RADIATIVE ENERGY TRANSFER

1 The Electromagnetic Spectrum

- The relation of between wavelength and frequency of electromagnetic radiation

$$\left(\begin{matrix}\lambda \\ wavelength\end{matrix}\right)\left(\begin{matrix}\upsilon \\ Frequency\end{matrix}\right)=\left(\begin{matrix}c \\ Speed\,of\,Light\end{matrix}\right) \quad (1)$$

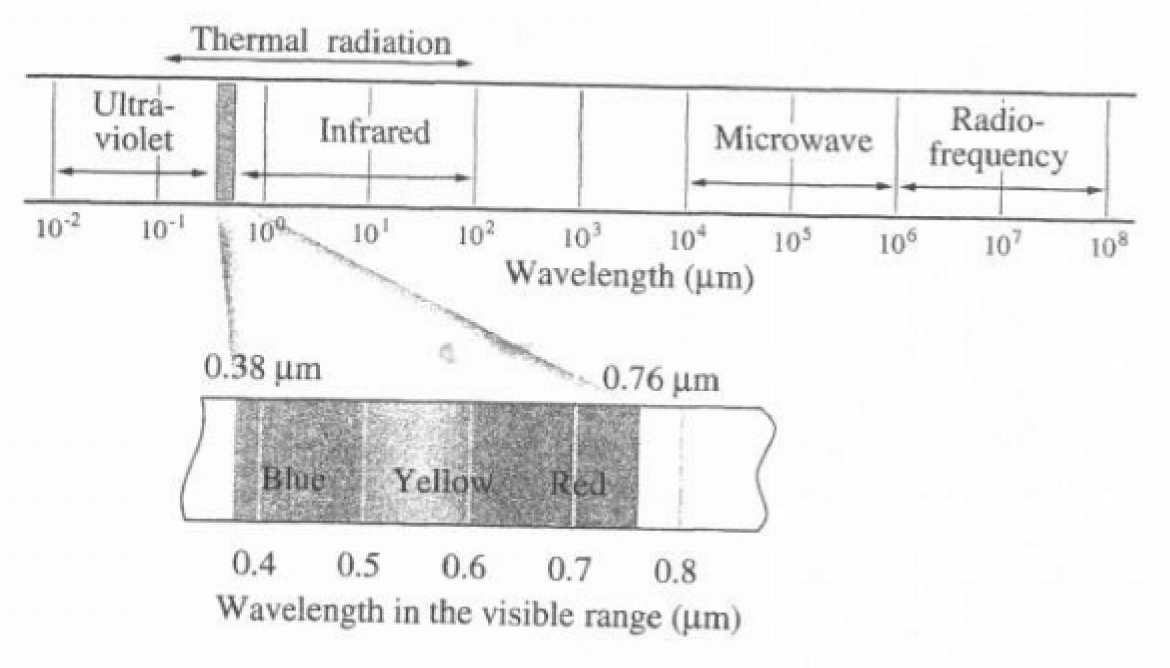


Figure 1. The electromagnetic spectrum.

The Electromagnetic Spectrum

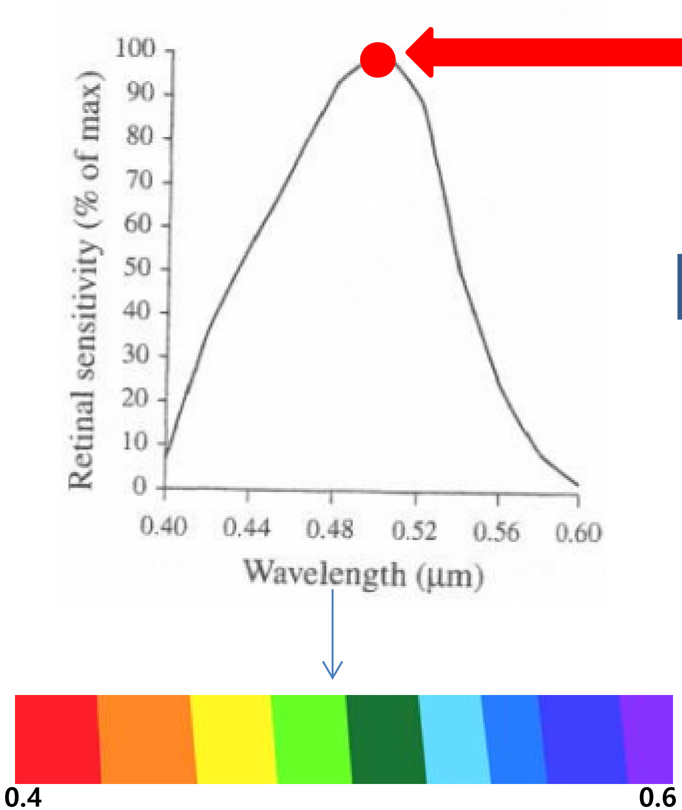
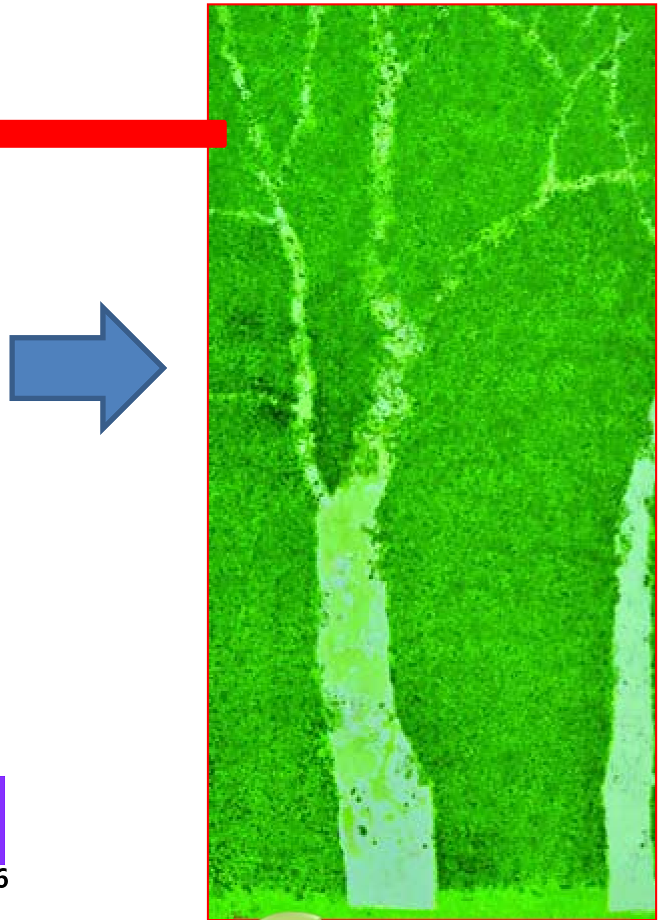


Figure 2. Sensitivity of the human eye to various wavelengths in the visible region.



