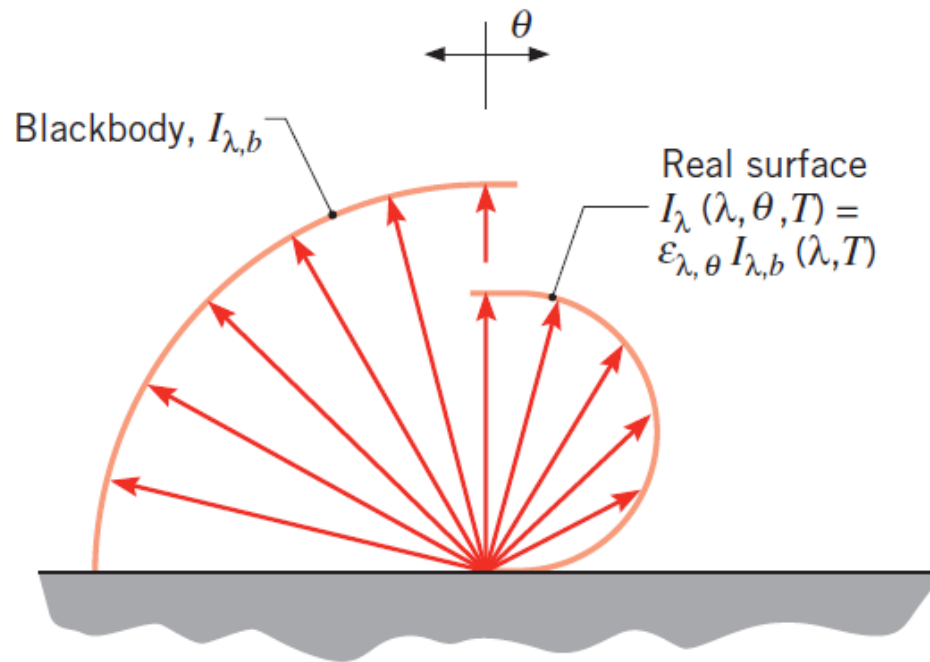


Surface Radiation

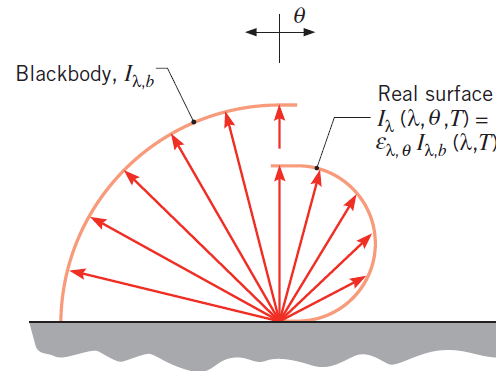


Surface Emissivity

- 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).

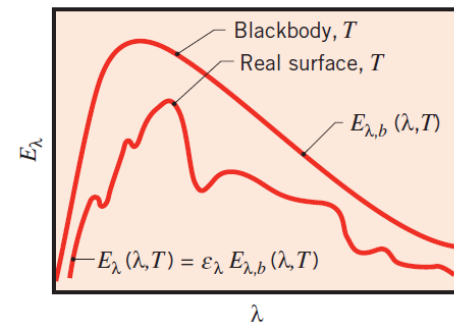
- The **spectral, directional emissivity**:

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



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

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



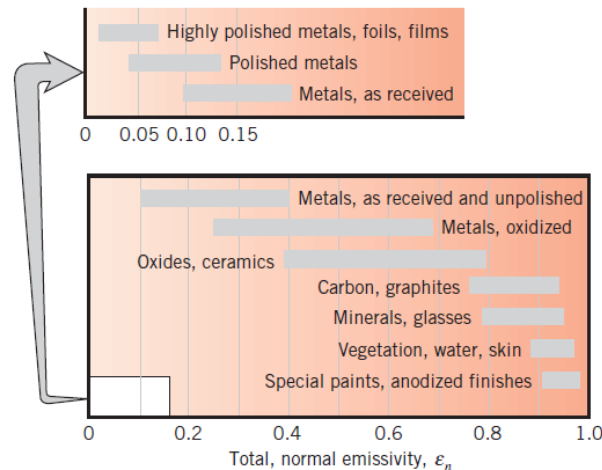
- The **total, hemispherical emissivity** (a directional and spectral average):

