Radiation Heat Transfer

EGR 4345
Heat Transfer

Blackbody Radiation

- Blackbody – a perfect emitter & absorber of radiation
- Emits radiation uniformly in all directions – no directional distribution – it's <u>diffuse</u>
- Joseph Stefan (1879)– total radiation emission per unit time & area over all wavelengths and in all directions:

$$E_b = \sigma T^4 \quad \left(\mathrm{W/m^2}\right)$$

- σ=Stefan-Boltzmann constant =5.67 x10^{-8} W/m^{2}K^4

Planck’s Distribution Law

- Sometimes we’re interested in radiation at a certain wavelength
- Spectral blackbody emissive power ($E_{b\lambda}$) = “amount of radiation energy emitted by a blackbody at an absolute temperature T per unit time, per unit surface area, and per unit wavelength about the wavelength λ.”

Planck's Distribution Law

- For a surface in a vacuum or gas

$$E_{b\lambda}(T) = \frac{C_1}{\lambda^5\left[exp\left(C_2/\lambda T\right)-1\right]} \quad \left(\mathrm{W/m^2 \cdot \mu m}\right)$$

where

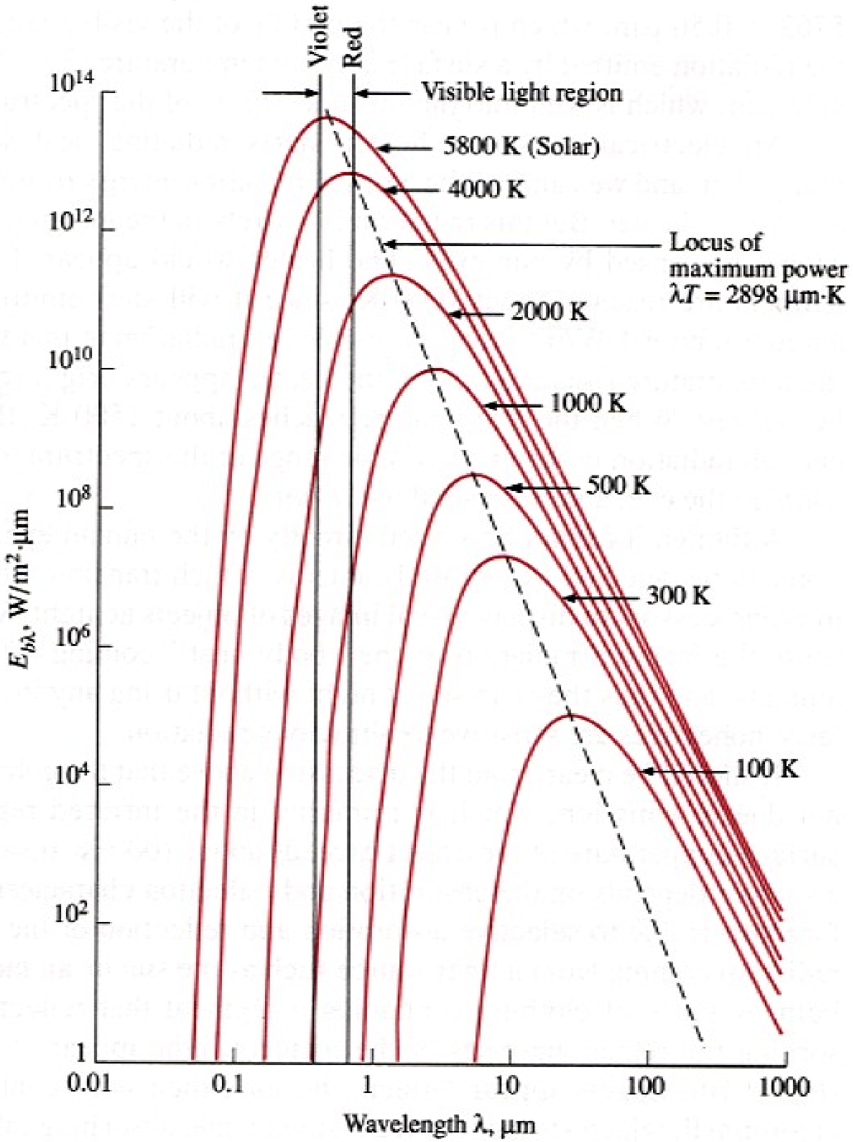
$$C_1 = 2\pi h c_o^2 = 3.742x10^8 \ \mathrm{W \cdot \mu m^4/m^2}$$

$$C_2 = hc_o/k = 1.439x10^4 \ \mathrm{\mu m \cdot K}$$

$$k = 1.3805x10^{-23} \ \mathrm{J/K} = \text{Boltzmann's constant}$$

- Other media: replace C_1 with C_1/n^2
- Integrating this function over all λ gives us the equation for E_b.

Radiation Distribution



- Radiation is a continuous function of wavelength
- Radiation increases with temp.
- At higher temps, more radiation is at shorter wavelengths.
- Solar radiation peak is in the visible range.

