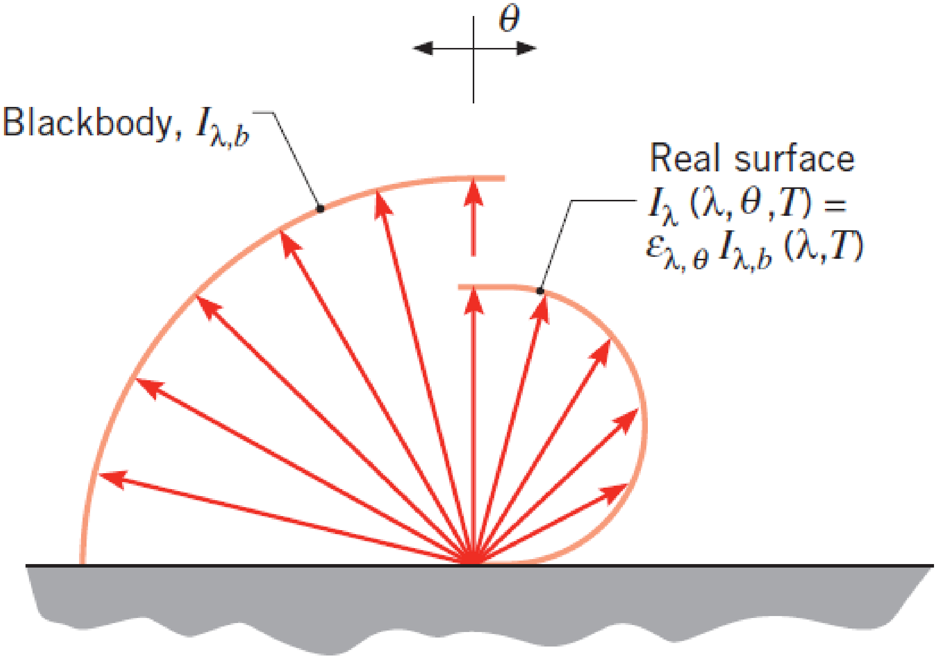
Surface Radiation



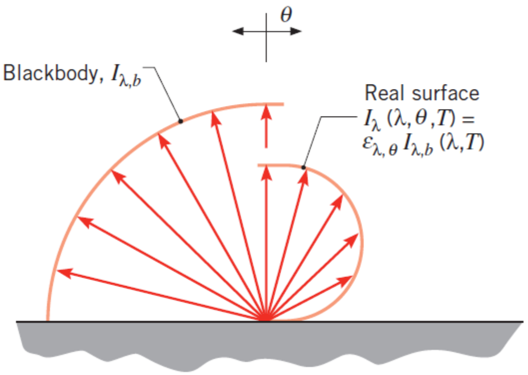
Surface Emissivity

- Radiation emitted by a surface may be determined by introducing a property (the emissivity) that contrasts its emission with the ideal behavior of a blackbody at the same temperature.

- The definition of the emissivity depends upon one's interest in resolving directional and/or spectral features of the emitted radiation, in contrast to averages over all directions (hemispherical) and/or wavelengths (total).

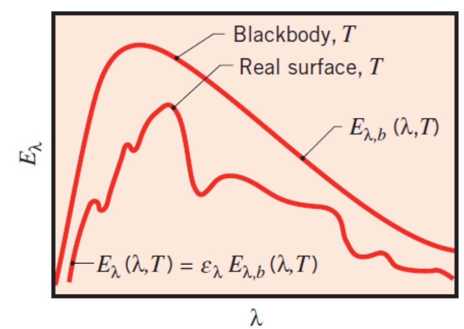
- The spectral, directional emissivity:

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



- The spectral, hemispherical emissivity (a directional average):

