.547	0.326
11.0	1.994	0.485	20.0	1.177	0.966	200.0	2.592	0.242
11.5	1.864	0.286	21.0	1.519	1.223	300.0	2.608	0.152

Table 2. Absorption coefficients in the solar spectrum for window glasses.

λ(μm)	n	Clear	Bronze	Grey	Green	Low-Iron
		k				
0.31	1.554	4.996×10^{-5}	-	-	-	1.191×10^{-5}
0.32	1.551	1.375×10^{-5}	7.310×10^{-5}	7.310×10^{-5}	7.310×10^{-5}	3.062×10^{-6}
0.33	1.549	6.281×10^{-6}	3.341×10^{-5}	2.433×10^{-5}	3.341×10^{-5}	1.399×10^{-6}
0.34	1.547	2.713×10^{-6}	1.583×10^{-5}	1.291×10^{-5}	1.291×10^{-5}	6.061×10^{-7}
0.35	1.545	1.118×10^{-6}	8.617×10^{-6}	6.584×10^{-6}	5.955×10^{-6}	2.458×10^{-7}
0.36	1.543	5.419×10^{-7}	5.081×10^{-6}	3.790×10^{-6}	2.999×10^{-6}	1.164×10^{-7}
0.37	1.542	4.061×10^{-7}	4.087×10^{-6}	2.974×10^{-6}	2.158×10^{-6}	9.300×10^{-8}
0.38	1.540	5.936×10^{-7}	4.514×10^{-6}	3.379×10^{-6}	2.944×10^{-6}	1.309×10^{-7}
0.39	1.539	2.828×10^{-7}	3.321×10^{-6}	4.036×10^{-6}	1.419×10^{-6}	6.261×10^{-8}
0.40	1.537	2.047×10^{-7}	3.076×10^{-6}	2.400×10^{-6}	1.025×10^{-6}	4.570×10^{-8}
0.41	1.536	2.182×10^{-7}	3.330×10^{-6}	2.863×10^{-6}	1.096×10^{-6}	5.013×10^{-8}
0.42	1.535	2.279×10^{-7}	3.586×10^{-6}	3.315×10^{-6}	1.147×10^{-6}	5.449×10^{-8}
0.43	1.534	2.397×10^{-7}	3.877×10^{-6}	3.793×10^{-6}	1.205×10^{-6}	5.878×10^{-8}
0.44	1.533	2.342×10^{-7}	4.107×10^{-6}	4.160×10^{-6}	1.181×10^{-6}	5.095×10^{-8}
0.45	1.532	1.925×10^{-7}	4.230×10^{-6}	4.325×10^{-6}	9.902×10^{-7}	4.252×10^{-8}
0.46	1.531	1.669×10^{-7}	4.354×10^{-6}	4.484×10^{-6}	8.684×10^{-7}	3.351×10^{-8}
0.47	1.530	1.700×10^{-7}	4.496×10^{-6}	4.607×10^{-6}	8.484×10^{-7}	3.675×10^{-8}
0.48	1.529	1.683×10^{-7}	4.606×10^{-6}	4.781×10^{-6}	8.408×10^{-7}	3.995×10^{-8}
0.49	1.529	1.554×10^{-7}	4.697×10^{-6}	5.051×10^{-6}	8.445×10^{-7}	2.972×10^{-8}
0.50	1.528	1.492×10^{-7}	4.723×10^{-6}	5.294×10^{-6}	8.659×10^{-7}	3.257×10^{-8}
0.51	1.527	1.499×10^{-7}	4.686×10^{-6}	5.568×10^{-6}	9.096×10^{-7}	3.538×10^{-8}
0.52	1.527	1.582×10^{-7}	4.569×10^{-6}	5.685×10^{-6}	9.657×10^{-7}	3.816×10^{-8}
0.53	1.526	1.769×10^{-7}	4.339×10^{-6}	5.588×10^{-6}	1.039×10^{-6}	4.091×10^{-8}
0.54	1.526	1.988×10^{-7}	4.095×10^{-6}	5.414×10^{-6}	1.118×10^{-6}	4.362×10^{-8}
0.55	1.525	2.200×10^{-7}	3.725×10^{-6}	4.913×10^{-6}	1.169×10^{-6}	4.632×10^{-8}
0.56	1.525	2.529×10^{-7}	3.564×10^{-6}	4.842×10^{-6}	1.297×10^{-6}	6.429×10^{-8}
0.57	1.524	3.051×10^{-7}	3.750×10^{-6}	5.519×10^{-6}	1.556×10^{-6}	6.721×10^{-8}
0.58	1.524	3.563×10^{-7}	3.880×10^{-6}	6.061×10^{-6}	1.805×10^{-6}	8.597×10^{-8}
0.59	1.523	4.003×10^{-7}	3.922×10^{-6}	6.414×10^{-6}	2.027×10^{-6}	8.913×10^{-8}
0.60	1.523	4.548×10^{-7}	3.953×10^{-6}	6.651×10^{-6}	2.264×10^{-6}	1.087×10^{-7}
0.61	1.522	5.217×10^{-7}	3.929×10^{-6}	6.654×10^{-6}	2.508×10^{-6}	1.121×10^{-7}
0.62	1.522	5.972×10^{-7}	3.978×10^{-6}	6.745×10^{-6}	2.781×10^{-6}	1.325×10^{-7}
0.63	1.522	6.913×10^{-7}	4.169×10^{-6}	7.073×10^{-6}	3.073×10^{-6}	1.534×10^{-7}
0.64	1.521	7.754×10^{-7}	4.314×10^{-6}	7.210×10^{-6}	3.426×10^{-6}	1.749×10^{-7}
0.65	1.521	8.371×10^{-7}	4.420×10^{-6}	7.189×10^{-6}	3.942×10^{-6}	1.790×10^{-7}
0.66	1.521	9.108×10^{-7}	4.451×10^{-6}	6.883×10^{-6}	4.334×10^{-6}	2.013×10^{-7}
0.67	1.520	1.009×10^{-6}	4.354×10^{-6}	6.148×10^{-6}	4.472×10^{-6}	2.242×10^{-7}
0.68	1.520	1.097×10^{-6}	4.276×10^{-6}	5.460×10^{-6}	4.686×10^{-6}	2.476×10^{-7}
0.69	1.520	1.159×10^{-6}	4.194×10^{-6}	4.720×10^{-6}	5.008×10^{-6}	2.526×10^{-7}
0.70	1.520	1.234×10^{-6}	4.186×10^{-6}	4.210×10^{-6}	5.363×10^{-6}	2.769×10^{-7}
0.71	1.519	1.349×10^{-6}	4.401×10^{-6}	4.297×10^{-6}	5.805×10^{-6}	3.017×10^{-7}
0.72	1.519	1.466×10^{-6}	4.628×10^{-6}	4.412×10^{-6}	6.260×10^{-6}	3.271×10^{-7}
0.73	1.519	1.585×10^{-6}	4.870×10^{-6}	4.556×10^{-6}	6.730×10^{-6}	3.531×10^{-7}
0.74	1.519	1.706×10^{-6}	5.125×10^{-6}	4.730×10^{-6}	7.213×10^{-6}	3.796×10^{-7}
0.75	1.518	1.830×10^{-6}	5.395×10^{-6}	4.937×10^{-6}	7.711×10^{-6}	4.067×10^{-7}
0.76	1.518	1.956×10^{-6}	5.715×10^{-6}	5.250×10^{-6}	8.245×10^{-6}	4.344×10^{-7}
0.77	1.518	2.085×10^{-6}	6.036×10^{-6}	5.567×10^{-6}	8.785×10^{-6}	4.627×10^{-7}
0.78	1.518	2.214×10^{-6}	6.355×10^{-6}	5.885×10^{-6}	9.327×10^{-6}	4.916×10^{-7}
0.79	1.517	2.345×10^{-6}	6.673×10^{-6}	6.207×10^{-6}	9.871×10^{-6}	5.210×10^{-7}
0.80	1.517	2.477×10^{-6}	6.988×10^{-6}	6.530×10^{-6}	1.042×10^{-5}	5.510×10^{-7}
0.81	1.517	2.617×10^{-6}	7.290×10^{-6}	6.872×10^{-6}	1.097×10^{-5}	5.816×10^{-7}
0.82	1.517	2.755×10^{-6}	7.593×10^{-6}	7.208×10^{-6}	1.153×10^{-5}	6.128×10^{-7}
0.83	1.517	2.890×10^{-6}	7.898×10^{-6}	7.536×10^{-6}	1.207×10^{-5}	6.446×10^{-7}
0.84	1.516	3.022×10^{-6}	8.202×10^{-6}	7.855×10^{-6}	1.260×10^{-5}	6.770×10^{-7}
0.85	1.516	3.150×10^{-6}	8.507×10^{-6}	8.165×10^{-6}	1.312×10^{-5}	7.099×10^{-7}
0.86	1.516	3.274×10^{-6}	8.837×10^{-6}	8.452×10^{-6}	1.360×10^{-5}	7.193×10^{-7}