Wien's Displacement Law

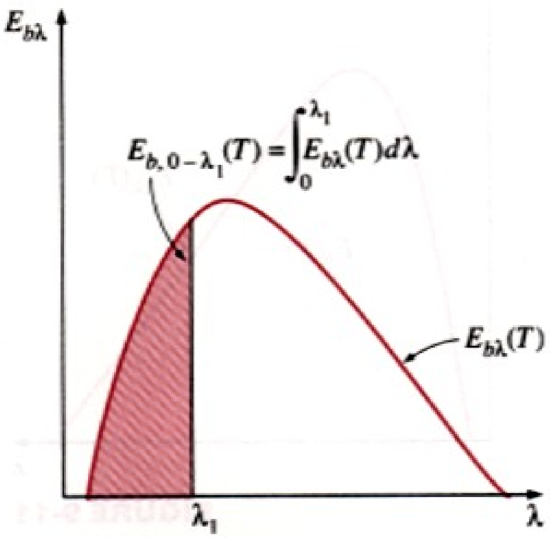
- Peak can be found for different temps using Wien's Displacement Law:

$$(\lambda T)_{max\,power} = 2897.5\,\mu\text{m}\cdot\text{K}$$

- Note that color is a function of absorption & reflection, not emission

Blackbody Radiation Function

- We often are interested in radiation energy emitted over a certain wavelength.



- This is a tough integral to do!