Green

Reflection, Absorption and Transmission of Waves at a surface

relation of reflectivity, Absorptivity and Transmissivity

$$\begin{pmatrix} \rho \\ \text{Reflectivity} \end{pmatrix} + \begin{pmatrix} \alpha \\ Absorptivity \end{pmatrix} + \begin{pmatrix} \tau \\ Transmissivity \end{pmatrix} = 1 \quad (2)$$

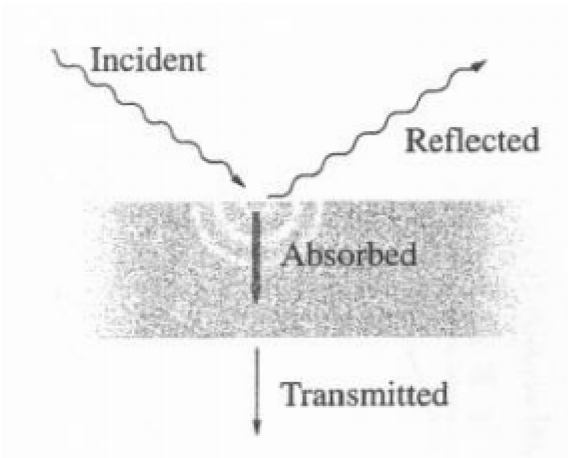
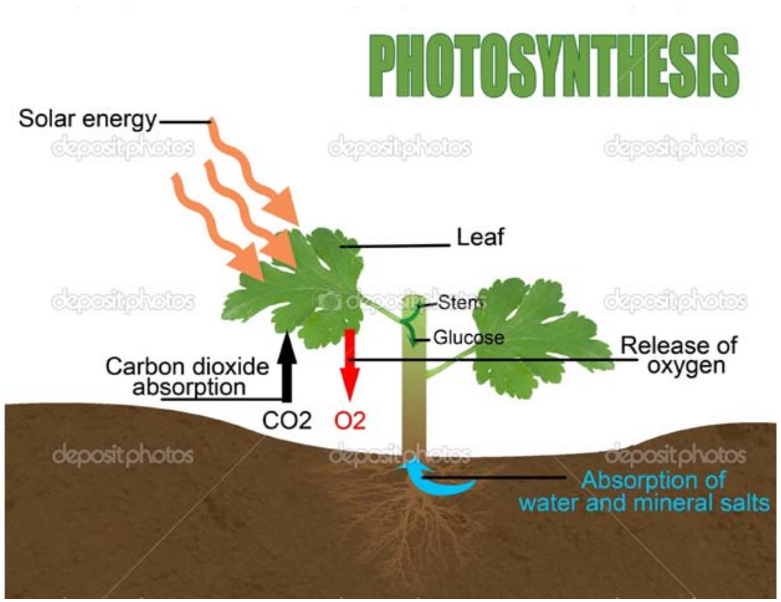


Figure 3. Reflection, absorption, and transmission of electromagnetic wave at a surface.

2 Reflection, Absorption and Transmission of Waves at a surface

Transmissivity of a Leaf Photosynthesis



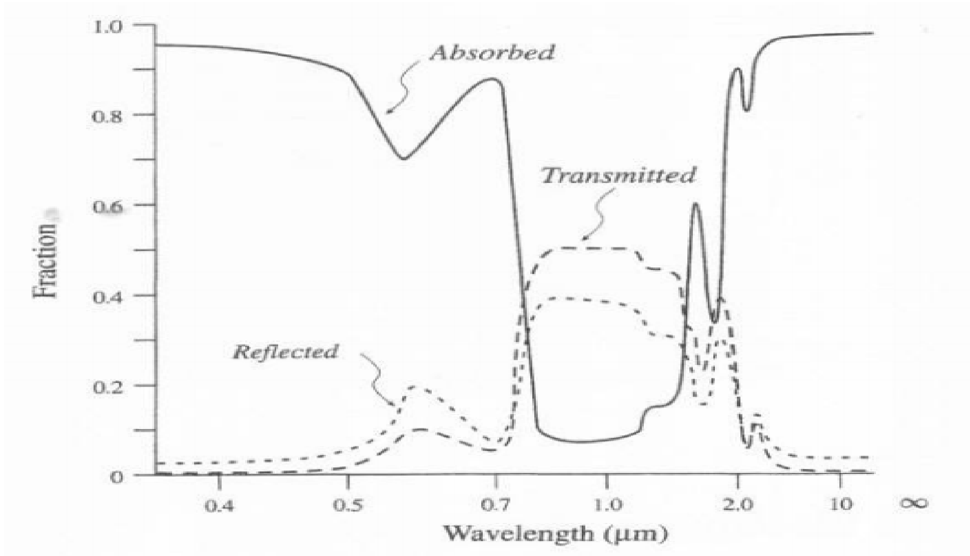


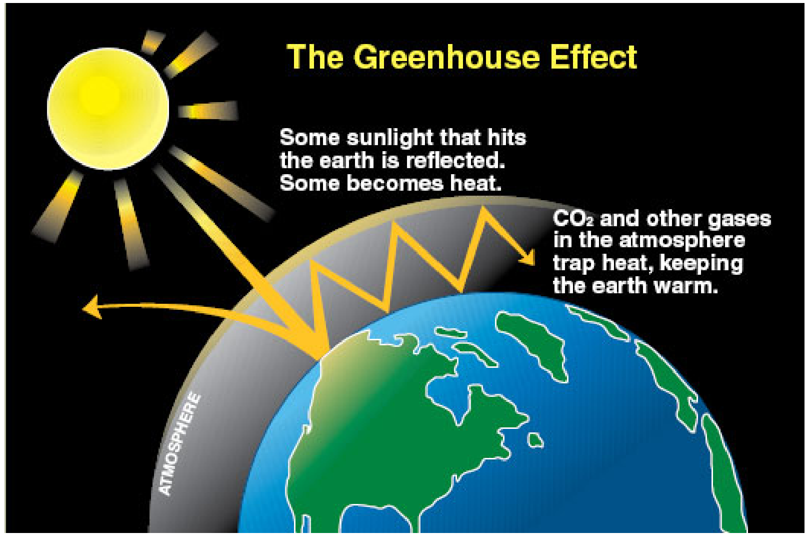
Figure 4. Representative spectral values for the reflectivity, absorptivity, and transmissivity of a leaf.