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



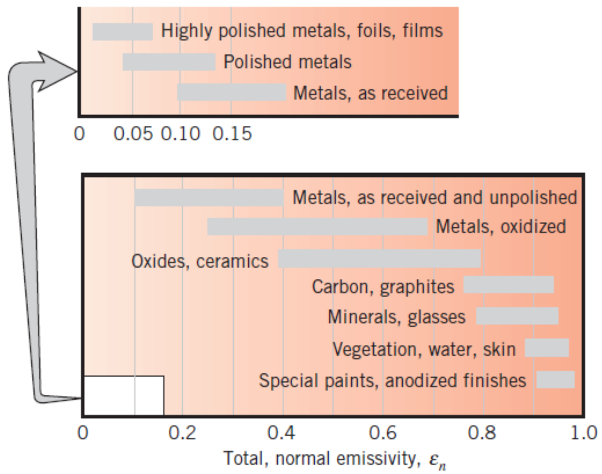
- The total, hemispherical emissivity (a directional and spectral average):

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

- To a reasonable approximation, the hemispherical emissivity is equal to the normal emissivity.

$$\varepsilon \approx \varepsilon_n$$

- Representative values of the total, normal emissivity:

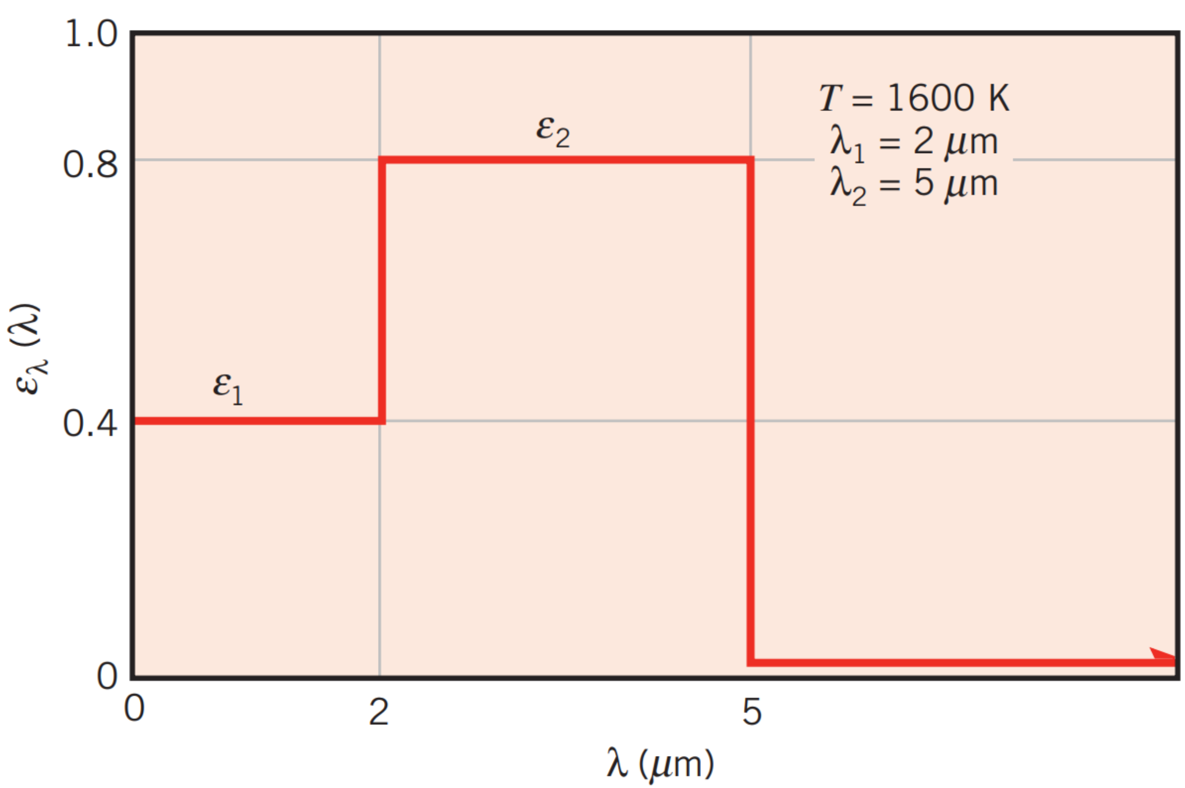


Note:

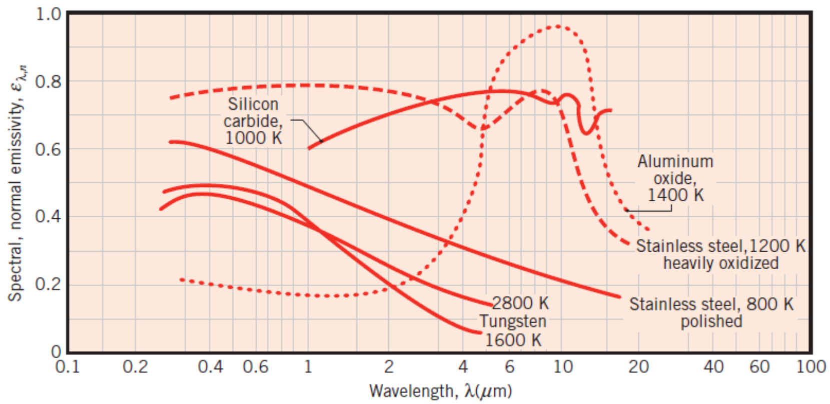
- ➢ Low emissivity of polished metals and increasing emissivity for unpolished and oxidized surfaces.
- ➢ Comparatively large emissivities of nonconductors.

Example 1

A diffuse surface at 1600 K has the spectral, hemispherical emissivity shown as follows. Determine the total, hemispherical emissivity and the total emissive power.

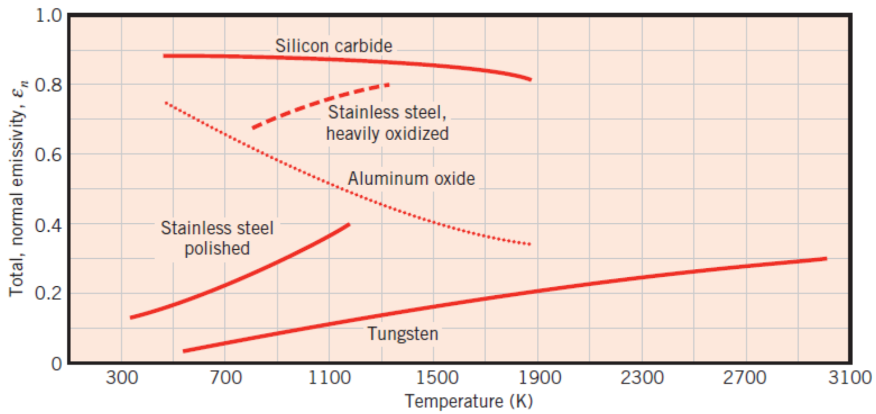


- Representative spectral variations:



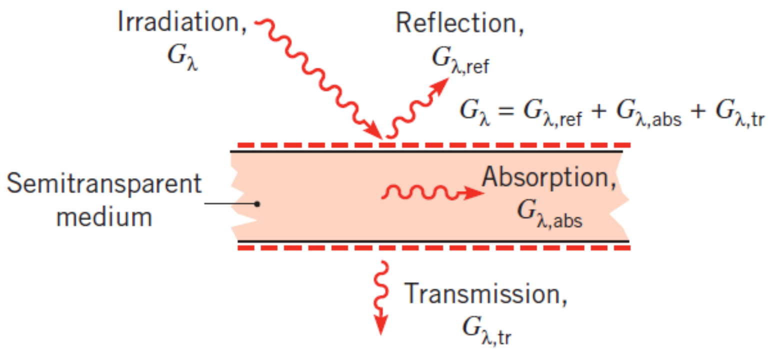
Note decreasing $\varepsilon_{\lambda,n}$ with increasing λ for metals and different behavior for nonmetals.

- Representative temperature variations:



Response to Surface Irradiation: Absorption, Reflection and Transmission

- There may be three responses of a semitransparent medium to irradiation:
  - Reflection from the medium $\left(G_{\lambda,\mathrm{ref}}\right)$.
  - Absorption within the medium $\left(G_{\lambda,\mathrm{abs}}\right)$.
  - Transmission through the medium $\left(G_{\lambda,\mathrm{tr}}\right)$.



Radiation balance →

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

- In contrast to the foregoing volumetric effects, the response of an opaque material to irradiation is governed by surface phenomena and $G_{\lambda,\mathrm{tr}} = 0$.

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

- The wavelength of the incident radiation, as well as the nature of the material, determine whether the material is semitransparent or opaque.