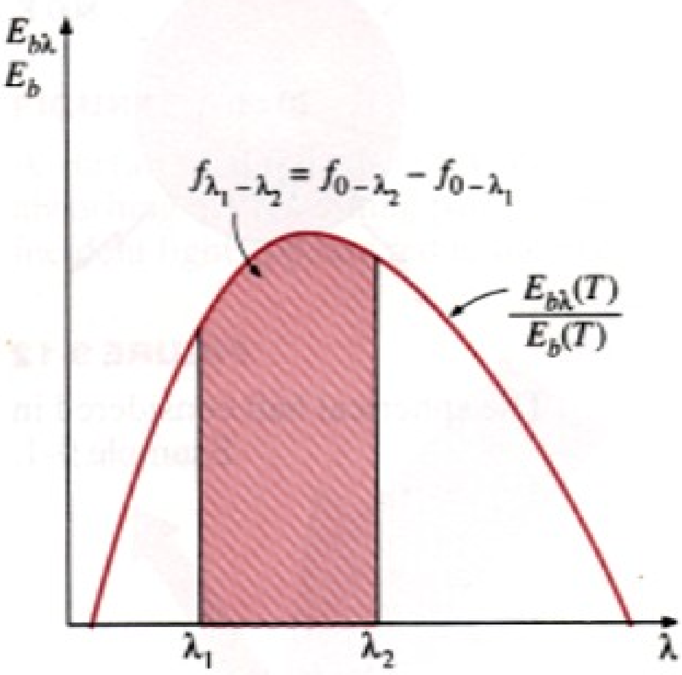
Blackbody Radiation Function

- Use blackbody radiation function, F_λ

$$F_\lambda(T) = \frac{\int_0^\lambda E_{b\lambda}(T)\,d\lambda}{\sigma T^4}$$

- If we want radiation between λ_1 & λ_2,

$$F_{\lambda_1-\lambda_2}(T) = F_{\lambda_2}(T) - F_{\lambda_1}(T)$$



Surface Emission

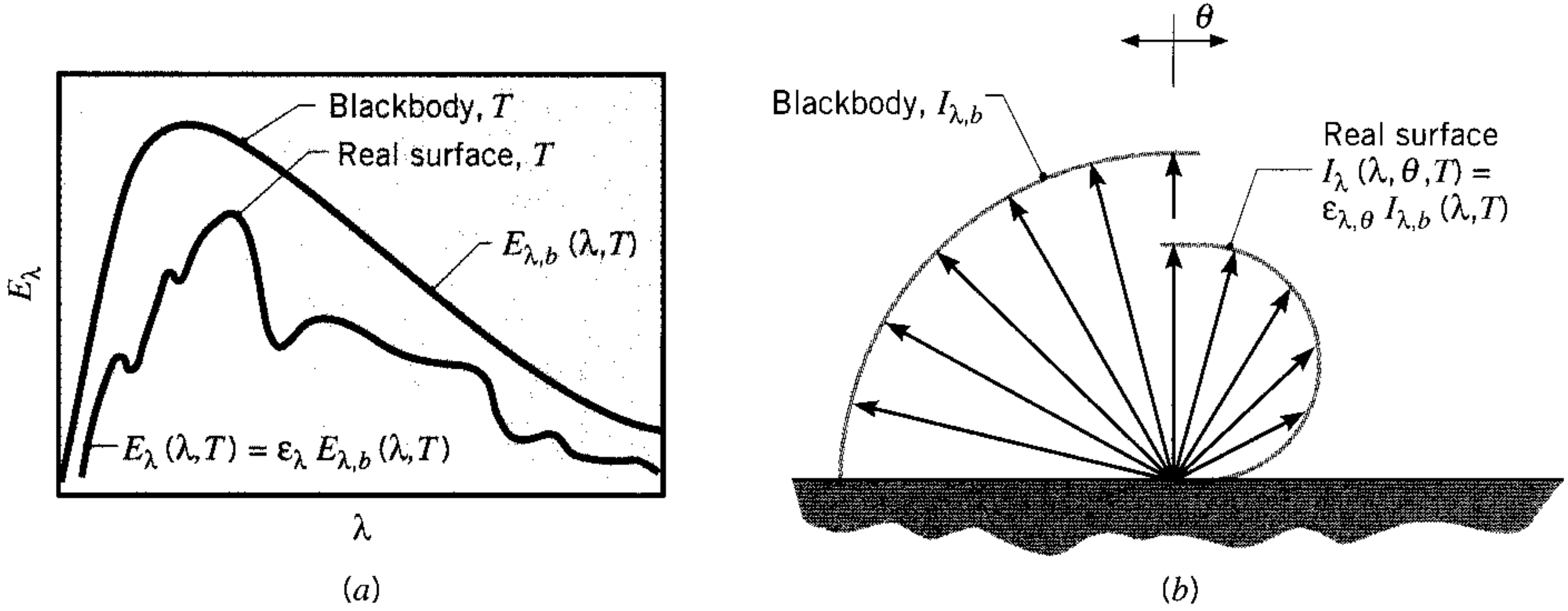


FIGURE 12.16 Comparison of blackbody and real surface emission. (*a*) Spectral distribution. (*b*) Directional distribution.

Surface Emission

Spectral, directional emissivity

$$\varepsilon_{\lambda,\theta}(\lambda, \theta, \phi, T) \equiv \frac{I_{\lambda,e}(\lambda, \theta, \phi, T)}{I_{\lambda,b}(\lambda, T)}$$

Total, directional emissivity

$$\varepsilon_{\theta}(\theta, \phi, T) \equiv \frac{I_{e}(\theta, \phi, T)}{I_{b}(T)}$$

Spectral, hemispherical emissivity

$$\varepsilon_{\lambda}(\lambda, T) \equiv \frac{E_{\lambda}(\lambda, T)}{E_{\lambda,b}(\lambda, T)}$$

$$\varepsilon_{\lambda}(\lambda, T) = \frac{\int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,e}(\lambda, \theta, \phi, T) \cos\theta \sin\theta \, d\theta \, d\phi}{\int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,b}(\lambda, T) \cos\theta \sin\theta \, d\theta \, d\phi}$$

Surface Emission

Spectral, hemispherical emissivity

$$\varepsilon_{\lambda}(\lambda, T) \equiv \frac{E_{\lambda}(\lambda, T)}{E_{\lambda,b}(\lambda, T)}$$

Substituting spectral emissive power

$$\varepsilon_{\lambda}(\lambda, T) = \frac{\int_{0}^{2\pi} \int_{0}^{\pi/2} I_{\lambda,e}(\lambda, \theta, \phi, T) \cos\theta \sin\theta \, d\theta \, d\phi}{\int_{0}^{2\pi} \int_{0}^{\pi/2} I_{\lambda,b}(\lambda, T) \cos\theta \sin\theta \, d\theta \, d\phi}$$

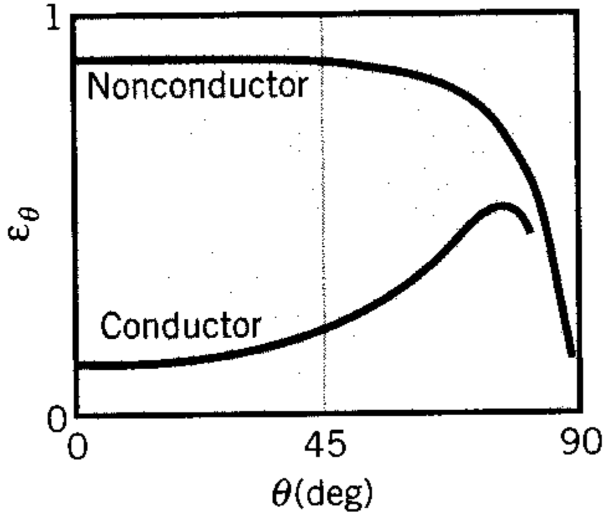
Surface Emission

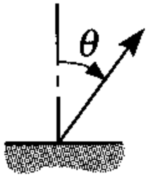
Total, hemispherical emissivity

$$\varepsilon(T) \equiv \frac{E(T)}{E_b(T)}$$

$$\varepsilon(T) = \frac{\int_0^\infty \varepsilon_\lambda(\lambda, T) E_{\lambda,b}(\lambda, T)\, d\lambda}{E_b(T)}$$