λ(μm)	n	Clear	Bronze	Grey	Green	Low-Iron
				k		
0.87	1.516	$3.394x10^{-6}$	$9.155x10^{-6}$	$8.733x10^{-6}$	$1.408x10^{-5}$	$7.531x10^{-7}$
0.88	1.516	$3.510x10^{-6}$	$9.459x10^{-6}$	$9.007x10^{-6}$	$1.455x10^{-5}$	$7.875x10^{-7}$
0.89	1.515	$3.621x10^{-6}$	$9.749x10^{-6}$	$9.273x10^{-6}$	$1.500x10^{-5}$	$7.975x10^{-7}$
0.90	1.515	$3.727x10^{-6}$	$1.002x10^{-5}$	$9.531x10^{-6}$	$1.545x10^{-5}$	$8.328x10^{-7}$
0.91	1.515	$3.817x10^{-6}$	$1.025x10^{-5}$	$9.766x10^{-6}$	$1.587x10^{-5}$	$8.430x10^{-7}$
0.92	1.515	$3.906x10^{-6}$	$1.047x10^{-5}$	$9.998x10^{-6}$	$1.627x10^{-5}$	$8.792x10^{-7}$
0.93	1.515	$3.995x10^{-6}$	$1.069x10^{-5}$	$1.023x10^{-5}$	$1.667x10^{-5}$	$8.897x10^{-7}$
0.94	1.515	$4.083x10^{-6}$	$1.090x10^{-5}$	$1.045x10^{-5}$	$1.705x10^{-5}$	$9.002x10^{-7}$
0.95	1.515	$4.170x10^{-6}$	$1.111x10^{-5}$	$1.066x10^{-5}$	$1.741x10^{-5}$	$9.376x10^{-7}$
0.96	1.514	$4.261x10^{-6}$	$1.132x10^{-5}$	$1.087x10^{-5}$	$1.774x10^{-5}$	$9.484x10^{-7}$
0.97	1.514	$4.349x10^{-6}$	$1.152x10^{-5}$	$1.107x10^{-5}$	$1.806x10^{-5}$	$9.592x10^{-7}$
0.98	1.514	$4.433x10^{-6}$	$1.172x10^{-5}$	$1.127x10^{-5}$	$1.837x10^{-5}$	$9.977x10^{-7}$
0.99	1.514	$4.514x10^{-6}$	$1.191x10^{-5}$	$1.147x10^{-5}$	$1.867x10^{-5}$	$1.009x10^{-6}$
1.00	1.514	$4.591x10^{-6}$	$1.210x10^{-5}$	$1.166x10^{-5}$	$1.897x10^{-5}$	$1.020x10^{-6}$
1.10	1.512	$5.111x10^{-6}$	$1.356x10^{-5}$	$1.346x10^{-5}$	$2.119x10^{-5}$	$1.132x10^{-6}$
1.20	1.511	$5.374x10^{-6}$	$1.454x10^{-5}$	$1.465x10^{-5}$	$2.250x10^{-5}$	$1.210x10^{-6}$
1.30	1.510	$5.353x10^{-6}$	$1.430x10^{-5}$	$1.469x10^{-5}$	$2.215x10^{-5}$	$1.211x10^{-6}$
1.40	1.509	$4.939x10^{-6}$	$1.335x10^{-5}$	$1.374x10^{-5}$	$2.049x10^{-5}$	$1.118x10^{-6}$
1.50	1.508	$4.234x10^{-6}$	$1.161x10^{-5}$	$1.239x10^{-5}$	$1.762x10^{-5}$	$9.585x10^{-7}$
1.60	1.506	$3.675x10^{-6}$	$1.026x10^{-5}$	$1.123x10^{-5}$	$1.560x10^{-5}$	$8.129x10^{-7}$
1.70	1.505	$3.656x10^{-6}$	$1.009x10^{-5}$	$1.122x10^{-5}$	$1.518x10^{-5}$	$8.301x10^{-7}$
1.80	1.504	$3.920x10^{-6}$	$1.058x10^{-5}$	$1.183x10^{-5}$	$1.581x10^{-5}$	$9.432x10^{-7}$
1.90	1.503	$4.190x10^{-6}$	$1.098x10^{-5}$	$1.217x10^{-5}$	$1.656x10^{-5}$	$1.117x10^{-6}$
2.00	1.501	$4.423x10^{-6}$	$1.117x10^{-5}$	$1.227x10^{-5}$	$1.706x10^{-5}$	$1.471x10^{-6}$
2.10	1.500	$4.476x10^{-6}$	$1.118x10^{-5}$	$1.196x10^{-5}$	$1.683x10^{-5}$	$1.739x10^{-6}$
