HEAT TRANSFER
SETN2223

RADIATION: PROCESSES AND PROPERTIES

CONTENTS

Fundamental Concepts

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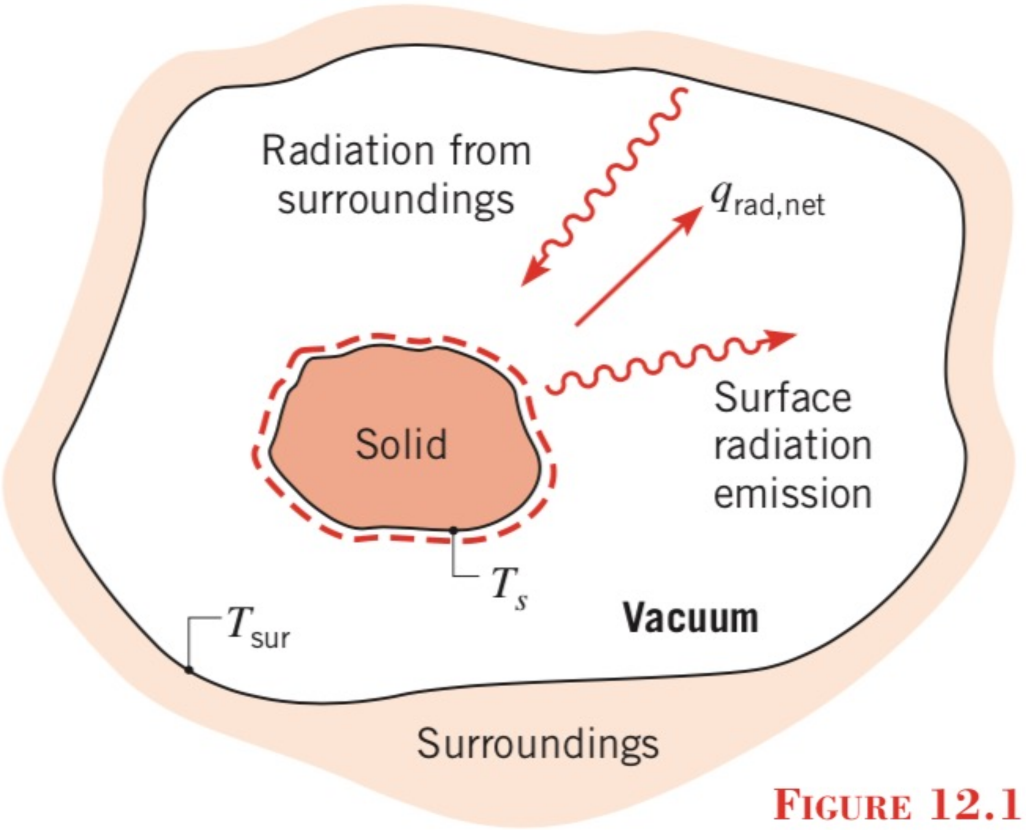
Fundamental Concepts

Recall

We have come to recognize that heat transfer by **conduction** and **convection** requires the presence of a **temperature gradient** in some form of **matter**



Thermal Radiation is **electromagnetic** radiation emitted by a **body** due to its **temperature**

FIGURE 12.1 Radiation cooling of a hot solid.