•A shaded leaf
→get radiation between 0.7~2 μm

→ Photosynthesis

Reflection, Absorption and Transmission of Waves at a surface

Transmissivity of the Atmosphere: Greenhouse Effect



- Greenhouse Effect
  -The atmosphere traps heat.
- Greenhouse gases
  → Infrared: opaque
  ↕
  →Atmosphere: Transparent

The radiation from earth by the atmosphere.

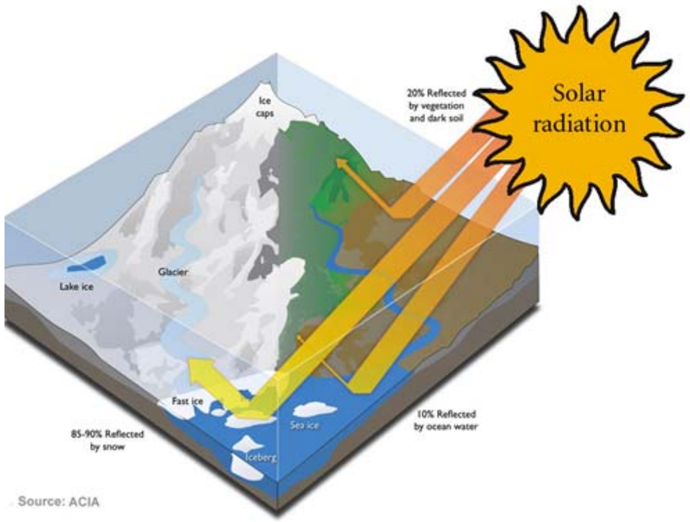
Increasing its temperature.

❖Greenhouse gases

$-CO_2$, *methane*, *chlorofluo rocarbons*

Reflection, Absorption and Transmission of Waves at a surface

Albedo-Reflection from Soil



•Albedo
-overall fraction of radiation

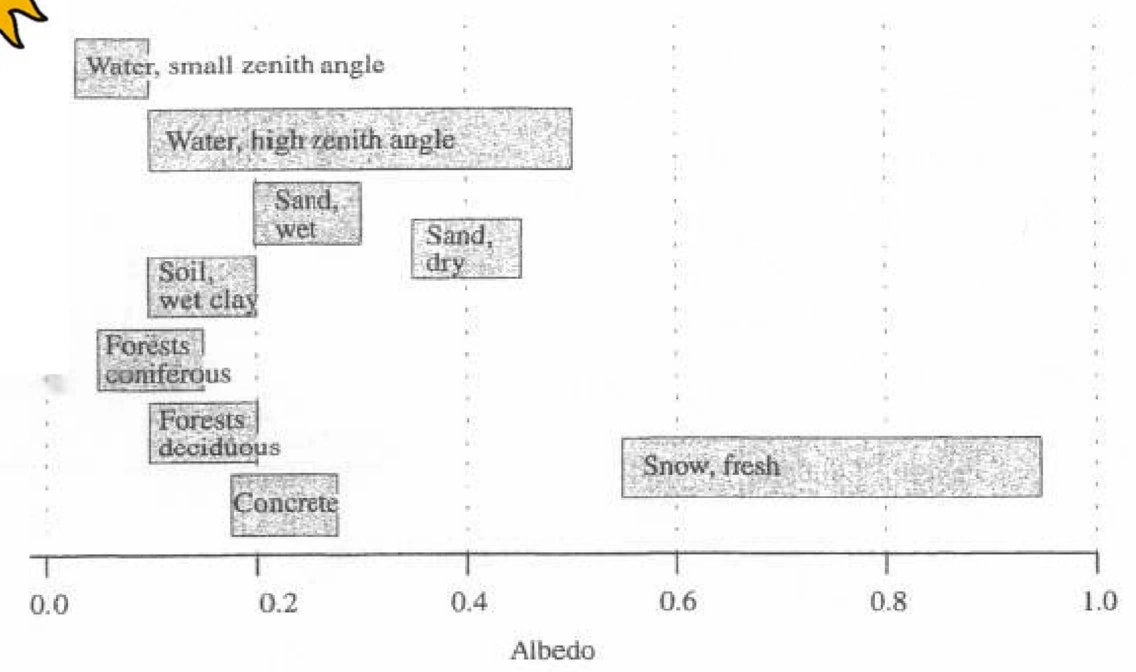


Figure 5. Albedo of various surfaces.

•Factors
-position of the sun
-surface composition
-roughness

Reflection, Absorption and Transmission of Waves at a surface

Absorption and Transmission in Biomaterials

Beer-Lambert law : $F = F_0 e^{-x/\delta}$ (3)

F :The flux in entering a material at its surface.

F_0 :The flux at a location inside the material at a distance x from surface.

δ :the penetration depth.

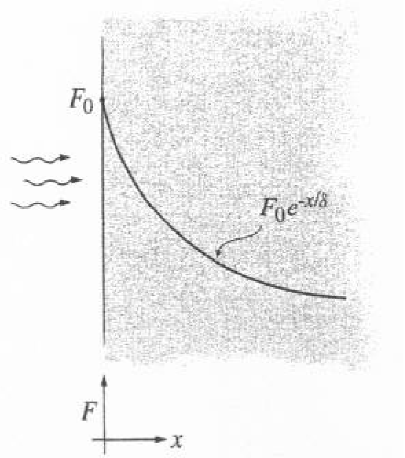


Figure 6. Illustration of the decay in the intensity of a wave as it is transmitted through a material, as given by Eqn.3.