2.20	1.498	$5.373x10^{-6}$	$1.196x10^{-5}$	$1.270x10^{-5}$	$1.757x10^{-5}$	$2.027x10^{-6}$
2.30	1.497	$5.082x10^{-6}$	$1.137x10^{-5}$	$1.198x10^{-5}$	$1.686x10^{-5}$	$2.401x10^{-6}$
2.40	1.495	$5.372x10^{-6}$	$1.150x10^{-5}$	$1.205x10^{-5}$	$1.693x10^{-5}$	$2.868x10^{-6}$
2.50	1.494	$6.324x10^{-6}$	$1.266x10^{-5}$	$1.324x10^{-5}$	$1.838x10^{-5}$	$3.441x10^{-6}$
2.60	1.492	$6.883x10^{-6}$	$1.319x10^{-5}$	$1.380x10^{-5}$	$1.924x10^{-5}$	$5.643x10^{-6}$
2.70	1.490	$1.020x10^{-5}$	$1.657x10^{-5}$	$1.629x10^{-5}$	$2.313x10^{-5}$	$9.156x10^{-6}$
2.80	1.489	$6.495x10^{-5}$	$9.122x10^{-5}$	$9.406x10^{-5}$	$1.027x10^{-4}$	$8.560x10^{-5}$
2.90	1.487	$7.931x10^{-5}$	$1.008x10^{-4}$	$1.040x10^{-4}$	$1.120x10^{-4}$	$9.745x10^{-5}$
3.00	1.485	$7.432x10^{-5}$	$9.488x10^{-5}$	$9.781x10^{-5}$	$1.067x10^{-4}$	$9.318x10^{-5}$
3.10	1.483	$7.424x10^{-5}$	$9.662x10^{-5}$	$9.928x10^{-5}$	$1.072x10^{-4}$	$9.489x10^{-5}$
3.20	1.481	$8.187x10^{-5}$	$1.080x10^{-4}$	$1.077x10^{-4}$	$1.164x10^{-4}$	$1.025x10^{-4}$
3.30	1.479	$9.341x10^{-5}$	$1.190x10^{-4}$	$1.186x10^{-4}$	$1.294x10^{-4}$	$1.128x10^{-4}$
3.40	1.477	$9.958x10^{-5}$	$1.286x10^{-4}$	$1.299x10^{-4}$	$1.388x10^{-4}$	$1.250x10^{-4}$
3.50	1.474	$1.065x10^{-4}$	$1.351x10^{-4}$	$1.355x10^{-4}$	$1.473x10^{-4}$	$1.299x10^{-4}$
3.60	1.472	$1.073x10^{-4}$	$1.345x10^{-4}$	$1.385x10^{-4}$	$1.500x10^{-4}$	$1.333x10^{-4}$
3.70	1.470	$1.049x10^{-4}$	$1.366x10^{-4}$	$1.375x10^{-4}$	$1.477x10^{-4}$	$1.319x10^{-4}$
3.80	1.468	$1.029x10^{-4}$	$1.347x10^{-4}$	$1.368x10^{-4}$	$1.459x10^{-4}$	$1.282x10^{-4}$
3.90	1.465	$1.033x10^{-4}$	$1.341x10^{-4}$	$1.357x10^{-4}$	$1.436x10^{-4}$	$1.242x10^{-4}$
4.00	1.463	$1.060x10^{-4}$	$1.384x10^{-4}$	$1.393x10^{-4}$	$1.474x10^{-4}$	$1.267x10^{-4}$
4.10	1.460	$1.222x10^{-4}$	$1.579x10^{-4}$	$1.583x10^{-4}$	$1.694x10^{-4}$	$1.460x10^{-4}$
4.20	1.457	$1.435x10^{-4}$	$1.868x10^{-4}$	$1.868x10^{-4}$	$2.003x10^{-4}$	$1.691x10^{-4}$
4.30	1.455	$1.781x10^{-4}$	$2.467x10^{-4}$	$2.467x10^{-4}$	$2.590x10^{-4}$	$2.124x10^{-4}$
4.40	1.452	$2.247x10^{-4}$	$3.296x10^{-4}$	$3.296x10^{-4}$	$3.394x10^{-4}$	$2.810x10^{-4}$
4.50	1.449	$2.978x10^{-4}$	$4.623x10^{-4}$	$4.623x10^{-4}$	$4.669x10^{-4}$	$3.657x10^{-4}$
4.60	1.446	$7.437x10^{-4}$	$1.054x10^{-3}$	$1.054x10^{-3}$	$1.054x10^{-3}$	$1.054x10^{-3}$