Total, directional emissivity
Normal emissivity predictable





Spectral, normal emissivity

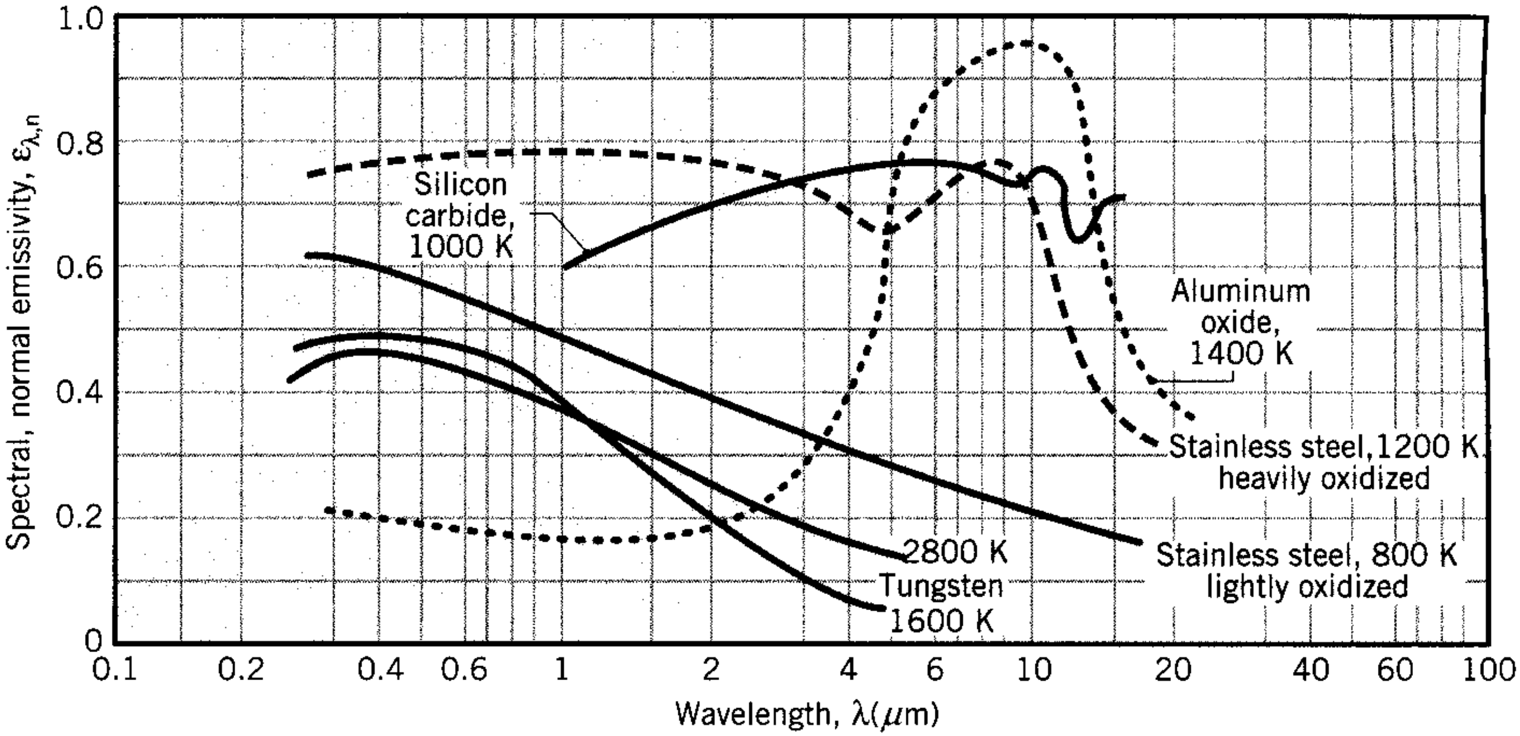


FIGURE 12.18 Spectral dependence of the spectral, normal emissivity $\varepsilon_{\lambda,n}$ of selected materials.