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

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

$$\varepsilon \approx \varepsilon_n$$

- Representative values of the total, normal emissivity:

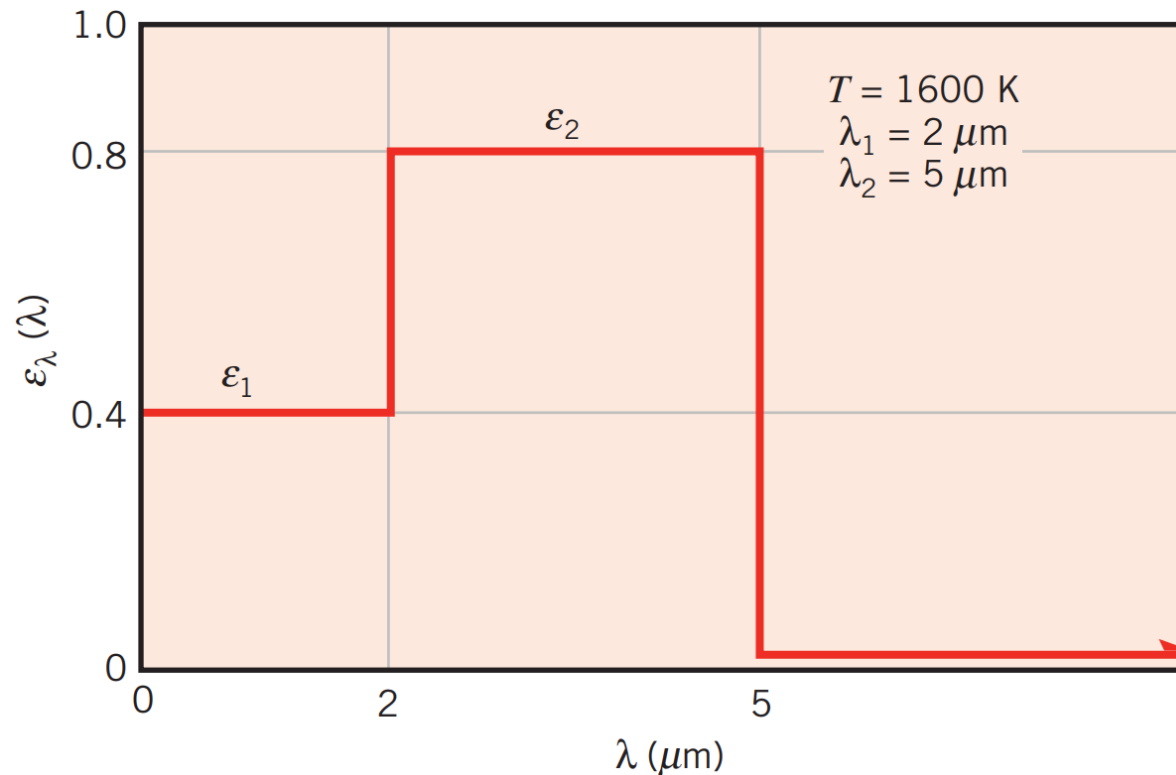


Note:

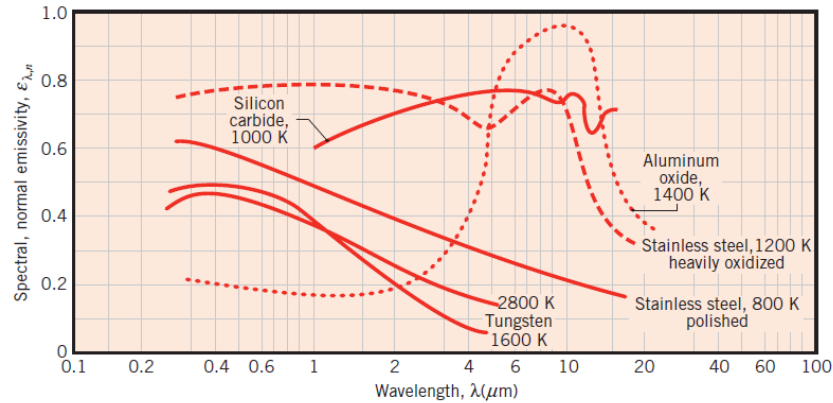
- Low emissivity of polished metals and increasing emissivity for unpolished and oxidized surfaces.
- Comparatively large emissivities of nonconductors.