X= δ : $F = F_0 e^{-\delta/\delta} = \dfrac{F_0}{e}$ (4)

3 Thermal Radiation from an Ideal (Black) Body

- E :Total emissive power of a surface
- E_b :The emissive of an ideal (Black) body
- E_λ :The emissive power of a wavelength λ

⇒ The monochromatic emissive power

$$dE = E_\lambda d\lambda$$

⇒ Energy emitted between λ_1 and λ_2

$$E = \int_{\lambda_1}^{\lambda_2} E_\lambda d\lambda$$

⇒ Total energy emitted by a body can be written as:

$$E = \int_0^\infty E_\lambda d\lambda$$

⇒ Fraction of total energy emitted two wavelengths

$$F = \frac{\int_{\lambda_1}^{\lambda_2} E_\lambda d\lambda}{\int_0^\infty E_\lambda d\lambda} \qquad (5)$$

Thermal Radiation from an Ideal (Black) Body

$$E_{b,\lambda} = \frac{2\pi c^2 h \lambda^{-5}}{\exp(ch/\kappa\lambda T) - 1} \qquad (6)$$

C : The speed of light.
H : The plank's constant.
κ: The Boltzmann's constant.

➡ Total energy emitted at all wavelengths

$$E_b = \int E_{b,\lambda} d\lambda = \frac{2\pi^5 \kappa^4 T^4}{15 c^2 h^3} = \sigma T^4 \qquad (7)$$

4 Fraction of Energy Emitted by an Ideal Body in a Given Range of Wavelengths

Energy emitted between λ_1 and λ_2

$$E = \int_{\lambda_1}^{\lambda_2} E_\lambda d\lambda$$

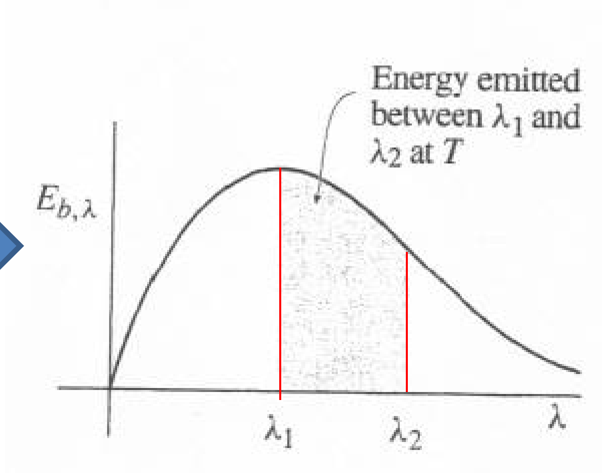


Figure 7. Illustration of energy emitted by a blackbody between two wavelengths.

Fraction of the total energy emitted by the same blackbody

$$\frac{\int_{\lambda_1}^{\lambda_2} E_{b,\lambda} d\lambda}{\int_0^{\infty} E_{b,\lambda} d\lambda} \qquad (8)$$

Fraction of Energy Emitted by an Ideal Body in a Given Range of Wavelengths

$$= \frac{\int_0^{\lambda_2} E_{b,\lambda} d\lambda - \int_0^{\lambda_1} E_{b,\lambda} d\lambda}{\sigma T^4}$$

$$= \int_0^{\lambda_2} \frac{E_{b,\lambda}}{\sigma T^4} d\lambda - \int_0^{\lambda_1} \frac{E_{b,\lambda}}{\sigma T^4} d\lambda$$

$$= \int_0^{\lambda_2} \frac{E_{b,\lambda}}{\sigma T^5} d(\lambda T) - \int_0^{\lambda_1} \frac{E_{b,\lambda}}{\sigma T^5} d(\lambda T) \quad (9)$$

-substituting Eqn.8.6 for the integrand in the two integrals

$$\frac{E_{b,\lambda}}{\sigma T^5} = \frac{2\pi c^2 h(\lambda T)^{-5}}{\exp(ch/\kappa\lambda T) - 1} \qquad (10)$$

Fraction of Energy Emitted by an Ideal Body in a Given Range of Wavelengths

Fraction

$$F_{0-\lambda T} = \int_0^{\lambda T} \frac{E_{b,\lambda}}{\sigma T^5} d(\lambda T) \qquad (11)$$

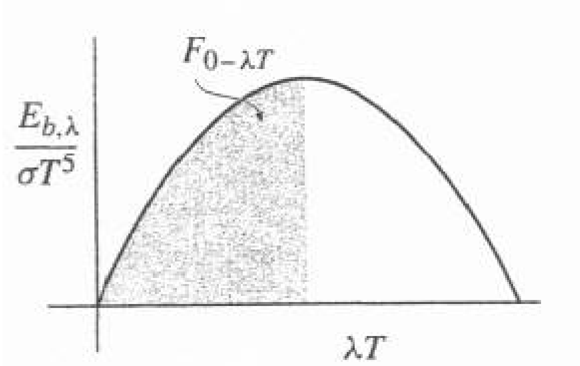


Figure 8. Graphical illustration of $F_{0-\lambda T}$

Fraction of energy between the λ_1 and λ_2

$$\begin{pmatrix} Fraction\, of\,\, energy\, between \\ \lambda_1\, and\, \lambda_2\, at\, temp\, T \end{pmatrix} = F_{0-\lambda_2 T} - F_{0-\lambda_1 T}$$

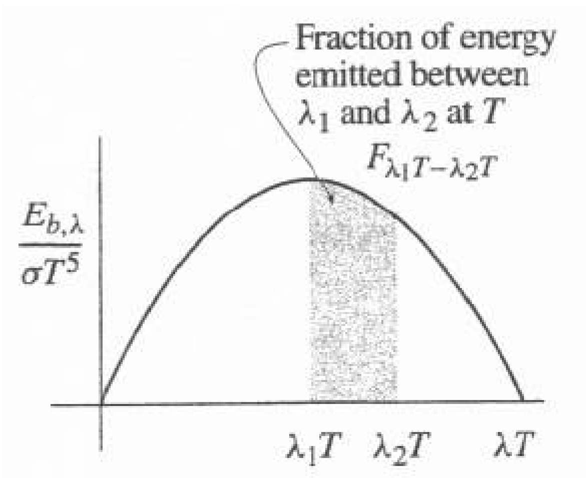


Figure 9. Graphical illustration of $F_{0-\lambda_2 T} - F_{0-\lambda_1 T}$ **.**