Total, normal emissivity

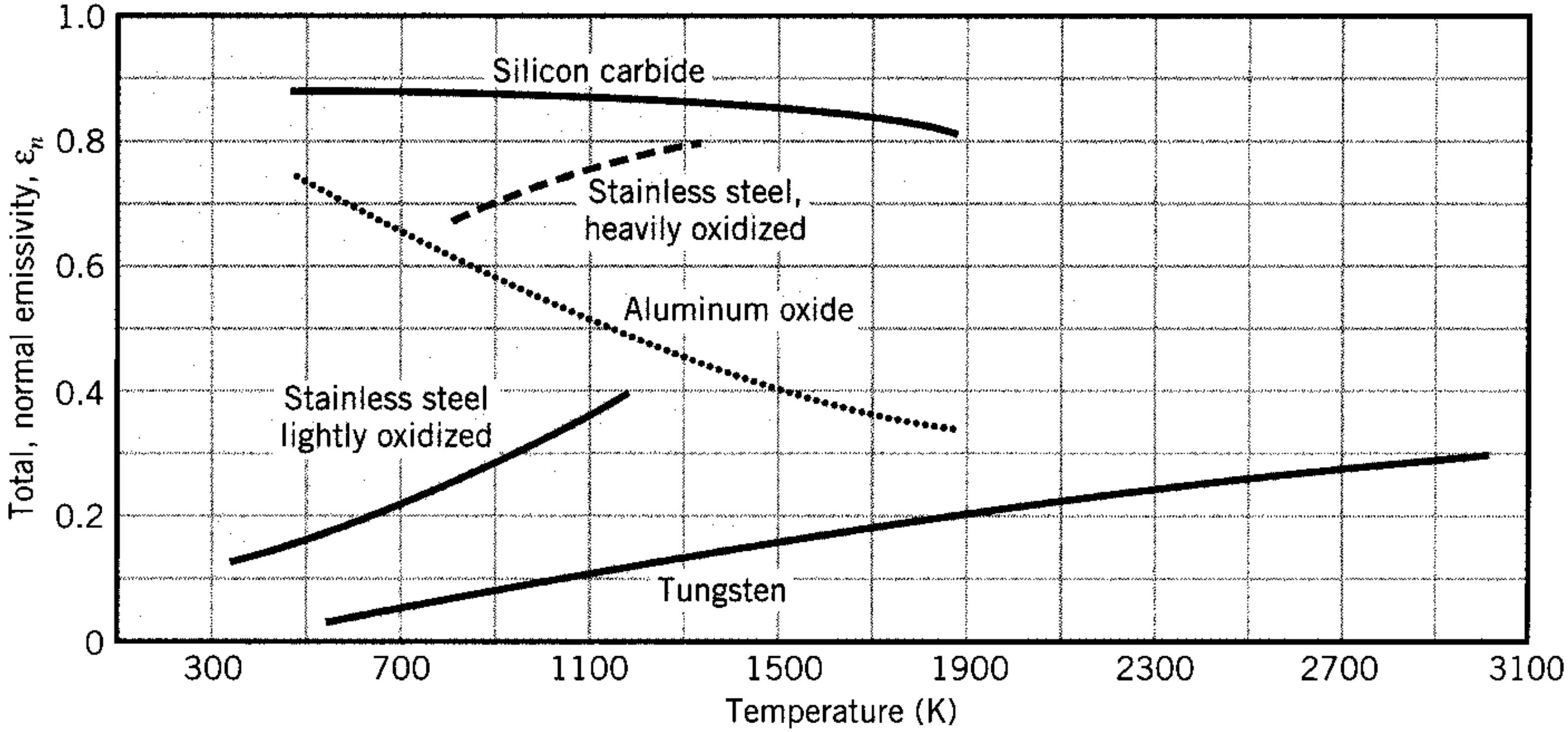


FIGURE 12.19 Temperature dependence of the total, normal emissivity ε_n of selected materials.

Total, normal emissivity

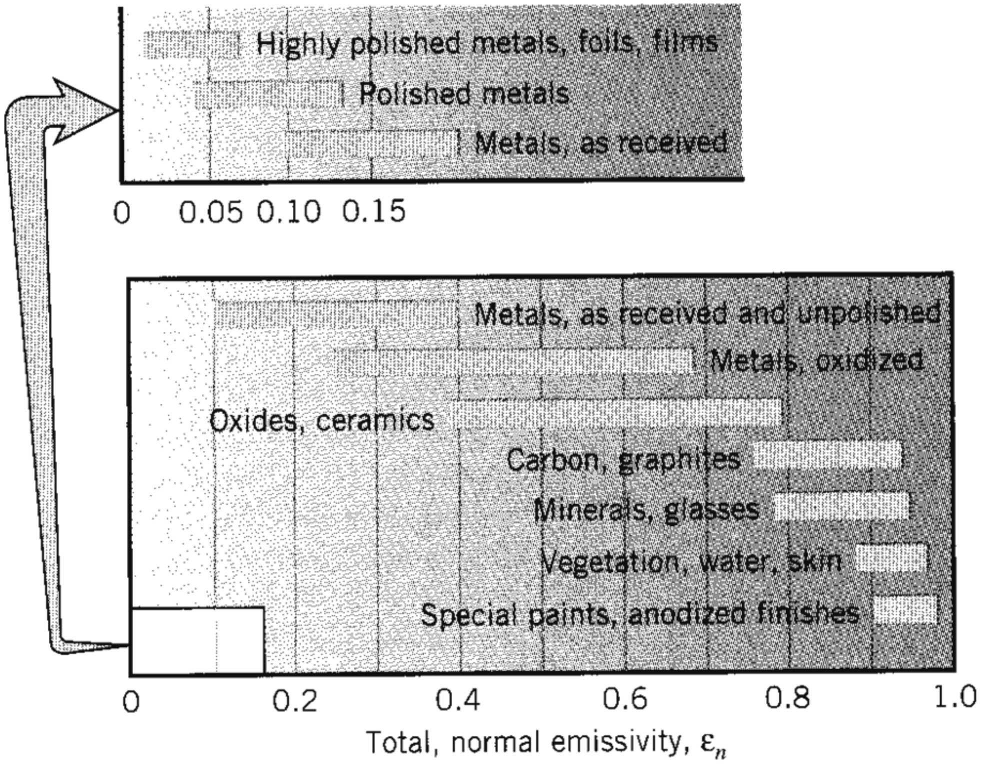


FIGURE 12.20 Representative values of the total, normal emissivity ε_n.

Absorption, Reflection, and Transmission

$$G_\lambda = G_{\lambda,\mathrm{ref}} + G_{\lambda,\mathrm{abs}} + G_{\lambda,\mathrm{tr}}$$