Table 3. Solar transmittance of window glasses.

Thickness[a] mm	in.	0°	20°	30°	40°	50°	60°	70°	80°	H[b]
		Angle of Incidence								
Clear										
2.5	3/32	0.856	0.854	0.850	0.842	0.821	0.773	0.659	0.405	0.782
3	1/8	0.837	0.834	0.830	0.821	0.800	0.752	0.640	0.391	0.762
5	3/16	0.800	0.797	0.792	0.781	0.759	0.712	0.603	0.365	0.724
6	1/4	0.775	0.772	0.766	0.755	0.732	0.685	0.579	0.349	0.699
10	3/8	0.701	0.696	0.689	0.676	0.653	0.607	0.510	0.303	0.624
12	1/2	0.653	0.647	0.640	0.626	0.603	0.558	0.467	0.276	0.577
19	3/4	0.558	0.552	0.543	0.529	0.506	0.465	0.386	0.225	0.486
25	1	0.488	0.481	0.472	0.458	0.436	0.400	0.330	0.191	0.420
Bronze										
3	1/8	0.645	0.639	0.630	0.616	0.592	0.546	0.454	0.263	0.567
5	3/16	0.544	0.536	0.526	0.510	0.486	0.444	0.365	0.207	0.467
6	1/4	0.482	0.474	0.464	0.447	0.423	0.384	0.313	0.176	0.408
10	3/8	0.326	0.317	0.307	0.291	0.270	0.239	0.191	0.104	0.263
12	1/2	0.246	0.237	0.227	0.213	0.195	0.170	0.134	0.072	0.192
Grey										
3	1/8	0.626	0.620	0.611	0.596	0.571	0.526	0.437	0.252	0.548
5	3/16	0.519	0.512	0.501	0.485	0.460	0.419	0.343	0.194	0.443
6	1/4	0.455	0.447	0.436	0.420	0.395	0.357	0.290	0.162	0.383
10	3/8	0.296	0.287	0.277	0.261	0.241	0.212	0.168	0.092	0.236
12	1/2	0.217	0.209	0.199	0.186	0.168	0.146	0.114	0.061	0.167
Green										
3	1/8	0.635	0.629	0.621	0.607	0.584	0.540	0.451	0.265	0.559
5	3/16	0.541	0.534	0.525	0.511	0.488	0.448	0.371	0.215	0.469
6	14	0.487	0.480	0.471	0.457	0.434	0.397	0.328	0.189	0.418
Low-Iron										
2.5	3/32	0.904	0.903	0.900	0.893	0.874	0.827	0.709	0.443	0.833
3	1/8	0.899	0.898	0.895	0.888	0.869	0.821	0.704	0.439	0.827
4	5/32	0.894	0.893	0.890	0.882	0.863	0.815	0.698	0.435	0.822
5	3/16	0.889	0.888	0.885	0.877	0.858	0.810	0.693	0.431	0.817