Fundamental Concepts

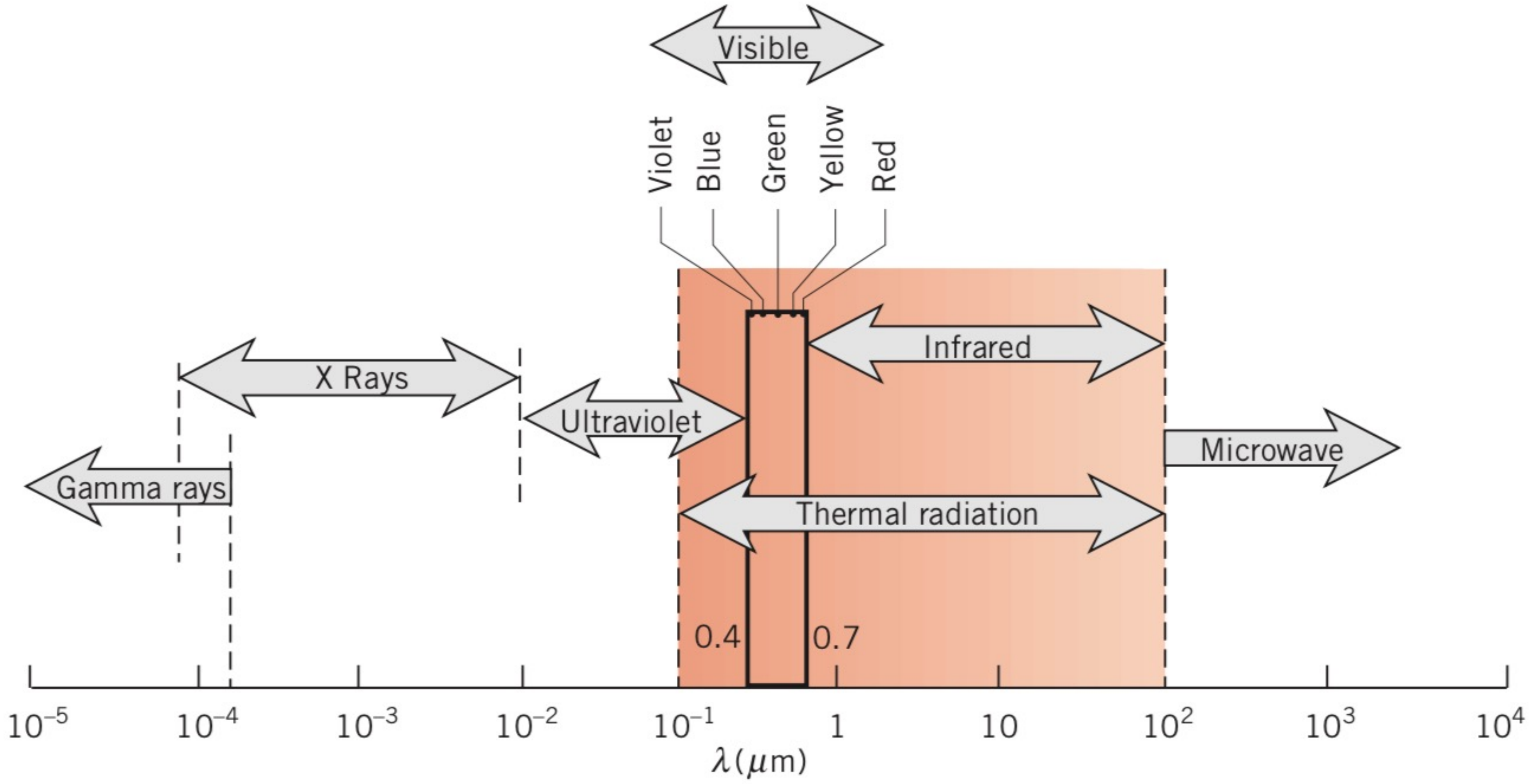


FIGURE 12.3 Spectrum of electromagnetic radiation.

Fundamental Concepts

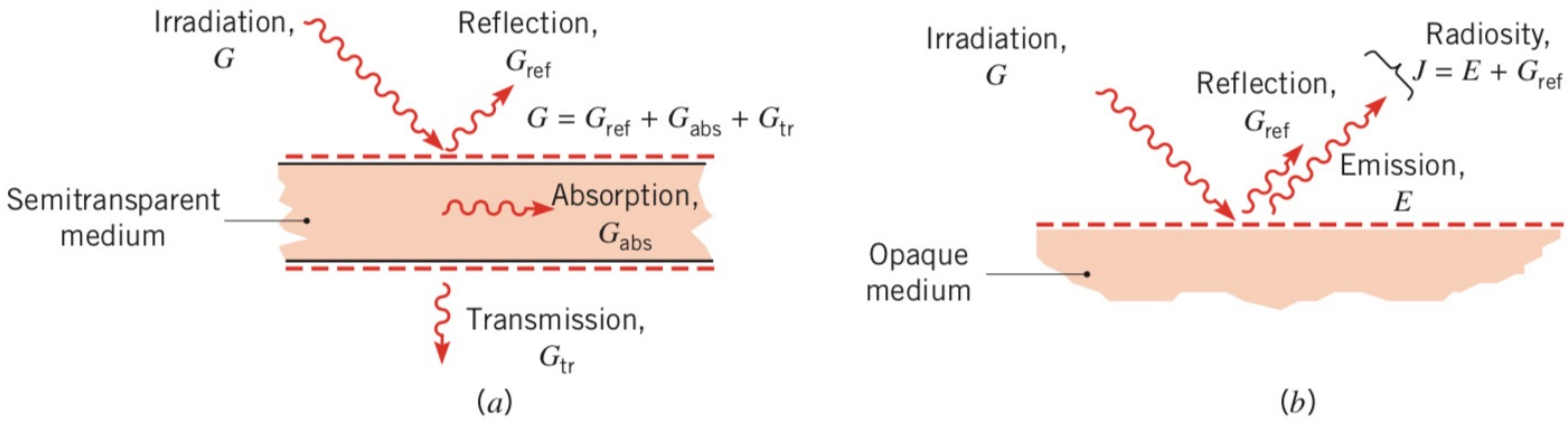


FIGURE 12.5 Radiation at a surface. (*a*) Reflection, absorption, and transmission of irradiation for a semitransparent medium. (*b*) The radiosity for an opaque medium.