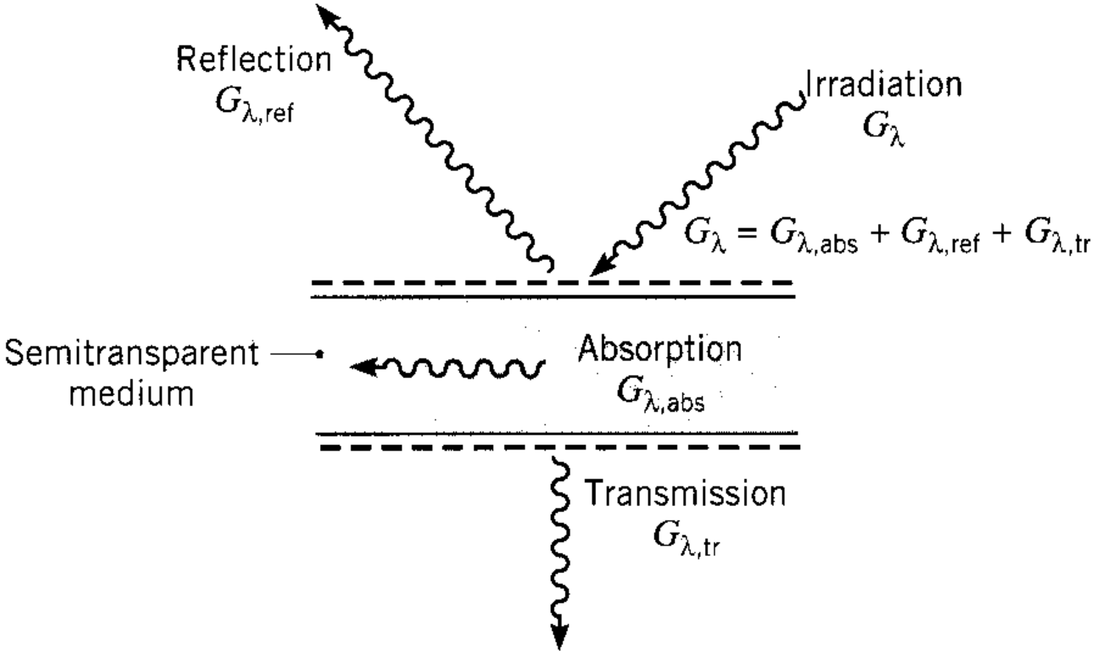


FIGURE 12.21
Absorption, reflection, and transmission processes associated with a semitransparent medium.

Absorptivity

Spectral, directional absorptivity

$$\alpha_{\lambda,\theta}(\lambda,\theta,\phi) \equiv \frac{I_{\lambda,i,\mathrm{abs}}(\lambda,\theta,\phi)}{I_{\lambda,i}(\lambda,\theta,\phi)}$$

Spectral, hemispherical absorptivity

$$\alpha_{\lambda}(\lambda) \equiv \frac{G_{\lambda,\mathrm{abs}}(\lambda)}{G_{\lambda}(\lambda)}$$

Total, hemispherical absorptivity

$$\alpha \equiv \frac{G_{\mathrm{abs}}}{G}$$

Reflectivity

Spectral, directional reflectivity

$$\rho_{\lambda,\theta}(\lambda,\theta,\phi) \equiv \frac{I_{\lambda,i,\mathrm{ref}}(\lambda,\theta,\phi)}{I_{\lambda,i}(\lambda,\theta,\phi)}$$

Spectral, hemispherical reflectivity

$$\rho_{\lambda}(\lambda) \equiv \frac{G_{\lambda,\mathrm{ref}}(\lambda)}{G_{\lambda}(\lambda)}$$

Total, hemispherical reflectivity

$$\rho \equiv \frac{G_{\mathrm{ref}}}{G}$$

Reflectivity

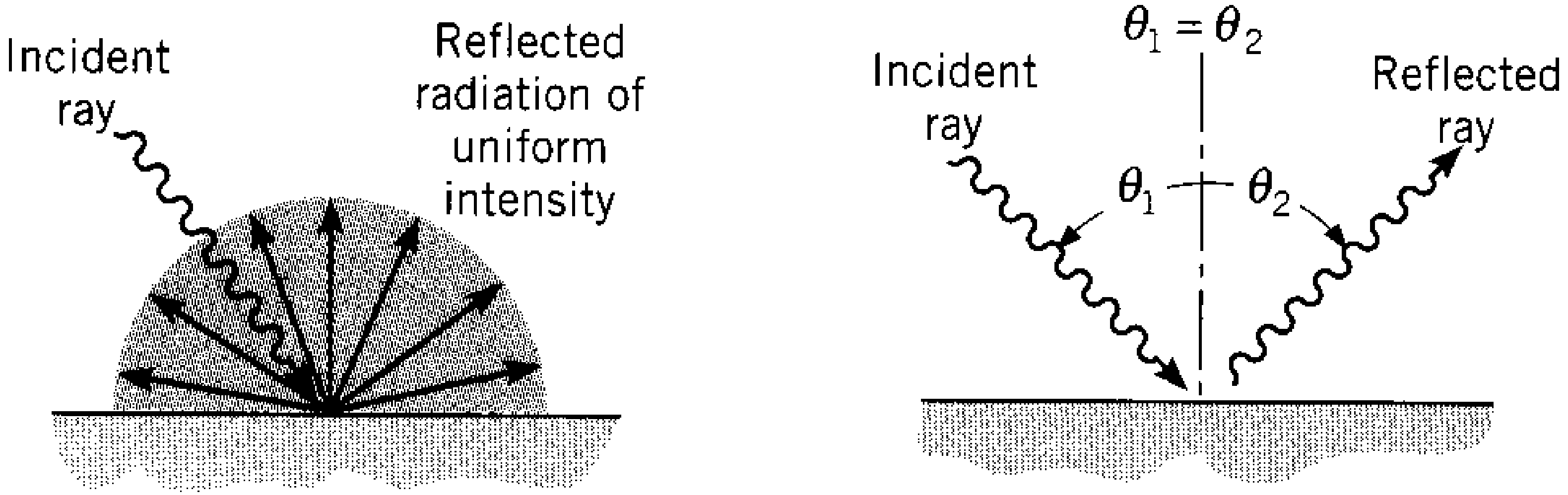


FIGURE 12.22 Diffuse and specular reflection.