5 Thermal radiation from a real body : Emissivity

Total emissivity

$$: \epsilon = \frac{E}{E_b} \ where\ 0 \le \epsilon \le 1 \qquad (12)$$

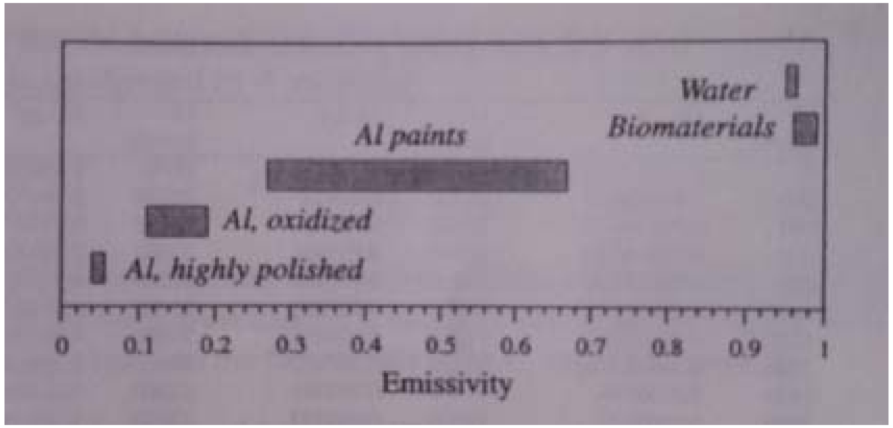


Figure 10. Emissivity of biomaterials as compared to other materials such as aluminum and water.

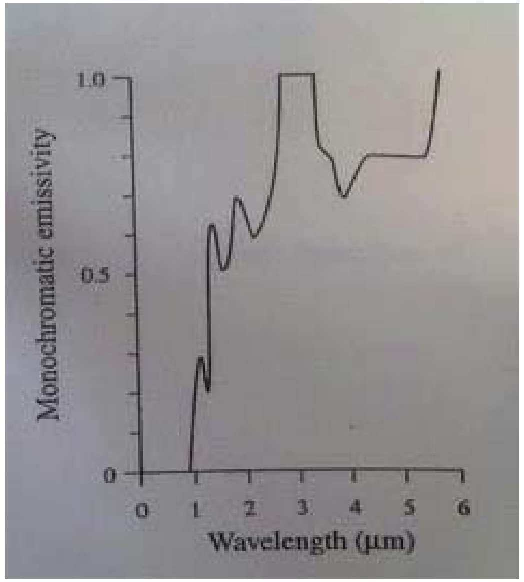
[Emissivity]
Polished metals < nonmetal surfaces < biomaterials

Thermal radiation from a real body : Emissivity

The monochromatic emissivity

$$: \; E_{\lambda} = \frac{E_{\lambda}}{E_{b,\lambda}} \;\; where \; 0 \le \epsilon \le 1 \qquad (13)$$

♣ **Gray body** :
The body which is independent of wave length for monochromatic emissivity



An average value of 0.98–0.99 for human skin monochromatic emissivity is often used.

Figure 11.The spectral emissivity of human skin at room temperature. The correspoinding total emittance is 0.993. Most authors use values between 0.98 and 0.99.

6 Emission from human bodies – Infrared and microwave thermography for clinical uses

All bodies above 0 K emit radiation over a range of wavelengths. So, a human body would also emit radiation.

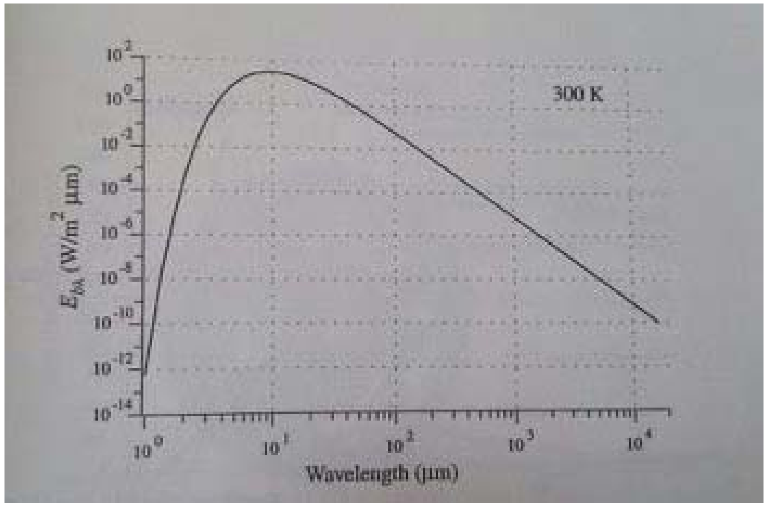


Figure 12. Radiation emitted from a blackbody at 300 K showing the approximate radiation emitted from humans.

1. Human radiation includes wavelengths from infrared to microwave region.

2. At a 300 K, which is near the human skin temperature, maximum intensity of radiative emission occurs at wavelengths near 10 μm .

3. It is used in the medical field.

7 Solar, Atmospheric, and Earth surface radiation

Solar radiation

Outside the atmosphere, the solar radiation reaches an approximate intensity E_{sc} of 1353 W/m^2.

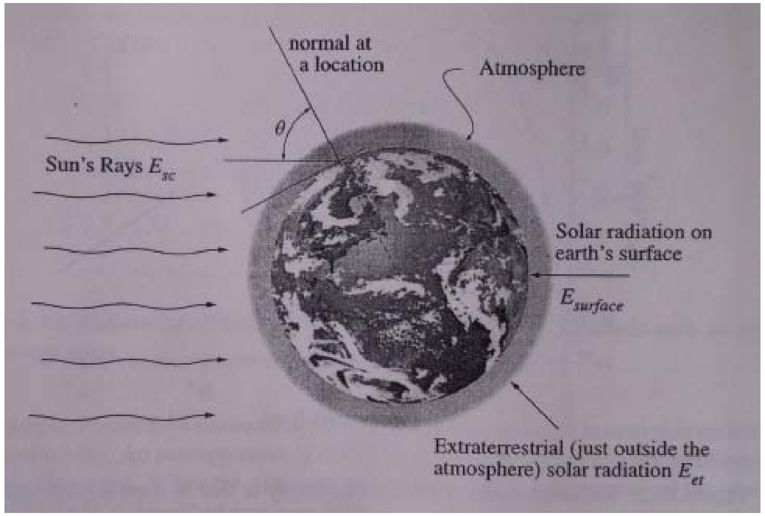


Figure 13. Relation of solar radiation on earth surface to the extraterrestrial solar radiation and the solar constant.