Fundamental Concepts

Absorption occurs when radiation interacts with the medium, causing an increase in the internal thermal energy of the medium. Reflection is the process of incident radiation being redirected away from the surface, with no effect on the medium. We define reflectivity ρ as the fraction of the irradiation that is reflected, absorptivity α as the fraction of the irradiation that is absorbed, and transmissivity τ as the fraction of the irradiation that is transmitted. Because all of the irradiation must be reflected, absorbed, or transmitted, it follows that

$$\rho + \alpha + \tau = 1 \tag{12.2}$$

A medium that experiences no transmission ($\tau = 0$) is *opaque,* in which case

$$\rho + \alpha = 1 \tag{12.3}$$

With this understanding of the partitioning of the irradiation into reflected, absorbed, and transmitted components, two additional and useful radiation fluxes can be defined. The *radiosity,* J (W/m^2), of a surface accounts for *all* the radiant energy leaving the surface. For an opaque surface, it includes emission and the reflected portion of the irradiation, as illustrated in Figure 12.5*b*. It is therefore expressed as

$$J = E + G_{\text{ref}} = E + \rho G \tag{12.4}$$

Fundamental Concepts

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$$J = E + G_{ref} = E + \rho G \qquad (12.4)$$

Radiosity can also be defined at a surface of a semitransparent medium. In that case, the radiosity leaving the top surface of Figure 12.5*a* (not shown) would include radiation transmitted through the medium from below.

Finally, the *net* radiative flux *from* a surface, q''_{rad} (W/m^2), is the difference between the outgoing and incoming radiation

$$q''_{rad} = J - G \qquad (12.5)$$

Combining Equations 12.5, 12.4, 12.3, and 1.4, the net flux for an opaque surface is

$$q''_{rad} = E + \rho G - G = \varepsilon \sigma T_s^4 - \alpha G \qquad (12.6)$$

Fundamental Concepts

Summary:

Table 12.1 Radiative fluxes (over all wavelengths and in all directions)

Flux (W/m^2)	Description	Comment
Emissive power, E	Rate at which radiation is emitted from a surface per unit area	$E = \varepsilon \sigma T_s^4$
Irradiation, G	Rate at which radiation is incident upon a surface per unit area	Irradiation can be reflected, absorbed, or transmitted
Radiosity, J	Rate at which radiation leaves a surface per unit area	For an opaque surface $J = E + \rho G$
Net radiative flux, $q''_{rad} = J - G$	Net rate of radiation leaving a surface per unit area	For an opaque surface $q''_{rad} = \varepsilon \sigma T_s^4 - \alpha G$

Blackbody Radiation

1. *A blackbody absorbs all incident radiation, regardless of wavelength and direction.*
2. *For a prescribed temperature and wavelength, no surface can emit more energy than a blackbody.*
3. *Although the radiation emitted by a blackbody is a function of wavelength and temperature, it is independent of direction. That is, the blackbody is a diffuse emitter.*

As the perfect absorber and emitter, the blackbody serves as a *standard* against which the radiative properties of actual surfaces may be compared.

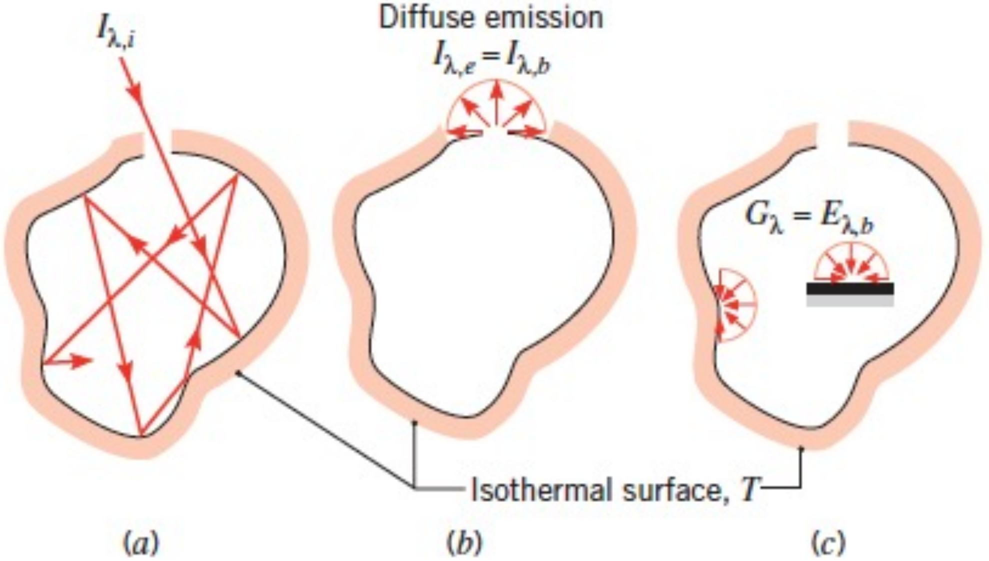


FIGURE 12.11 Characteristics of an isothermal blackbody cavity. (*a*) Complete absorption. (*b*) Diffuse emission from an aperture. (*c*) Diffuse irradiation of interior surfaces.