Transmissivity

Spectral, hemispherical transmissivity

$$\tau_\lambda = \frac{G_{\lambda,\mathrm{tr}}(\lambda)}{G_\lambda(\lambda)}$$

Total, hemispherical reflectivity

$$\tau = \frac{G_{\mathrm{tr}}}{G}$$

Special Considerations

Semitransparent medium

$$\rho + \alpha + \tau = 1$$

Opaque

$$\rho + \alpha = 1$$

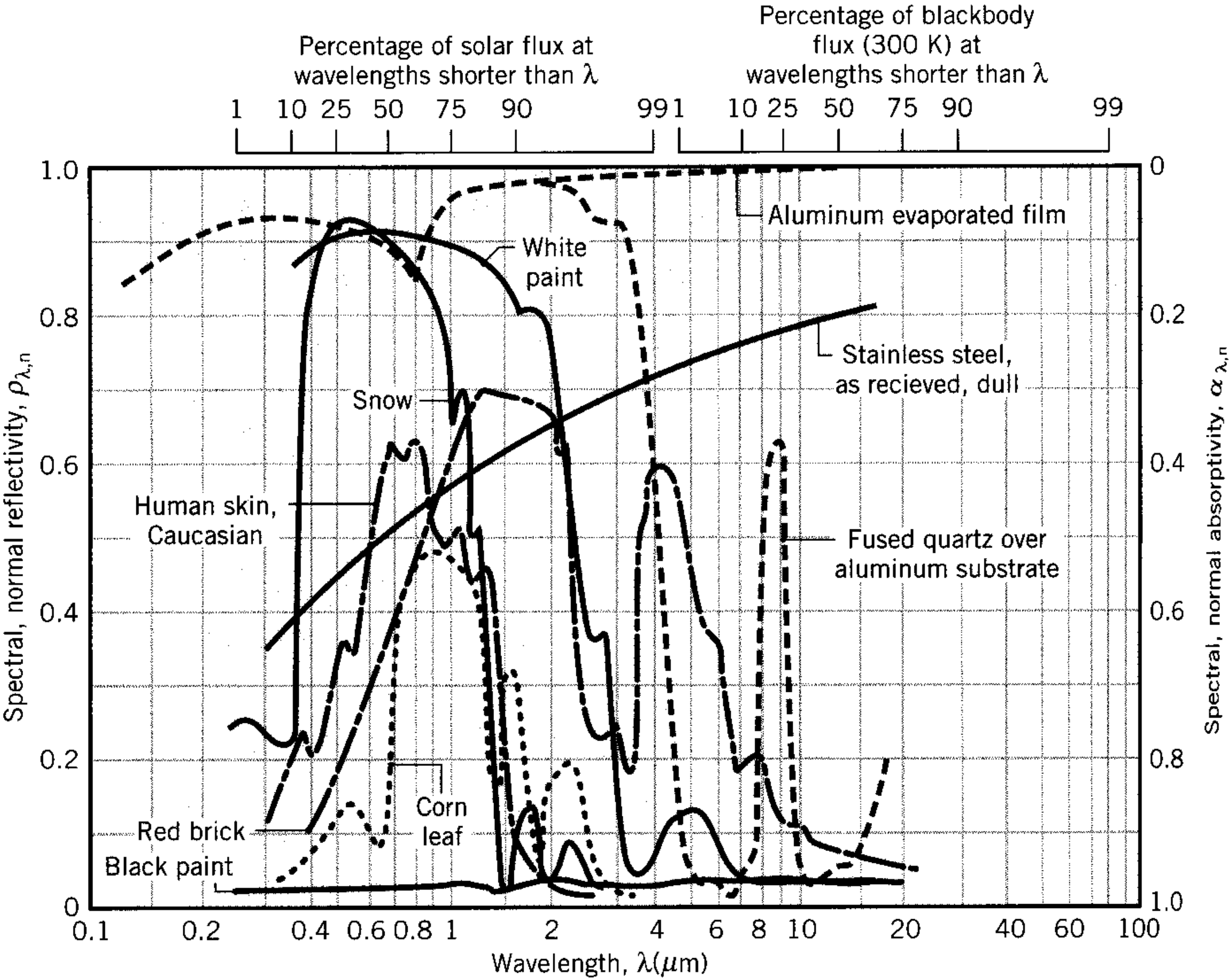


FIGURE 12.23 Spectral dependence of the spectral, normal absorptivity $\alpha_{\lambda,n}$ and reflectivity $\rho_{\lambda,n}$ of selected opaque materials.