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.

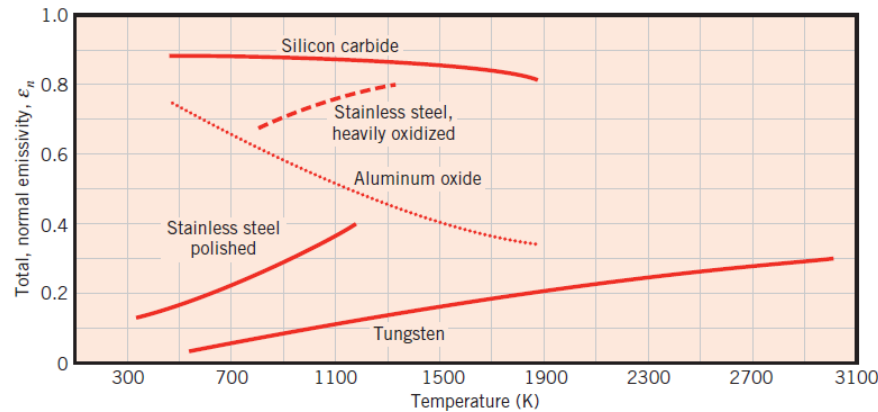


- Representative spectral variations:



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

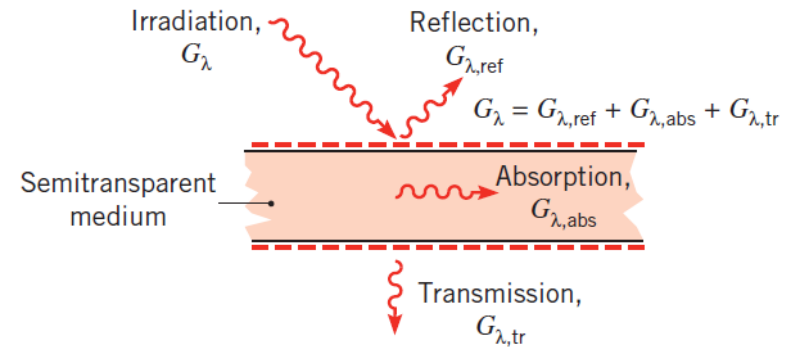
- Representative temperature variations:



Response to Surface Irradiation: Absorption, Reflection and Transmission

- There may be three responses of a **semitransparent medium** to irradiation:

- **Reflection** from the medium ($G_{\lambda,\text{ref}}$).
- **Absorption** within the medium ($G_{\lambda,\text{abs}}$).
- **Transmission** through the medium ($G_{\lambda,\text{tr}}$).



Radiation balance \longrightarrow

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

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

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

- 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**:

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

Reflectivity of an Opaque Material

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

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

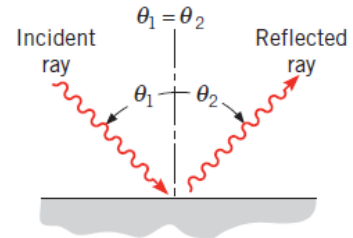
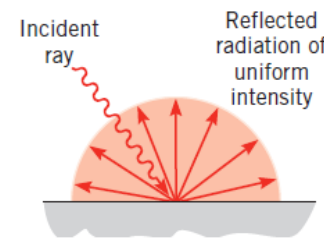
- **The spectral, hemispherical reflectivity:**