[a] See New Federal Specification DD-G-451d (1977) for thickness tolerances.
[b] Hemispherical average based on angle interval of 5°.

Table 4. Solar absorptance of window glasses.

Thickness[a] mm	in.	0°	20°	30°	40°	50°	60°	70°	80°	H[b]
		Angle of Incidence								
Clear										
2.5	3/32	0.067	0.069	0.071	0.074	0.077	0.081	0.083	0.080	0.075
3	1/8	0.088	0.090	0.093	0.097	0.101	0.105	0.107	0.102	0.098
5	3/16	0.128	0.131	0.134	0.139	0.145	0.150	0.152	0.141	0.141
6	1/4	0.154	0.158	0.162	0.168	0.174	0.179	0.181	0.165	0.169
10	3/8	0.233	0.238	0.244	0.251	0.259	0.265	0.263	0.231	0.251
12	1/2	0.283	0.289	0.296	0.304	0.313	0.319	0.313	0.269	0.302
19	3/4	0.383	0.389	0.397	0.406	0.415	0.419	0.404	0.335	0.400
25	1	0.456	0.463	0.471	0.480	0.488	0.489	0.467	0.379	0.470
Bronze										
3	1/8	0.293	0.299	0.306	0.316	0.326	0.334	0.331	0.291	0.315
5	3/16	0.400	0.407	0.416	0.428	0.439	0.446	0.435	0.367	0.423
6	1/4	0.464	0.472	0.482	0.494	0.505	0.510	0.493	0.408	0.486
10	3/8	0.626	0.635	0.645	0.656	0.665	0.663	0.627	0.495	0.638
12	1/2	0.709	0.717	0.726	0.736	0.742	0.734	0.688	0.532	0.712
Grey										
3	1/8	0.313	0.320	0.327	0.337	0.348	0.356	0.352	0.307	0.336
5	3/16	0.426	0.433	0.443	0.454	0.466	0.472	0.459	0.384	0.449
6	1/4	0.492	0.501	0.511	0.523	0.534	0.538	0.518	0.425	0.514
10	3/8	0.657	0.666	0.675	0.687	0.695	0.691	0.651	0.510	0.667
12	1/2	0.739	0.746	0.755	0.764	0.769	0.759	0.709	0.545	0.738
Green										
3	1/8	0.302	0.308	0.315	0.324	0.333	0.339	0.332	0.284	0.321
5	3/16	0.401	0.408	0.415	0.425	0.434	0.438	0.422	0.350	0.418
6	14	0.457	0.464	0.472	0.482	0.491	0.492	0.471	0.383	0.472
Low-Iron										
2.5	3/32	0.016	0.017	0.017	0.018	0.019	0.020	0.021	0.021	0.018
3	1/8	0.022	0.022	0.023	0.024	0.025	0.026	0.027	0.027	0.024
4	5/32	0.027	0.028	0.029	0.030	0.031	0.033	0.034	0.034	0.031
5	3/16	0.032	0.033	0.034	0.035	0.037	0.039	0.040	0.040	0.036

[a] See New Federal Specification DD-G-451d (1977) for thickness tolerances.
[b] Hemispherical average based on angle interval of 5°.

Table 5. Visible transmittance of window glasses.