$$E_{et} = E_{sc} \cdot \beta \cdot cos\theta$$

E_{et} ⇒ The extraterrestrial solar irradiation (W/m^2)

E_{sc} ⇒ the solar constant of 1353 W/m^2

β ⇒ A correction factor to account for the eccentricity of the earth's orbit about the sun ($0.97 \le \beta \le 1.03$)

θ ⇒ The zenith angle

Solar, Atmospheric, and Earth surface radiation

Solar radiation

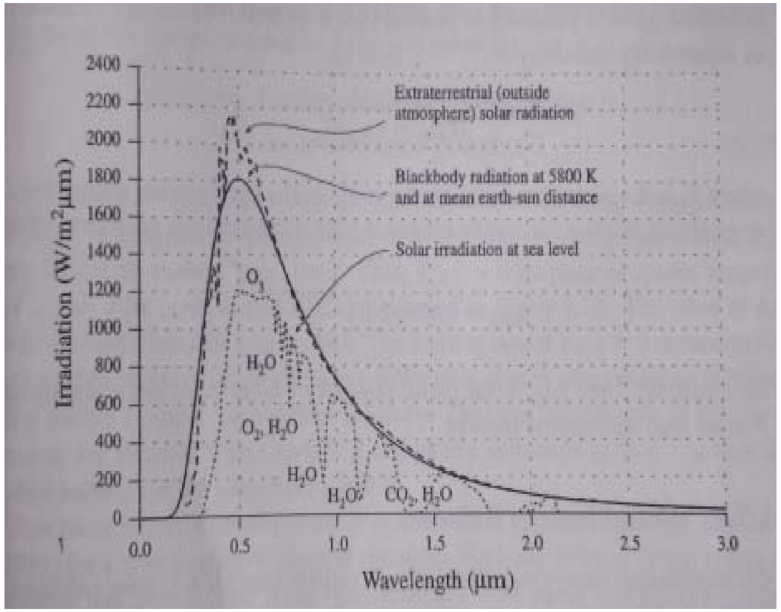


Figure 14. Spectral distribution of solar radiation outside the earth's atmosphere and on the earth surface.

Comparison of black body to extraterrestrial solar radiation and solar irradiation at sea level

Solar, Atmospheric, and Earth surface radiation

Emission from Earth's surface

The energy emitted by the earth is given by :

$$E_{earth} = \epsilon_{earth}\sigma T_{earth}{}^4 \qquad (14)$$

The average temperature of the earth's surface is considered to be 14℃.
The emissivity of the earth surface will be made up of that of water, soil, etc.

Solar, Atmospheric, and Earth surface radiation

Atmospheric emissions

The atmospheric gases emit considerable radiation.
Effective concentration of these atmospheric gases can vary from time to time.

$$G_{atm} = \epsilon_{sky} \sigma T_a{}^4 \qquad (15)$$

T_a : the air temperature near the ground.

The apparent sky emissivity, ϵ_{sky}, is an empirical constant.

$$\epsilon_{sky} = 0.55 + 1.8 \left(\frac{p_{H_2O}}{P}\right)^{1/2} \qquad (16)$$

p_{H_2O} : the partial pressure of water vapor in the atmosphere.
P : the total atmospheric pressure.

Solar, Atmospheric, and Earth surface radiation

Global energy balance

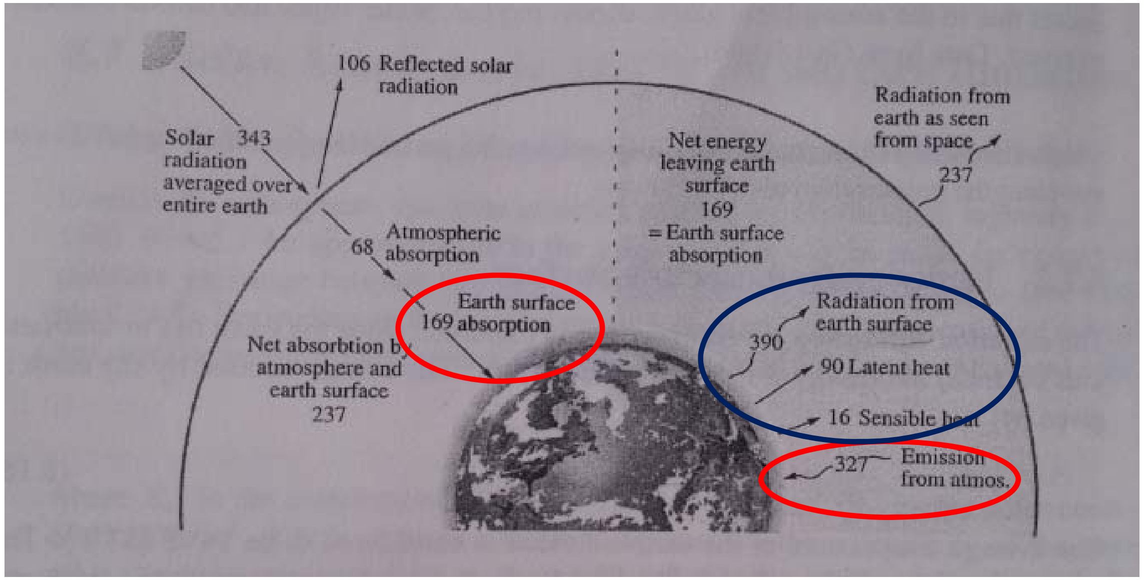


Figure 15. The global energy balance for annual mean conditions.

At the earth's surface, energy balance is

Input – Output = (169+327) – (390+90+16) = 0

8 Radiative Exchange Between Bodies

When two bodies exchange thermal radiation, the net radiative exchange between them will depend on their size, shape, and the relative orientation of their radiating surfaces.

'F_{1-2}', which is called as configuration factor or view factor, includes size, shape and orientation factor.

F_{1-2} = fraction of radiation leaving surface 1 that is intercepted by surface 2

View factor is dimensionless. The range of this is zero to one.