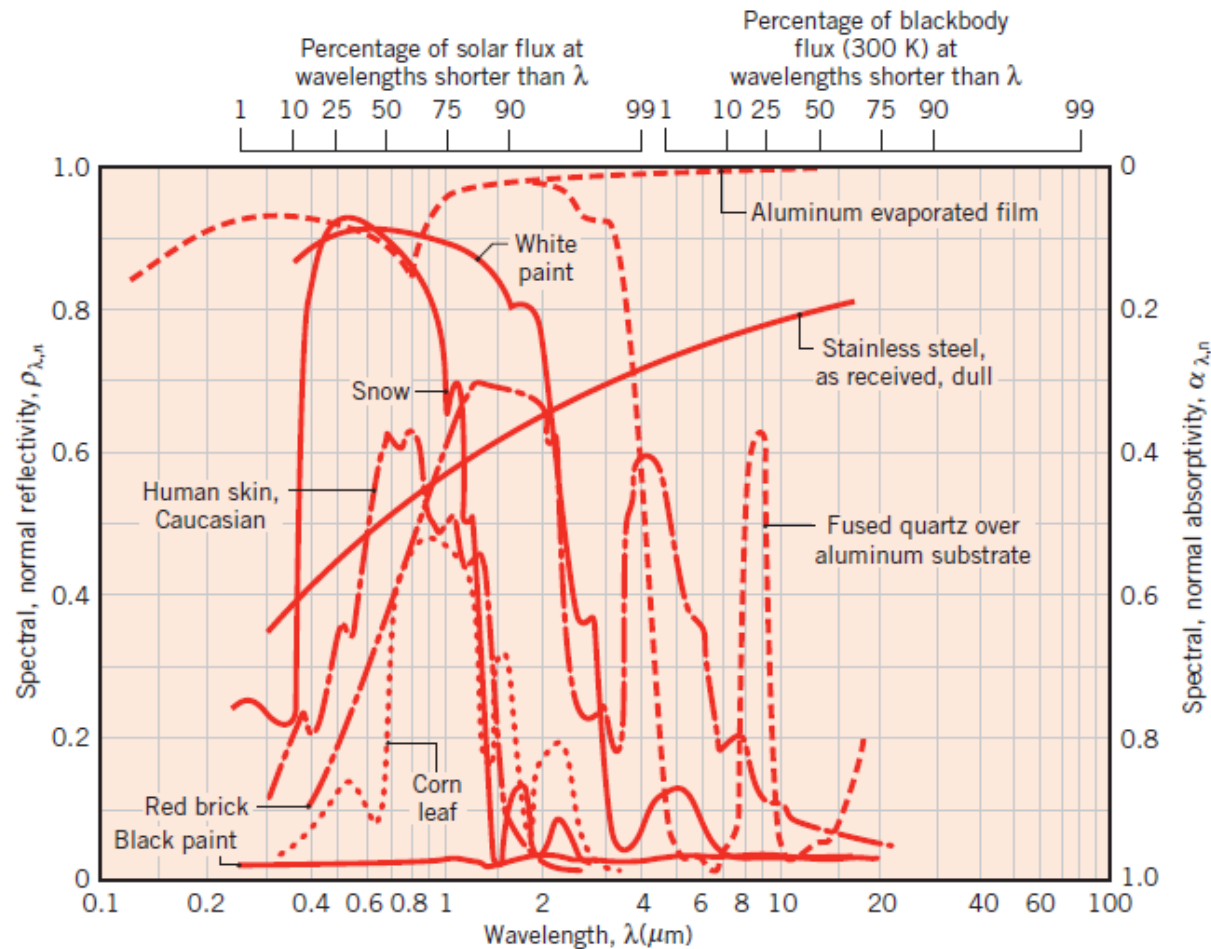
$$\rho_{\lambda} \equiv \frac{G_{\lambda,\text{ref}}(\lambda)}{G_{\lambda}(\lambda)} = \frac{\int_0^{2\pi} \int_0^{\pi/2} \rho_{\lambda,\theta}(\lambda,\theta,\phi) I_{\lambda,i}(\lambda,\theta,\phi) \cos \theta \sin \theta d\theta d\phi}{I_{\lambda,i}(\lambda,\theta,\phi)}$$