Thickness[a] mm	in.	0°	20°	30°	40°	50°	60°	70°	80°	H[b]
		Angle of Incidence								
Clear										
2.5	3/32	0.902	0.902	0.899	0.892	0.873	0.826	0.708	0.443	0.831
3	1/8	0.898	0.897	0.894	0.887	0.868	0.820	0.703	0.439	0.826
5	3/16	0.888	0.887	0.884	0.876	0.857	0.809	0.693	0.431	0.816
6	1/4	0.881	0.880	0.877	0.869	0.849	0.802	0.686	0.425	0.809
10	3/8	0.859	0.857	0.854	0.845	0.825	0.777	0.663	0.408	0.786
12	1/2	0.843	0.841	0.837	0.828	0.807	0.759	0.646	0.395	0.769
19	3/4	0.807	0.804	0.799	0.788	0.767	0.719	0.609	0.369	0.731
25	1	0.774	0.770	0.764	0.753	0.731	0.683	0.577	0.346	0.697
Bronze										
3	1/8	0.685	0.679	0.671	0.658	0.633	0.587	0.490	0.286	0.606
5	3/16	0.592	0.585	0.575	0.560	0.535	0.491	0.405	0.232	0.513
6	1/4	0.534	0.526	0.516	0.500	0.475	0.433	0.355	0.201	0.457
10	3/8	0.379	0.370	0.359	0.342	0.319	0.285	0.229	0.126	0.311
12	1/2	0.294	0.286	0.275	0.259	0.239	0.210	0.166	0.090	0.234
Grey										
3	1/8	0.611	0.604	0.595	0.580	0.555	0.510	0.422	0.242	0.532
5	3/16	0.498	0.490	0.480	0.463	0.438	0.398	0.325	0.182	0.423
6	1/4	0.431	0.423	0.412	0.395	0.371	0.334	0.270	0.150	0.359
10	3/8	0.267	0.258	0.248	0.233	0.213	0.186	0.146	0.079	0.210
12	1/2	0.187	0.180	0.170	0.158	0.142	0.121	0.093	0.050	0.141
Green										
3	1/8	0.822	0.819	0.815	0.805	0.783	0.735	0.624	0.379	0.747
5	3/16	0.778	0.775	0.769	0.758	0.736	0.688	0.581	0.348	0.702
6	14	0.749	0.745	0.738	0.727	0.704	0.656	0.553	0.329	0.672
Low-Iron										
2.5	3/32	0.914	0.913	0.911	0.905	0.886	0.838	0.720	0.453	0.844
3	1/8	0.913	0.912	0.910	0.903	0.885	0.837	0.719	0.452	0.842
4	5/32	0.911	0.911	0.909	0.902	0.884	0.836	0.718	0.451	0.841
5	3/16	0.910	0.910	0.908	0.901	0.882	0.835	0.717	0.450	0.840

[a] See New Federal Specification DD-G-451d (1977) for thickness tolerances.
[b] Hemispherical average based on angle interval of 5°.

Table 6. Visible reflectance of window glasses.

Thickness[a] mm	in.	Angle of Incidence 0°	20°	30°	40°	50°	60°	70°	80°	H[b]
Clear										
2.5	3/32	0.082	0.082	0.084	0.090	0.108	0.155	0.272	0.537	0.148
3	1/8	0.081	0.082	0.083	0.090	0.108	0.154	0.270	0.534	0.147
5	3/16	0.080	0.081	0.083	0.089	0.106	0.153	0.268	0.529	0.145
6	1/4	0.080	0.080	0.082	0.088	0.106	0.152	0.266	0.526	0.144
10	3/8	0.078	0.078	0.080	0.086	0.103	0.148	0.260	0.516	0.141
12	1/2	0.077	0.077	0.079	0.085	0.101	0.146	0.256	0.509	0.139
19	3/4	0.074	0.074	0.076	0.081	0.098	0.140	0.247	0.495	0.134
25	1	0.072	0.072	0.073	0.079	0.094	0.136	0.240	0.484	0.130
Bronze										
3	1/8	0.065	0.065	0.067	0.071	0.086	0.125	0.222	0.455	0.120
5	3/16	0.060	0.060	0.061	0.065	0.079	0.115	0.207	0.434	0.111
6	1/4	0.057	0.057	0.058	0.062	0.075	0.110	0.200	0.424	0.107
10	3/8	0.050	0.050	0.051	0.055	0.068	0.101	0.186	0.405	0.098
12	1/2	0.047	0.047	0.049	0.053	0.065	0.097	0.181	0.398	0.095
Grey										
3	1/8	0.061	0.061	0.062	0.067	0.080	0.117	0.210	0.438	0.113
5	3/16	0.055	0.055	0.056	0.060	0.073	0.108	0.196	0.418	0.104
6	1/4	0.052	0.052	0.053	0.057	0.070	0.103	0.190	0.410	0.100
10	3/8	0.047	0.047	0.048	0.052	0.064	0.096	0.180	0.397	0.094
12	1/2	0.045	0.045	0.046	0.050	0.063	0.095	0.177	0.394	0.092
Green										
3	1/8	0.075	0.075	0.077	0.083	0.099	0.142	0.251	0.501	0.136
5	3/16	0.072	0.072	0.074	0.079	0.095	0.136	0.241	0.485	0.131
6	14	0.070	0.070	0.071	0.077	0.092	0.133	0.235	0.475	0.127
Low-Iron										
2.5	3/32	0.083	0.083	0.085	0.091	0.110	0.157	0.275	0.543	0.149
3	1/8	0.082	0.083	0.085	0.091	0.109	0.157	0.275	0.542	0.149
4	5/32	0.082	0.083	0.085	0.091	0.109	0.157	0.275	0.541	0.149
5	3/16	0.082	0.083	0.085	0.091	0.109	0.156	0.274	0.541	0.149

[a] See New Federal Specification DD-G-451d (1977) for thickness tolerances.
[b] Hemispherical average based on angle interval of 5°.