Absorptivity of an Opaque Material

- The spectral, directional absorptivity: Assuming negligible temperature dependence,

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

- The spectral, hemispherical absorptivity:

$$\alpha_{\lambda}(\lambda) \equiv \frac{G_{\lambda,\text{abs}}(\lambda)}{G_{\lambda}(\lambda)} = \frac{\int_0^{2\pi}\int_0^{\pi/2} \alpha_{\lambda,\theta}(\lambda,\theta,\phi) I_{\lambda,i}(\lambda,\theta,\phi)\cos\theta\sin\theta d\theta d\phi}{\int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,i}(\lambda,\theta,\phi)\cos\theta\sin\theta d\theta d\phi}$$

- The total, hemispherical absorptivity:

$$\alpha \equiv \frac{G_{\text{abs}}}{G} = \frac{\int_o^{\infty} \alpha_{\lambda}(\lambda) G_{\lambda}(\lambda) d\lambda}{\int_0^{\infty} G_{\lambda}(\lambda) d\lambda}$$

Reflectivity of an Opaque Material

- The spectral, directional reflectivity: Assuming negligible temperature dependence:

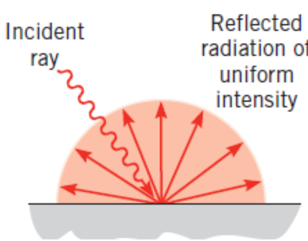
$$\rho_{\lambda,\theta}(\lambda,\theta,\phi) \equiv \frac{I_{\lambda,i,\mathrm{ref}}(\lambda,\theta,\phi)}{I_{\lambda,i}(\lambda,\theta,\phi)}$$

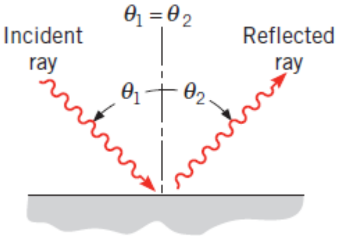
- The spectral, hemispherical reflectivity:

$$\rho_\lambda \equiv \frac{G_{\lambda,\mathrm{ref}}(\lambda)}{G_\lambda(\lambda)} = \frac{\int_0^{2\pi}\int_0^{\pi/2} \rho_{\lambda,\theta}(\lambda,\theta,\phi) I_{\lambda,i}(\lambda,\theta,\phi)\cos\theta \sin\theta d\theta d\phi}{I_{\lambda,i}(\lambda,\theta,\phi)}$$