- **The total, hemispherical reflectivity:**

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

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



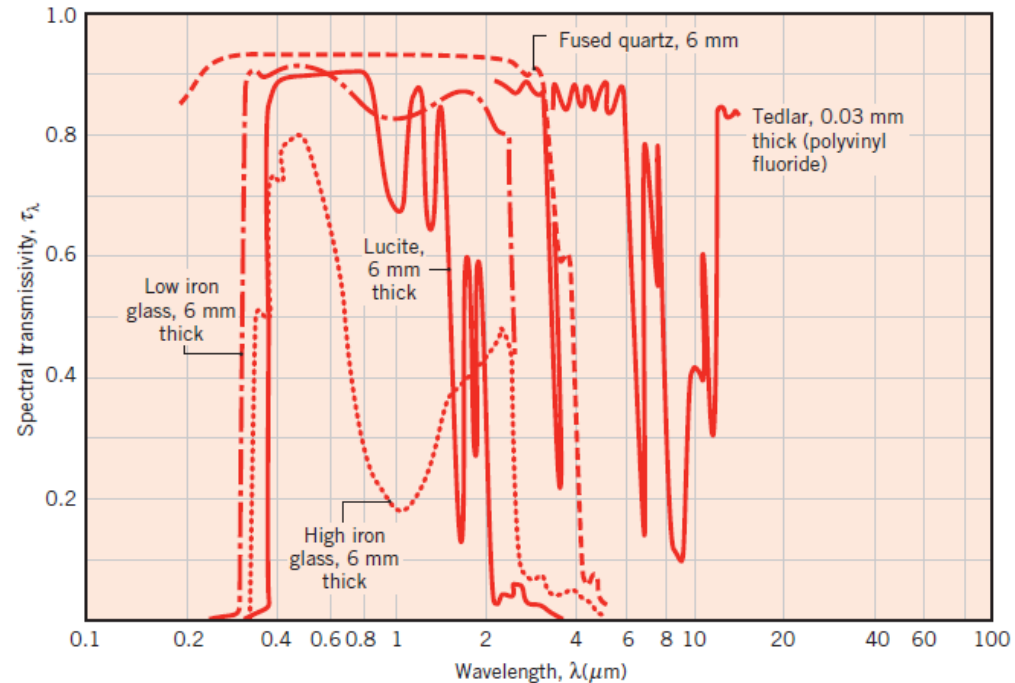


- Note strong dependence of ρ_{λ} (and $\alpha_{\lambda} = 1 - \rho_{\lambda}$) on λ .
- Is snow a highly reflective substance? White paint?

Transmissivity

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

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



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

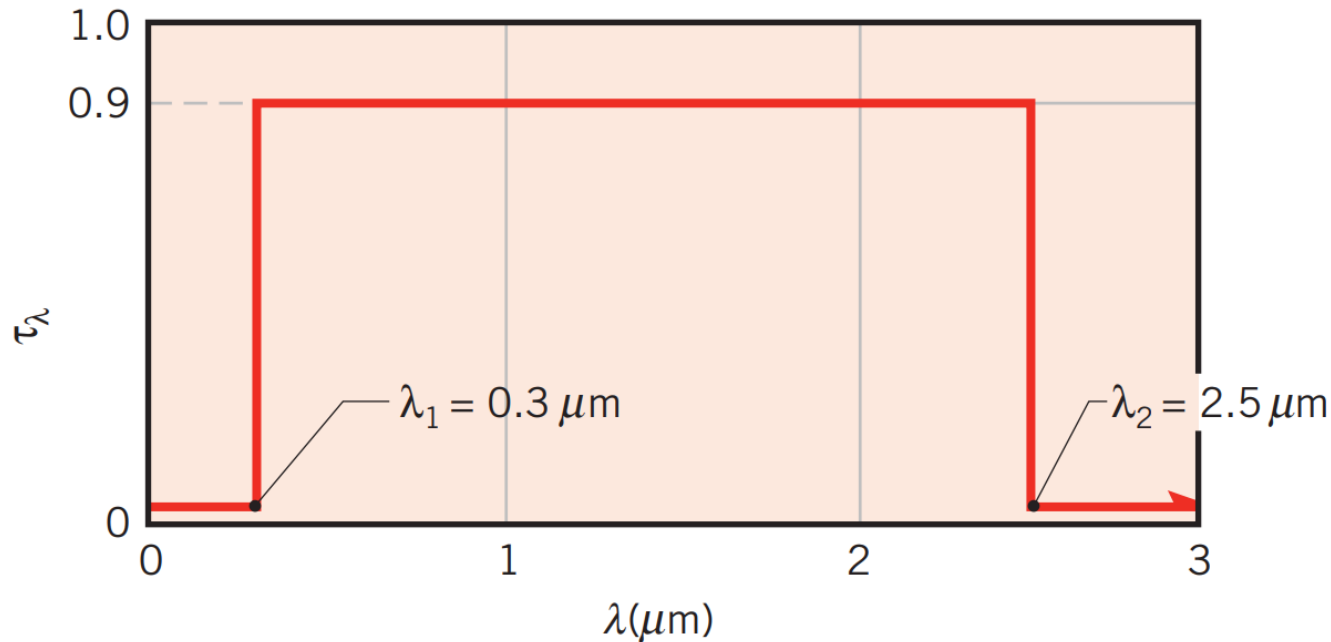
- The **total, hemispherical transmissivity**:
- For a semitransparent medium,