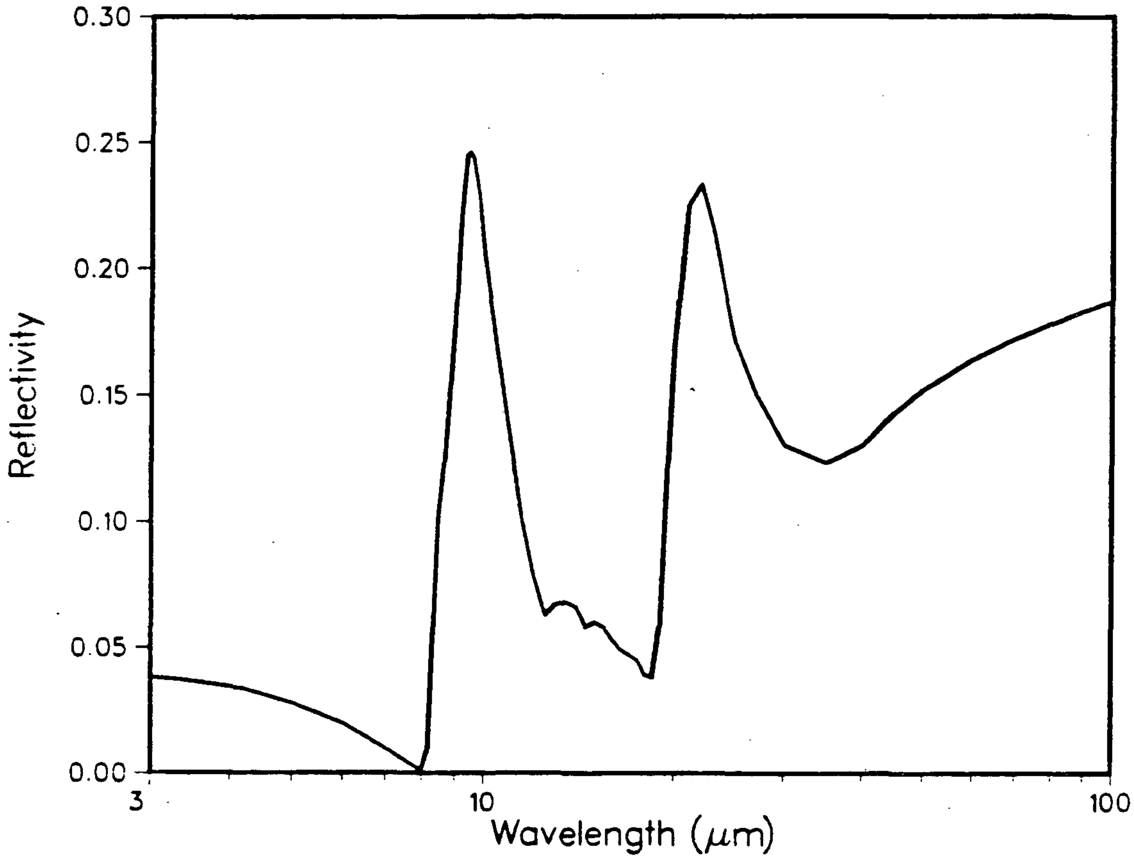

Figure 1. Far-infrared spectral reflectivity of a typical window glass.