Radiative Exchange Between Bodies

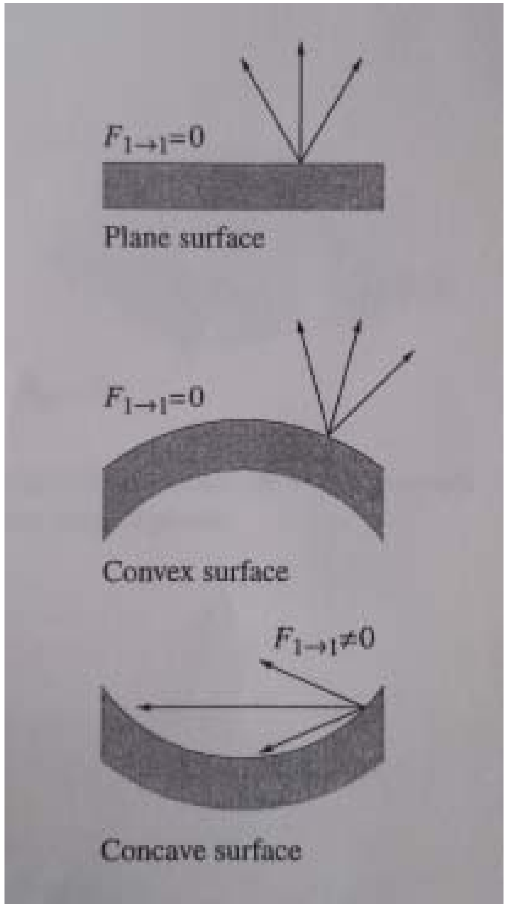


Figure 16. Illustration of view factors showing view factor is zero for a surface to itself for a plane or a convex surface, but non-zero for a concave surface.

1. The view factor from a surface to itself will be zero unless the surface "sees" itself.

2. $F_{1-1} = 0$ for plane or convex surfaces and $F_{1-1} \neq 0$ for concave surfaces.

3. There are two limiting case of view factor. One case of $F_{1-2} = 0$ represents the situation when two surfaces do not have a direct view of each other. The other case $F_{1-2} = 1$ represents the situation where surface 2 completely surrounds surface 1.

Radiative Exchange Between Bodies

This page is method of calculating view factor. Main factors are distance(D) between two bodies and the sides of the rectangles (X and Y).
($\bar{X} = \frac{X}{D}$ $\;and\;$ $\bar{Y} = \frac{Y}{D}$)

$$F_{1-2} = \frac{2}{\pi \bar{X}\bar{Y}} ln\left[\frac{(1+\bar{X}^2)(1+\bar{Y}^2)}{1+\bar{X}^2+\bar{Y}^2}\right]^{1/2}$$

$$+\bar{X}(1+\bar{Y}^2)^{1/2}\tan^{-1}\frac{\bar{X}}{(1+\bar{Y}^2)^{1/2}}$$

$$+\bar{Y}(1+\bar{X}^2)^{1/2}\tan^{-1}\frac{\bar{Y}}{(1+\bar{X}^2)^{1/2}}$$

$$-\bar{X}tan^{-1}\bar{X}-\bar{Y}tan^{-1}\bar{Y}$$

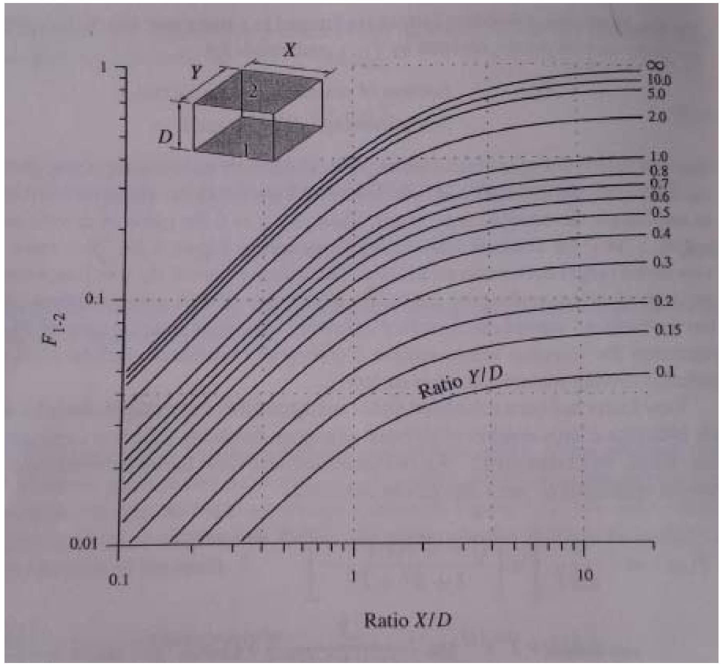


Figure 17. View factor between two aligned parallel rectangles of equal size.

Radiative Exchange Between Bodies

The simplest situation of radiative exchange occurs when two blackbodies are exchanging radiation.

The net radiative exchange between two such bodies is given by

$$q_{1-2} = \sigma A_1 F_{1-2}(T_1^4 - T_2^4) \qquad (17)$$

or

$$q_{2-1} = \sigma A_2 F_{2-1}(T_2^4 - T_1^4) \qquad (18)$$

$q_{1-2}(W)$: The net energy transfer between bodies 1 and 2.
A_1, $A_2(m^2)$: The areas of bodies.
F_{1-2} : The view factor between bodies 1 and 2.
T_1, $T_2(K)$: The absolute temperature of the respective surfaces.

Radiative Exchange Between Bodies

Instead of blackbodies, when two gray bodies are exchanging radiation, the situation becomes more complex since these bodies are also reflecting part of the radiation.

For the special case when two gray surfaces form a complete enclosure or close to it, as illustrated in Figure 18.

The net radiative exchange is given by

$$q_{1-2} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{\epsilon_1 A_1} + \frac{1}{F_{1-2}A_1} + \frac{1-\epsilon_2}{\epsilon_2 A_2}} \qquad (19)$$

$q_{1-2}(W)$: The net energy transfer between bodies 1 and 2.
ϵ_i : The emissivity of body i.
$A_i(m^2)$: The area of body i.
$T_i(K)$: The absolute temperature of surface i.
F_{1-2} : The view factor between bodies 1 and 2.

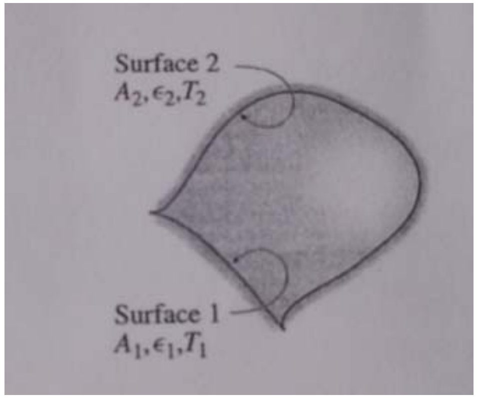


Figure 18. Schematic of two gray surfaces that form a complete enclosure.