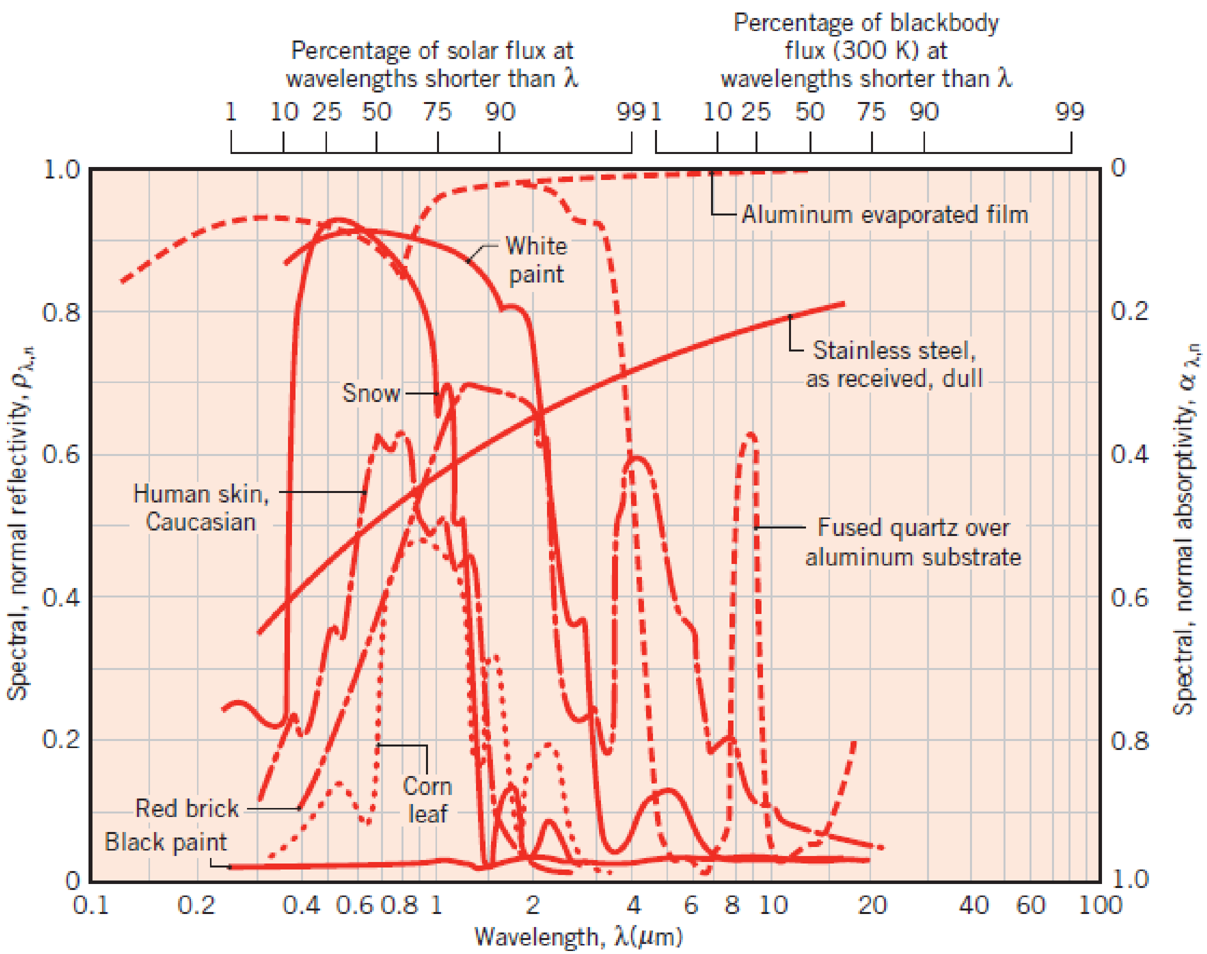
- The total, hemispherical reflectivity:

$$\rho \equiv \frac{G_{\mathrm{ref}}}{G} = \frac{\int_0^\infty \rho_\lambda(\lambda) G_\lambda(\lambda) d\lambda}{\int_0^\infty G_\lambda(\lambda) d\lambda}$$





- Limiting conditions of diffuse and specular reflection. Polished and rough surfaces.