Planck's Distribution

Spectral Emissive Power of a Blackbody

$$E_{\lambda,b}(\lambda, T) = \pi I_{\lambda,b}(\lambda, T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]} \qquad (12.30)$$

where the first and second radiation constants are $C_1 = 2\pi h c_o^2 = 3.742 \times 10^8\ \mathrm{W \cdot \mu m^4/m^2}$ and $C_2 = (hc_o/k_B) = 1.439 \times 10^4\ \mathrm{\mu m \cdot K}$.

Equation 12.30, known as the *Planck distribution*, or *Planck's law*, is plotted in Figure 12.12 for selected temperatures. Several important features should be noted.

1. The emitted radiation varies *continuously* with wavelength.[1]
2. At any wavelength the magnitude of the emitted radiation increases with increasing temperature.
3. The spectral region in which the radiation is concentrated depends on temperature, with *comparatively* more radiation appearing at shorter wavelengths as the temperature increases.
4. A significant fraction of the radiation emitted by the sun, which may be approximated as a blackbody at 5800 K, is in the visible region of the spectrum. In contrast, for $T \lesssim 800$ K, emission is predominantly in the infrared region of the spectrum and is not visible to the eye.

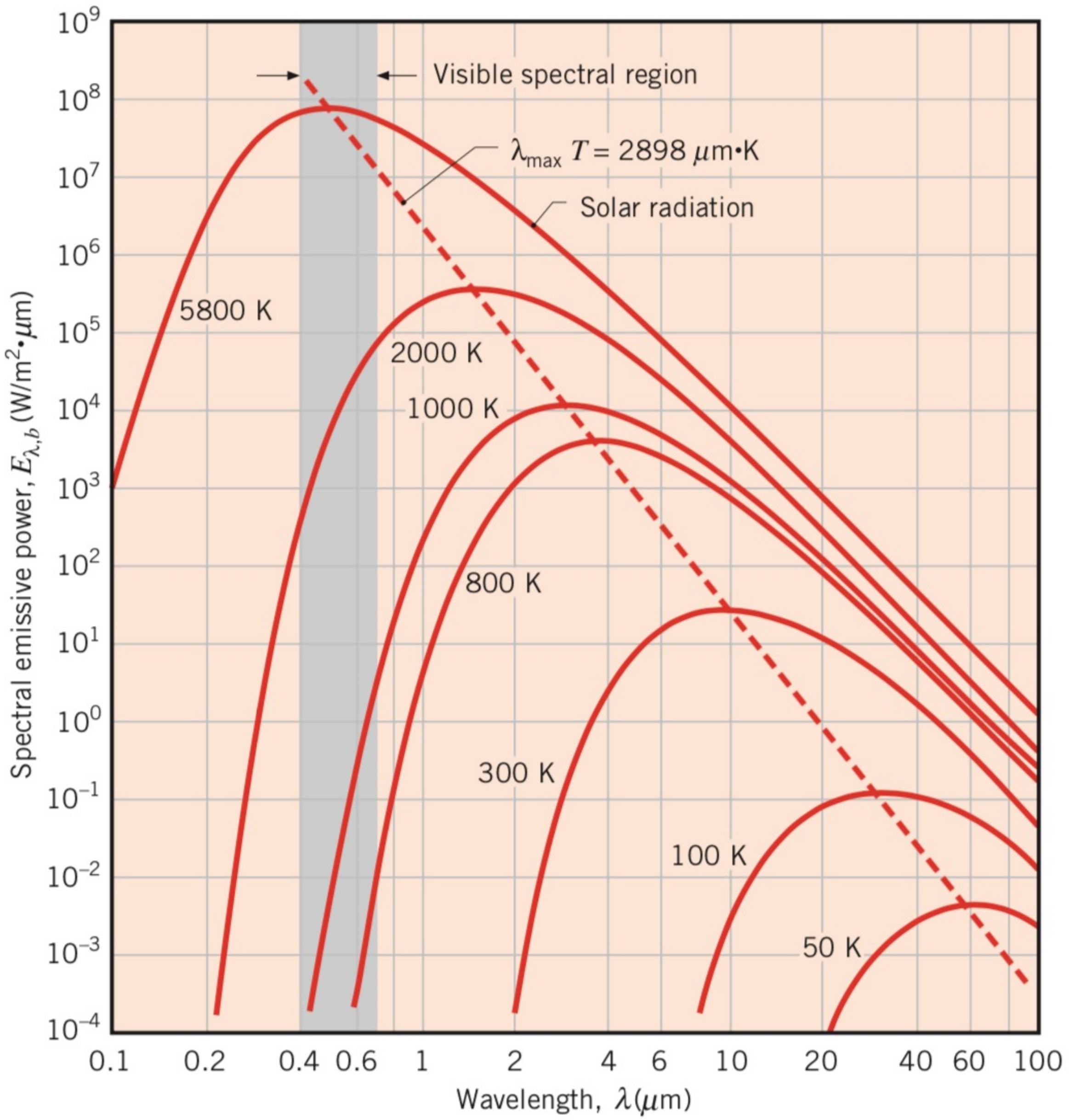


FIGURE 12.12 Spectral blackbody emissive power.