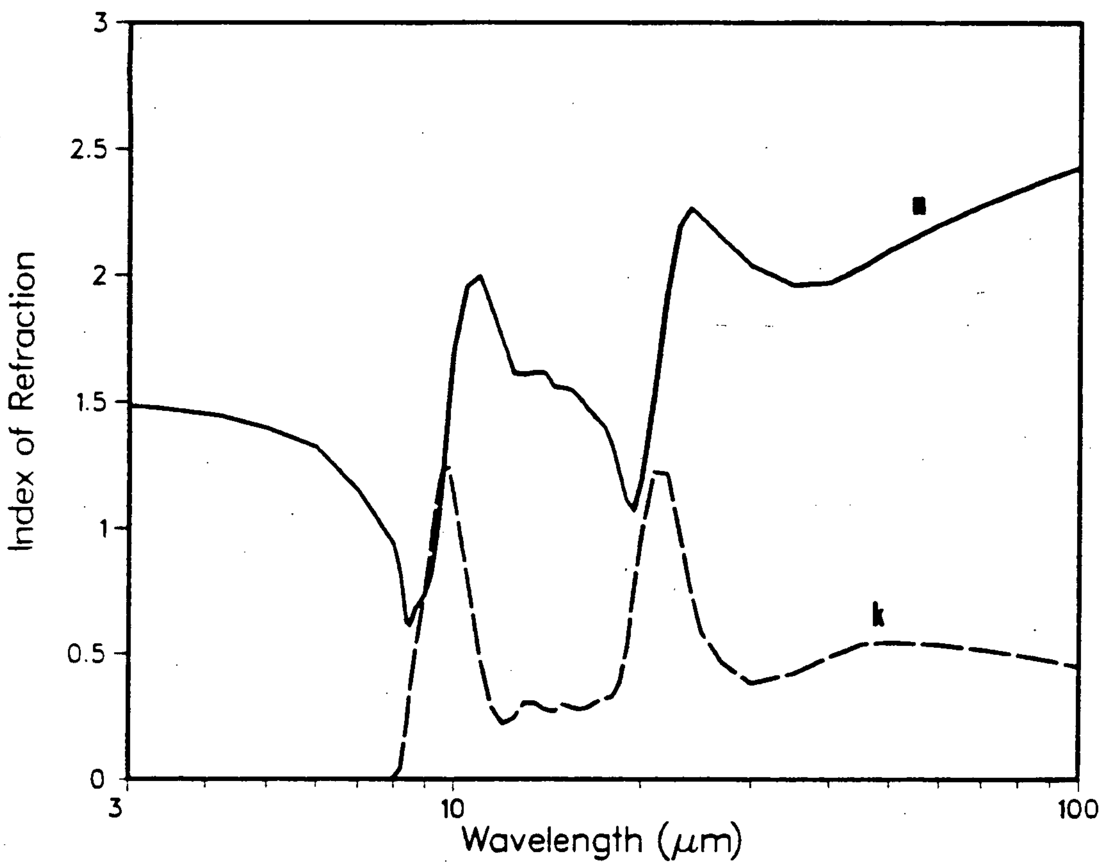

Figure 2. Real part (n) and imaginary part (k) of the complex index of refraction of a typical window glass.

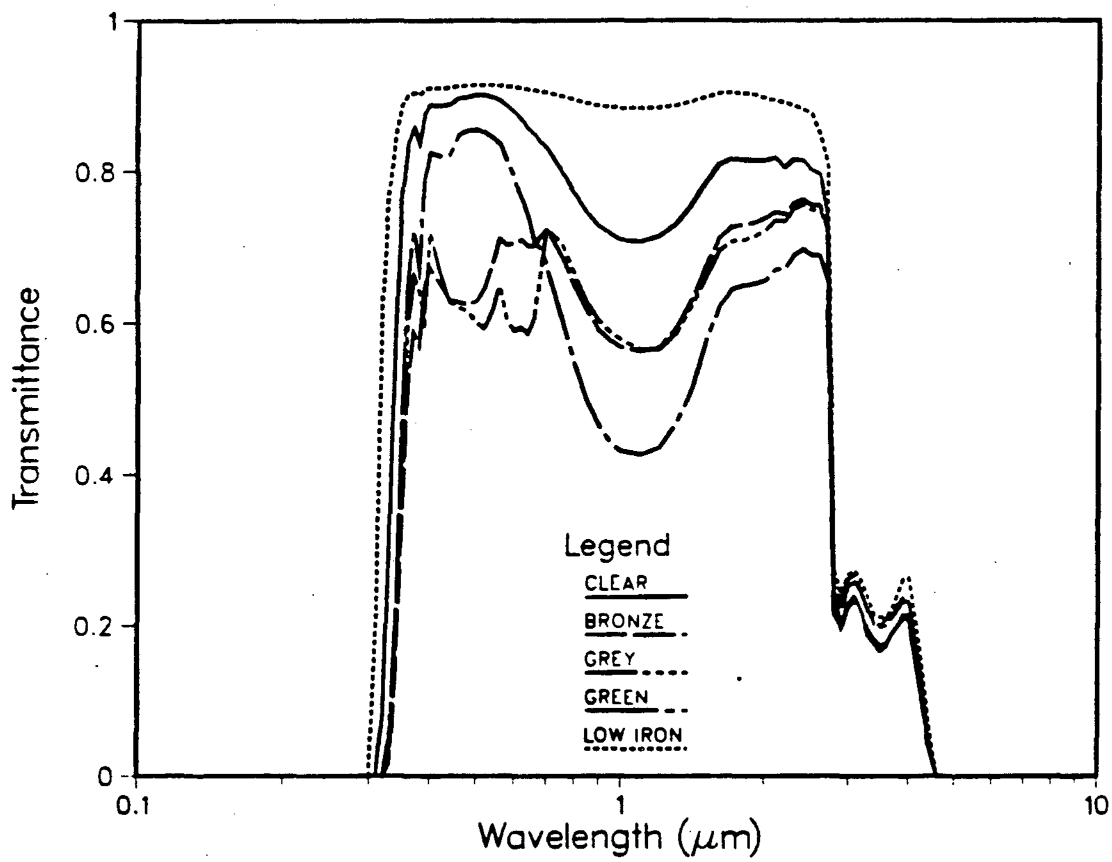

Figure 3. Solar spectral transmittance of five window glasses.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720