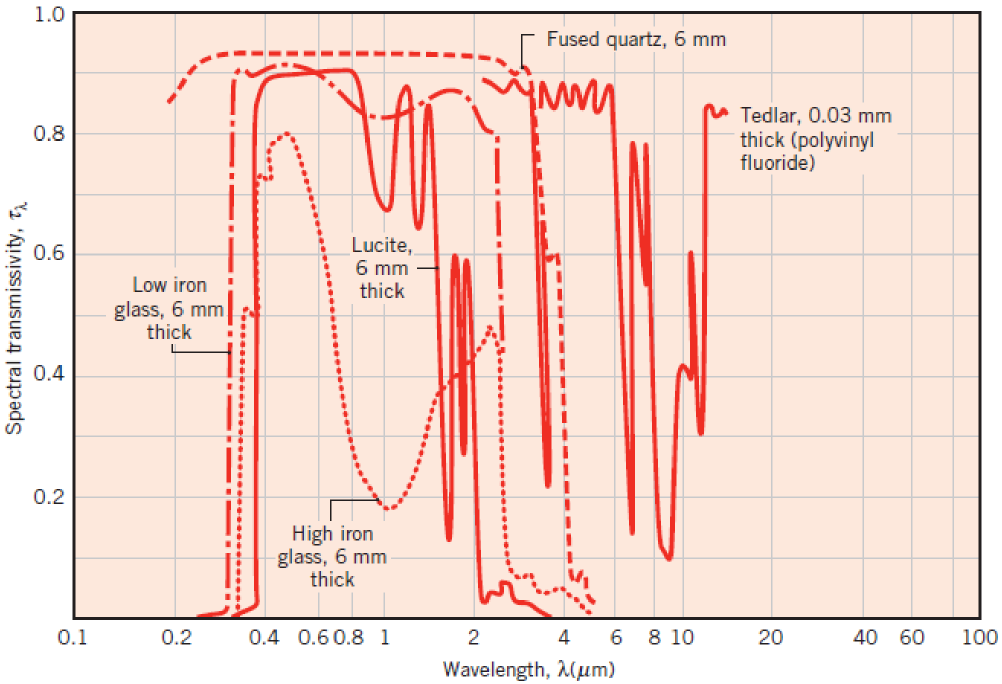


- Note strong dependence of ρ_λ $\left(\text{and } \alpha_\lambda = 1 - \rho_\lambda\right)$ on λ.
- Is snow a highly reflective substance? White paint?

Transmissivity

- The spectral, hemispherical transmissivity: Assuming negligible temperature dependence,

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



Note shift from semitransparent to opaque conditions at large and small wavelengths.

- The total, hemispherical transmissivity:

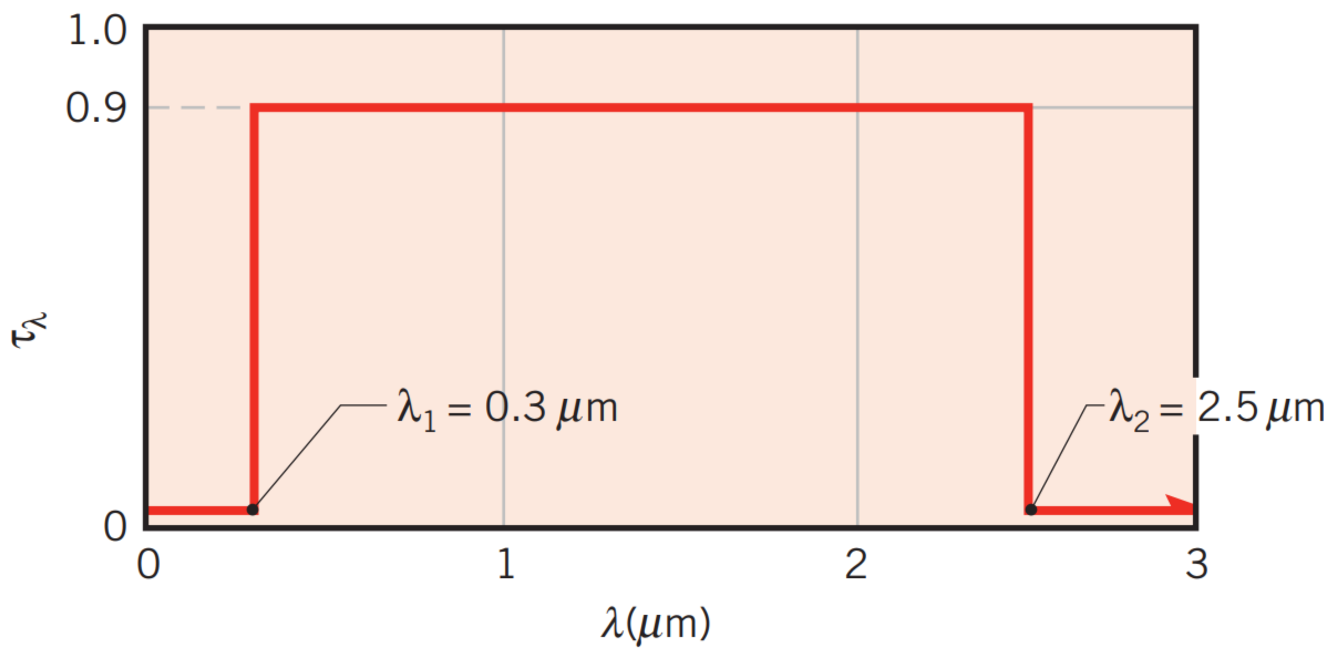
$$\tau \equiv \frac{G_{\mathrm{tr}}}{G} = \frac{\int_0^\infty G_{\lambda,\mathrm{tr}}(\lambda)\,d\lambda}{\int_0^\infty G_\lambda(\lambda)\,d\lambda}$$

- For a semitransparent medium,

$$\rho_\lambda + \alpha_\lambda + \tau_\lambda = 1$$
$$\rho + \alpha + \tau + 1$$

Example 2

The cover glass on a flat-plate solar collector has a low iron content, and its spectral transmissivity may be approximated by the following distribution. What is the total transmissivity of the cover glass to solar radiation?