Wien's Displacement Law

From Figure 12.12 we see that the blackbody spectral distribution has a maximum and that the corresponding wavelength λ_{max} depends on temperature. The nature of this dependence may be obtained by differentiating Equation 12.30 with respect to λ and setting the result equal to zero. In so doing, we obtain

$$\lambda_{max} T = C_3 \tag{12.31}$$

where the third radiation constant is $C_3 = 2898\ \mu m \cdot K$.

Equation 12.31 is known as *Wien's displacement law*, and the locus of points described by the law is plotted as the dashed line of Figure 12.12. According to this result, the maximum spectral emissive power is displaced to shorter wavelengths with increasing temperature. This emission is in the middle of the visible spectrum ($\lambda \approx 0.50\ \mu m$) for solar radiation, since the sun emits approximately as a blackbody at 5800 K. For a blackbody at 1000 K, peak emission occurs at 2.90 μm, with some of the emitted radiation appearing visible as red light. With increasing temperature, shorter wavelengths become more prominent, until eventually significant emission occurs over the entire visible spectrum. For example, a tungsten filament lamp operating at 2900 K ($\lambda_{max} = 1\ \mu m$) emits white light, although most of the emission remains in the IR region.

Stefan-Boltzman's Law

Substituting the Planck distribution, Equation 12.30, into Equation 12.14, the total emissive power of a blackbody E_b may be expressed as

$$E_b = \int_0^\infty \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]}\, d\lambda$$

Performing the integration, it may be shown that

$$E_b = \sigma T^4 \qquad (12.32)$$

where the *Stefan–Boltzmann* constant, which depends on C_1 and C_2, has the numerical value

$$\sigma = 5.670 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$$

This simple, yet important, result is termed the *Stefan–Boltzmann law*. It enables calculation of the amount of radiation emitted in all directions and over all wavelengths simply from knowledge of the temperature of the blackbody. Because this emission is diffuse, it follows

Band Emission

To account for spectral effects, it is often necessary to know the fraction of the total emission from a blackbody that is in a certain wavelength interval or *band*. For a prescribed temperature and the interval from 0 to λ, this fraction is determined by the ratio of the shaded section to the total area under the curve of Figure 12.13. Hence

$$F_{(0\to\lambda)} \equiv \frac{\int_0^{\lambda} E_{\lambda,b}\, d\lambda}{\int_0^{\infty} E_{\lambda,b}\, d\lambda} = \frac{\int_0^{\lambda} E_{\lambda,b}\, d\lambda}{\sigma T^4} = \int_0^{\lambda T} \frac{E_{\lambda,b}}{\sigma T^5}\, d(\lambda T) = f(\lambda T) \tag{12.34}$$

Since the integrand $(E_{\lambda,b}/\sigma T^5)$ is exclusively a function of the wavelength–temperature product λT, the integral of Equation 12.34 may be evaluated to obtain $F_{(0\to\lambda)}$ as a function of only λT. The results are presented in Table 12.2 and Figure 12.14. They may also be used to obtain the fraction of the radiation between any two wavelengths λ_1 and λ_2, since

$$F_{(\lambda_1\to\lambda_2)} = \frac{\int_0^{\lambda_2} E_{\lambda,b}\, d\lambda - \int_0^{\lambda_1} E_{\lambda,b}\, d\lambda}{\sigma T^4} = F_{(0\to\lambda_2)} - F_{(0\to\lambda_1)} \tag{12.35}$$