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

$$\begin{aligned} \rho_{\lambda} + \alpha_{\lambda} + \tau_{\lambda} &= 1 \\ \rho + \alpha + \tau &= 1 \end{aligned}$$

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

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

and

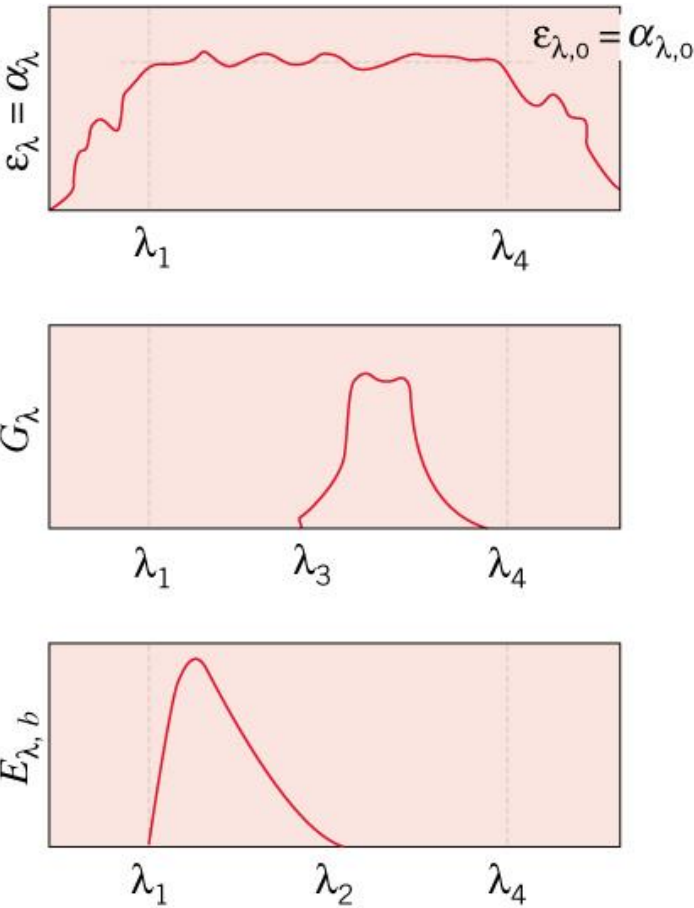
$$\alpha_{\lambda} = \frac{\int_0^{2\pi} \int_0^{\pi/2} \alpha_{\lambda,\theta} I_{\lambda,i} \cos \theta \sin \theta d\theta d\phi}{\int_0^{2\pi} \int_0^{\pi/2} I_{\lambda,i} \cos \theta \sin \theta d\theta d\phi}$$

- With

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

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?