Kirchhoff's Law

- Kirchhoff's law equates the total, hemispherical emissivity of a surface to its total, hemispherical absorptivity:

$$\varepsilon = \alpha$$

However, conditions associated with its derivation are highly restrictive:

Irradiation of the surface corresponds to emission from a blackbody at the same temperature as the surface.

- But, Kirchhoff's law may be applied to the spectral, directional properties without restriction:

$$\varepsilon_{\lambda,\theta} = \alpha_{\lambda,\theta}$$

Diffuse/Gray Surfaces

- With

$$\varepsilon_\lambda = \frac{\int_0^{2\pi}\int_0^{\pi/2}\varepsilon_{\lambda,\theta}\cos\theta\sin\theta d\theta d\phi}{\int_0^{2\pi}\int_0^{\pi/2}\cos\theta\sin\theta d\theta d\phi}$$

and

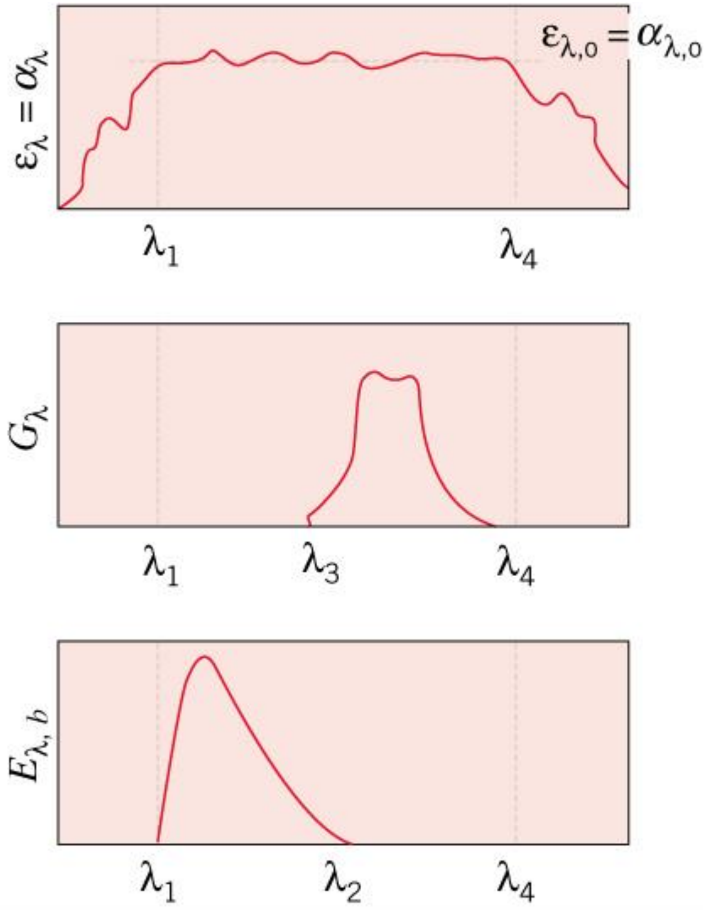
$$\alpha_\lambda = \frac{\int_0^{2\pi}\int_0^{\pi/2}\alpha_{\lambda,\theta}I_{\lambda,i}\cos\theta\sin\theta d\theta d\phi}{\int_0^{2\pi}\int_0^{\pi/2}I_{\lambda,i}\cos\theta\sin\theta d\theta d\phi}$$

- With

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

and

$$\alpha = \frac{\int_0^{\infty}\alpha_\lambda G_\lambda(\lambda)d\lambda}{G}$$



Example 3

A diffuse, fire brick wall of temperature $T_s = 500K$ has the spectral emissivity shown and is exposed to a bed of coals at $2000\ K$. Determine the total, hemispherical emissivity and emissive power of the fire brick wall. What is the total absorptivity of the wall to irradiation resulting from emission by the coals?