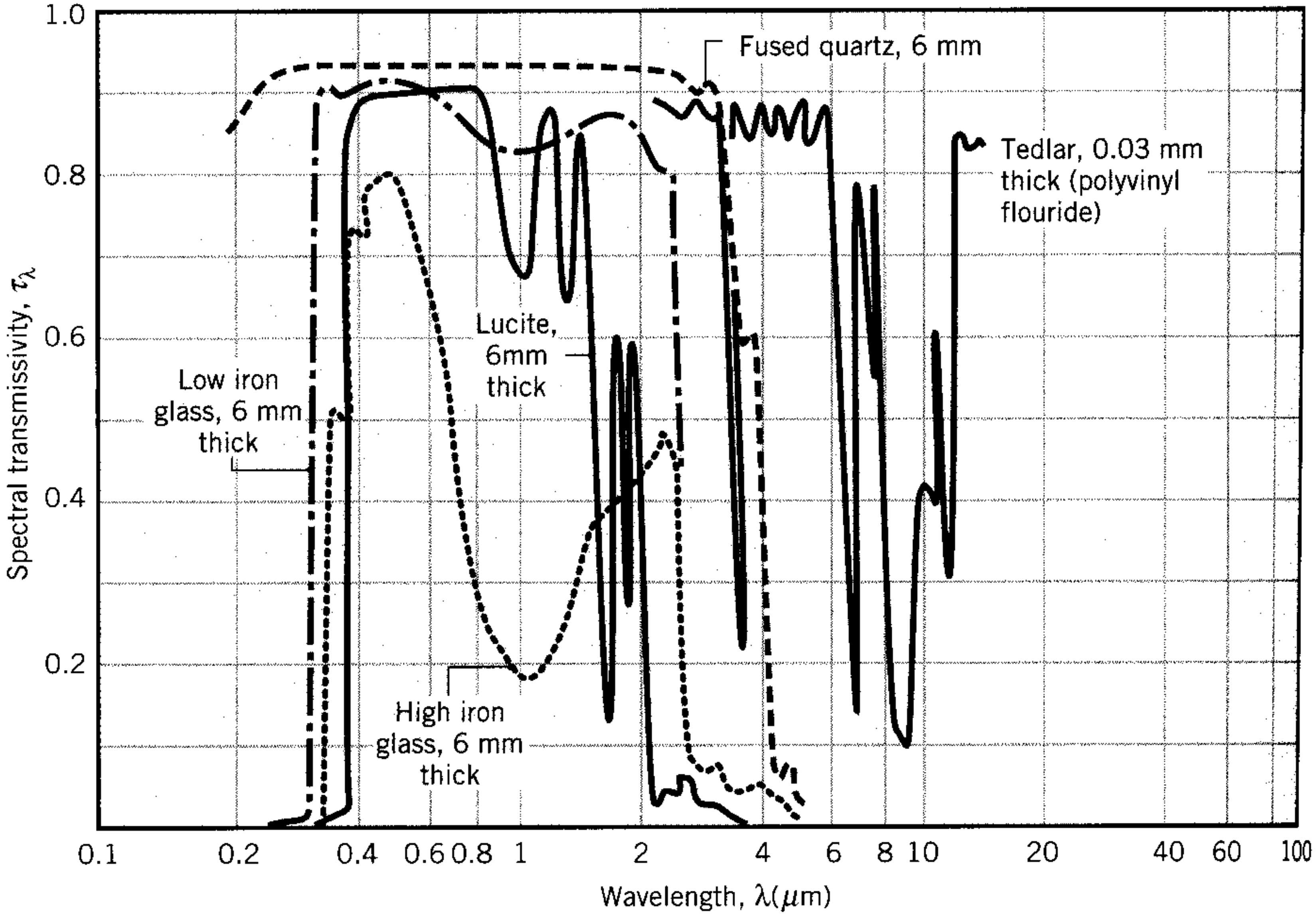


Figure 12.24 Spectral dependence of the spectral transmissivities τ_λ of selected semitransparent materials.

Kirchhoff’s Law

$$\varepsilon = \alpha$$

$$\frac{E_1(T_s)}{\alpha_1} = E_b(T_s)$$

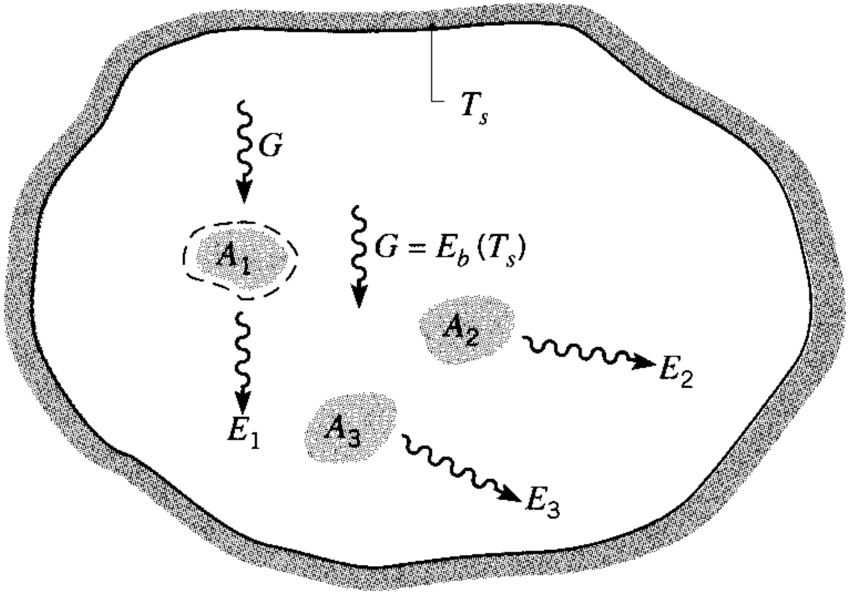


FIGURE 12.25
Radiative exchange in an isothermal enclosure.

No real surface can have an emissive power exceeding that of a black surface at the same temperature.