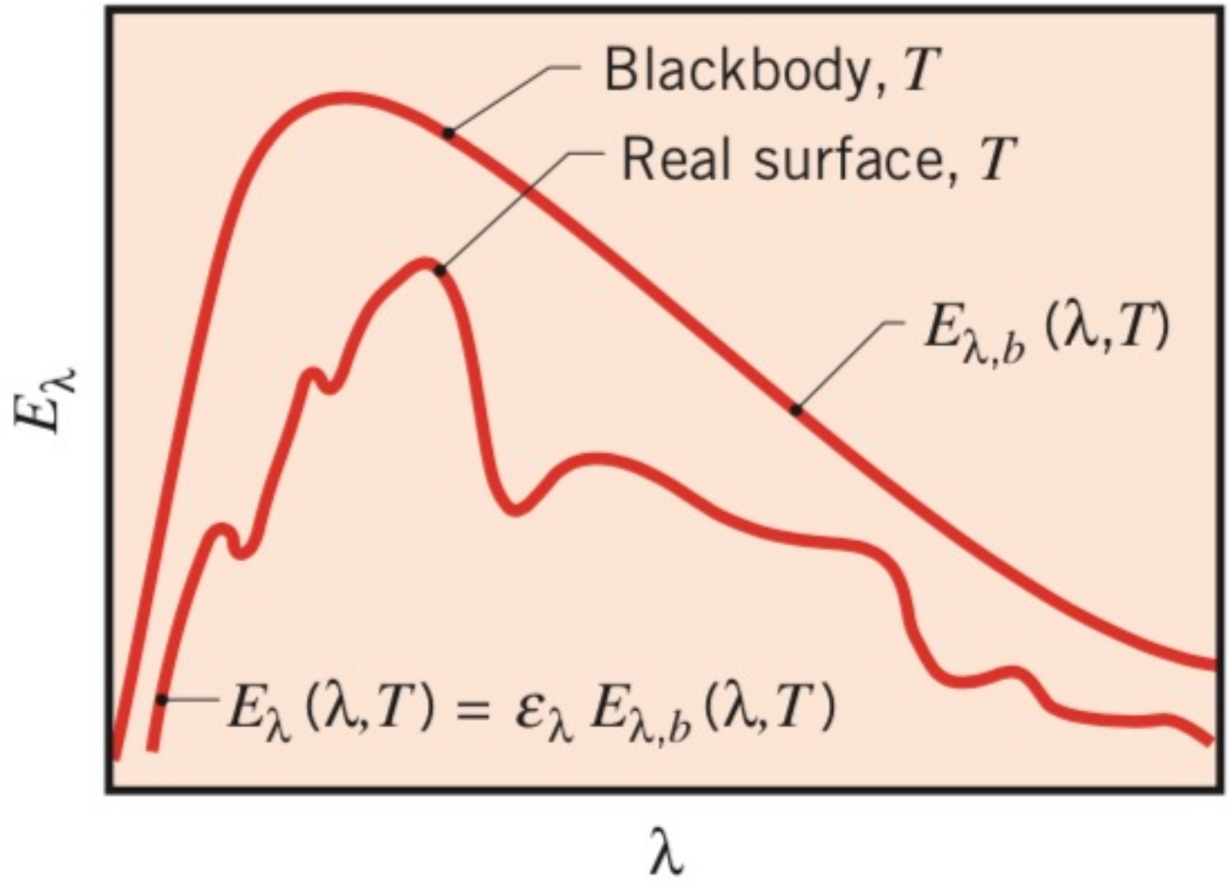
TABLE 12.2 Blackbody Radiation Functions

λT (μm·K)	$F_{(0\rightarrow\lambda)}$	$I_{\lambda,b}(\lambda,T)/\sigma T^5$ $(\mu\text{m}\cdot\text{K}\cdot\text{sr})^{-1}$	$\dfrac{I_{\lambda,b}(\lambda,T)}{I_{\lambda,b}(\lambda_{max},T)}$
200	0.000000	0.375034×10^{-27}	0.000000
400	0.000000	0.490335×10^{-13}	0.000000
600	0.000000	0.104046×10^{-8}	0.000014
800	0.000016	0.991126×10^{-7}	0.001372
1,000	0.000321	0.118505×10^{-5}	0.016406
1,200	0.002134	0.523927×10^{-5}	0.072534
1,400	0.007790	0.134411×10^{-4}	0.186082
1,600	0.019718	0.249130	0.344904
1,800	0.039341	0.375568	0.519949
2,000	0.066728	0.493432	0.683123
2,200	0.100888	0.589649×10^{-4}	0.816329
2,400	0.140256	0.658866	0.912155
2,600	0.183120	0.701292	0.970891
2,800	0.227897	0.720239	0.997123
2,898	0.250108	0.722318×10^{-4}	1.000000