Radiative Exchange Between Bodies

For example, radiative exchange between two large parallel planes, as shown in Figure 19, would be given by a special case of Eqn. 8.24 for $A_1 = A_2 = A$ and $F_{1-2} = 1$.

$$q_{1-2} = \frac{\sigma A(T_1^4 - T_2^4)}{\frac{1-\epsilon_1}{\epsilon_1} + 1 + \frac{1-\epsilon_2}{\epsilon_2}} \qquad (20)$$

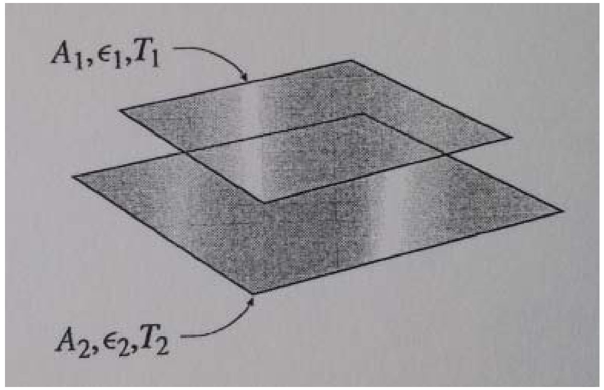


Figure 19. Schematic of two gray infinite parallel planes.

When a relatively small object 1 is completely enclosed by a much larger surface 2, $A_1/A_2 \approx 0$ and $F_{1-2} = 1$, and Eqn. 8.24 simplifies to

$$q_{1-2} = \epsilon_1 \sigma A_1 (T_1^4 - T_2^4) \qquad (21)$$

Radiative Exchange Between Bodies

Radiative Heat Transfer Coefficient

For a special case of radiative heat exchange, when temperatures T_1 and T_2 are close, Eqn 8.21 can be written as

$$q_{1-2} = \sigma A_1 F_{1-2} 4T^3 (T_1 - T_2) \qquad (22)$$

$$= A_1 F_{1-2} h_r (T_1 - T_2) \qquad (23)$$

$h_r(\frac{W}{m^2 \cdot K})$ is a radiative heat transfer coefficient similar to the convective heat transfer coefficient.

$$h_r = 4\sigma T_1^3 \qquad (24)$$

h_r may be determined experimentally.
The radiative heat transfer coefficient was measured experimentally as:

$$h_r = 3.5[1 + 0.0055(T_s + T_a)] \qquad (25)$$

$T_s(K)$: The average skin temperature.
$T_a(K)$: The environmental temperature.

Radiative Exchange Between Bodies

Radiative Exchange Between a Leaf and Surrondings

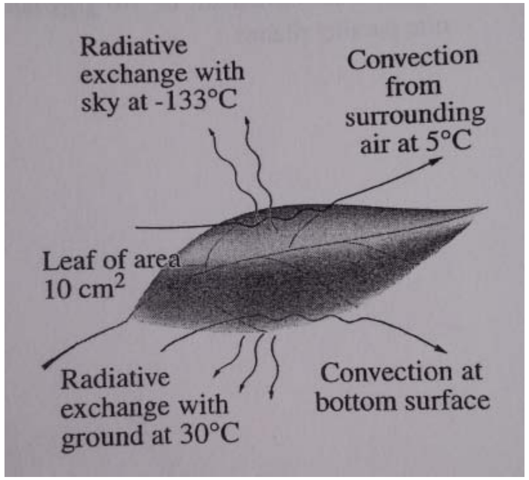


Figure 20. Schematic of radiation exchange of a leaf with the sky and the ground.

Radiative heat loss from an unshaded leaf has important consequences.

Radiative freeze typically occurs when the wind is calm or still.

So the uppermost leaves in a tress will tend to have the lowest temperatures and frost tends to form there first.

Consequently, when such freezing is imminent, large fans are employed to blow air.

Radiative Exchange Between Bodies

Radiative Exchange Between Animal and Its Surroundings

♣ MRT(mean radiant temperature) : An average temperature of the walls.

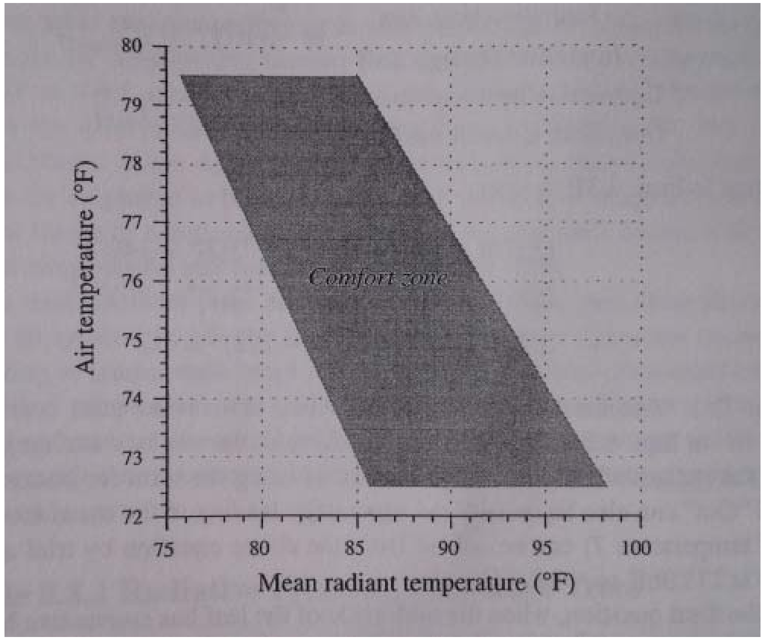


Figure 21. Human Thermal Comfort and Mean Radiant Temperature.

1. Body heat loss by radiation is an important mechanism for maintaining a thermal balance and comfort.

2. The shaded zone for human thermal comfort as related to surrounding wall temperature shown in Fig. 21.

3. The higher the MRT value, the lower the corresponding air temperature required for comfort.

By this theory, We should maintain thermal comfort by controlling the convective heat loss.