TABLE 12.2 *Continued*

λT ($\mu m \cdot K$)	$F_{(0 \to \lambda)}$	$I_{\lambda,b}(\lambda, T)/\sigma T^5$ $(\mu m \cdot K \cdot sr)^{-1}$	$\dfrac{I_{\lambda,b}(\lambda, T)}{I_{\lambda,b}(\lambda_{max}, T)}$
3,000	0.273232	0.720254×10^{-4}	0.997143
3,200	0.318102	0.705974	0.977373
3,400	0.361735	0.681544	0.943551
3,600	0.403607	0.650396	0.900429
3,800	0.443382	0.615225×10^{-4}	0.851737
4,000	0.480877	0.578064	0.800291
4,200	0.516014	0.540394	0.748139
4,400	0.548796	0.503253	0.696720
4,600	0.579280	0.467343	0.647004
4,800	0.607559	0.433109	0.599610
5,000	0.633747	0.400813	0.554898
5,200	0.658970	0.370580×10^{-4}	0.513043
5,400	0.680360	0.342445	0.474092
5,600	0.701046	0.316376	0.438002
5,800	0.720158	0.292301	0.404671
6,000	0.737818	0.270121	0.373965
6,200	0.754140	0.249723×10^{-4}	0.345724
6,400	0.769234	0.230985	0.319783
6,600	0.783199	0.213786	0.295973
6,800	0.796129	0.198008	0.274128
7,000	0.808109	0.183534	0.254090
7,200	0.819217	0.170256×10^{-4}	0.235708
7,400	0.829527	0.158073	0.218842
7,600	0.839102	0.146891	0.203360
7,800	0.848005	0.136621	0.189143
8,000	0.856288	0.127185	0.176079
8,500	0.874608	0.106772×10^{-4}	0.147819
9,000	0.890029	0.901463×10^{-5}	0.124801
9,500	0.903085	0.765338	0.105956
10,000	0.914199	0.653279×10^{-5}	0.090442
10,500	0.923710	0.560522	0.077600
11,000	0.931890	0.483321	0.066913
11,500	0.939959	0.418725	0.057970
12,000	0.945098	0.364394×10^{-5}	0.050448
13,000	0.955139	0.279457	0.038689
14,000	0.962898	0.217641	0.030131
15,000	0.969981	0.171866×10^{-5}	0.023794
16,000	0.973814	0.137429	0.019026
18,000	0.980860	0.908240×10^{-6}	0.012574
20,000	0.985602	0.623310	0.008629
25,000	0.992215	0.276474	0.003828
30,000	0.995340	0.140469×10^{-6}	0.001945
40,000	0.997967	0.473891×10^{-7}	0.000656
50,000	0.998953	0.201605	0.000279
75,000	0.999713	0.418597×10^{-8}	0.000058
100,000	0.999905	0.135752	0.000019

Emission from Real Surfaces



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

Absorption, Reflection and Transmission by Real Surfaces

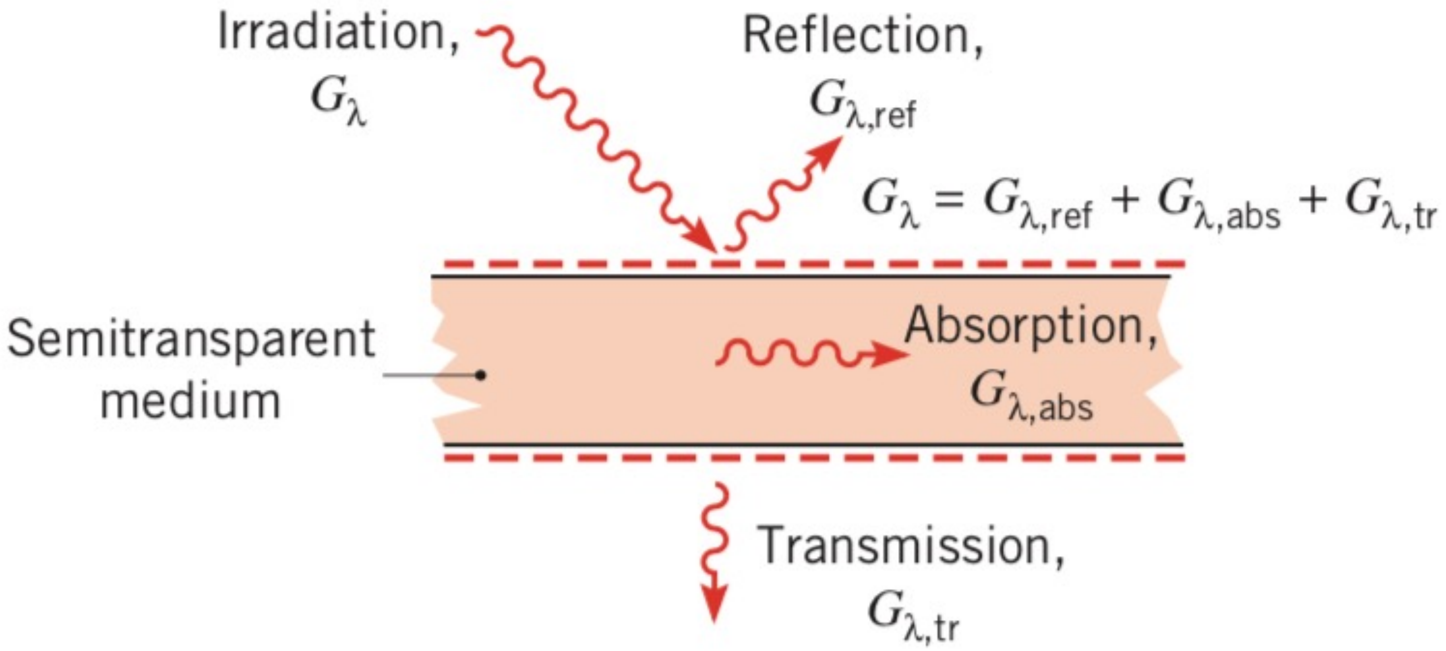


FIGURE 12.20 Spectral absorption, reflection, and transmission processes associated with a semitransparent medium.

Absorption, Reflection and Transmission by Real Surfaces

TOTAL ABSORBTIVITY

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

TOTAL REFLECTIVITY

$$\rho = \frac{\int_0^\infty \rho_\lambda(\lambda) G_\lambda(\lambda)\, d\lambda}{\int_0^\infty G_\lambda(\lambda)\, d\lambda}$$

TOTAL TRANSMISSIVITY

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

Kirchhoff's Law

$$\varepsilon_\lambda = \alpha_\lambda$$

If surface is diffuse or if G is diffuse

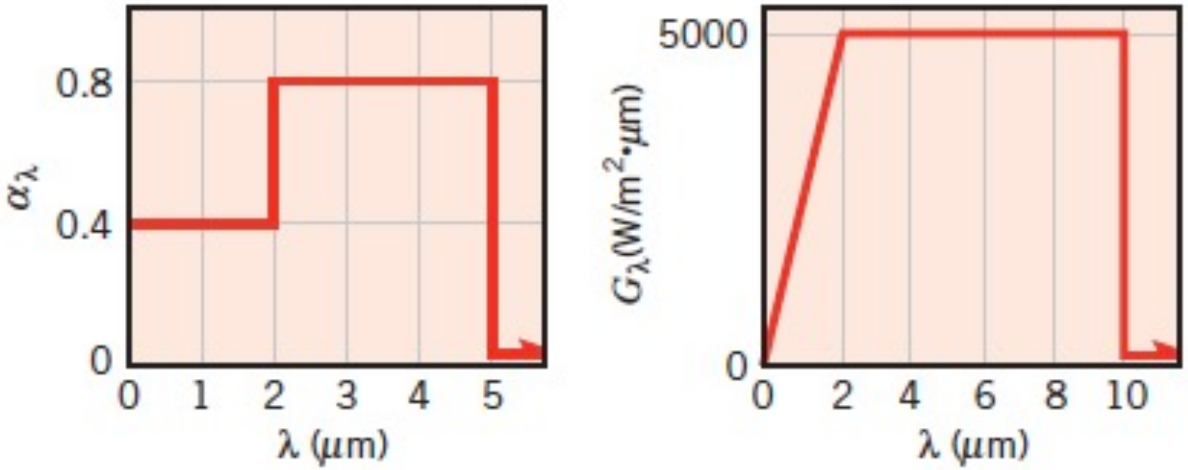
$$\varepsilon = \alpha$$

If the surface is grey

Grey surface → Properties independent of wavelength

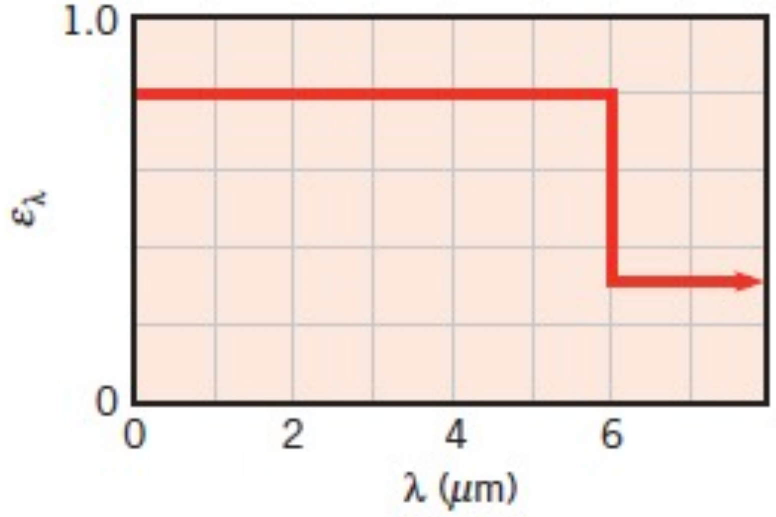
Example

12.58 Consider an opaque, diffuse surface for which the spectral absorptivity and irradiation are as follows:



What is the total absorptivity of the surface for the prescribed irradiation? If the surface is at a temperature of 1250 K, what is its emissive power?

12.59 The spectral emissivity of an opaque, diffuse surface is as shown.



(a) If the surface is maintained at 1000 K, what is the total, hemispherical emissivity?

(b) What is the total, hemispherical absorptivity of the surface when irradiated by large surroundings of emissivity 0.8 and temperature 1500 K?

(c) What is the radiosity of the surface when it is maintained at 1000 K and subjected to the irradiation prescribed in part (b)?

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