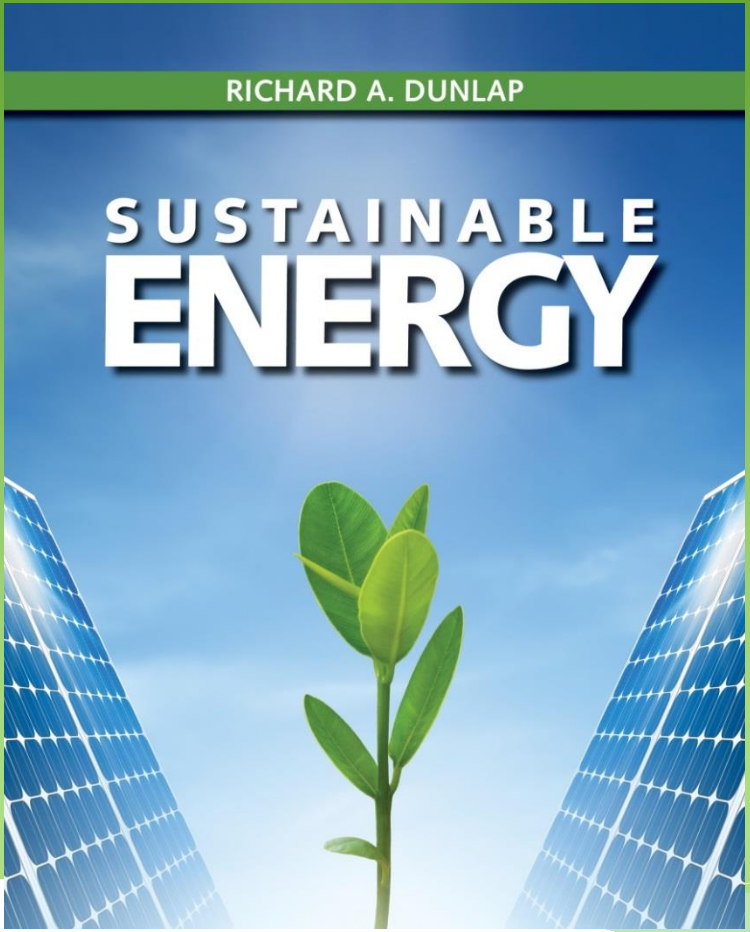
Sustainable Energy



Chapter 8

- Direct Use of Solar Energy

Learning Objectives

- The energy content and properties of the sunlight incident on the earth.
- The mechanisms for heat transfer.
- Conductive heat transfer through materials and the use of *R*-values.
- Radiative heat transfer from surfaces.
- The design and operation of a thermal solar collector.
- The energy requirements for residential space heating.
- The description of heating needs on the basis of degree days.
- The storage of thermal energy and the heat capacity of solids.
- The use of passive solar heating techniques as a component of residential heating needs.

The solar constant

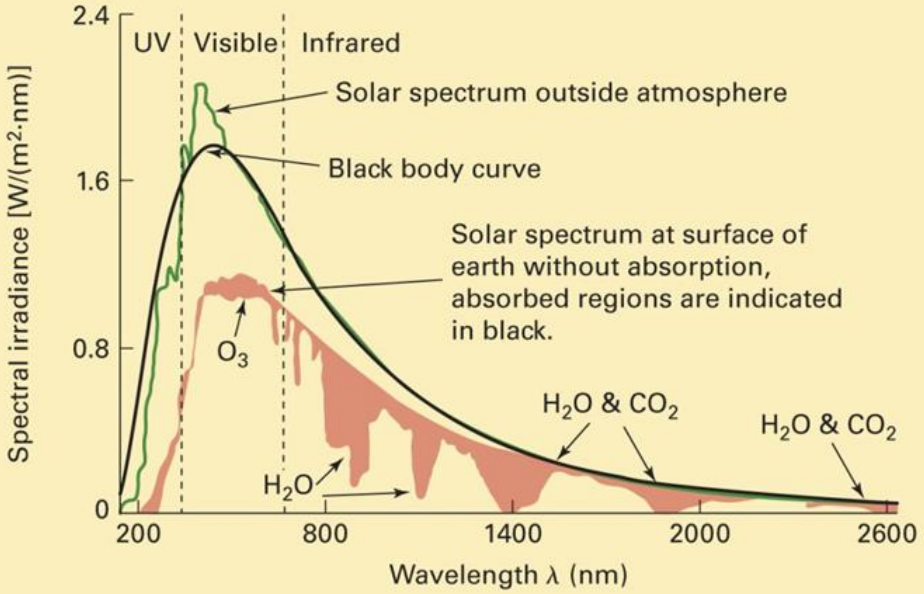
The solar constant is the power density of the sun's radiation at a distance of the earth's orbit.

The solar constant is calculated as the total power radiated by the sun divided by the surface area of a sphere at the earth's orbit

$$\frac{P}{A} = \frac{3.8 \times 10^{26}\,\mathrm{W}}{4\pi \times (1.49 \times 10^{11}\,\mathrm{m})^2} = 1367\ \mathrm{W/m^2} \qquad \textbf{(8.1)}$$

The solar radiation outside the earth's atmosphere is approximated by a black body radiation curve at 6000 K.

Absorption in the atmosphere



Based on G. Li et al. "Recent Progress in Modeling, Simulation, and Optimization of Polymer Solar Cells" Photovoltaics, an IEEE Journal, 2 (2012) 320–340 AND http://www.itacanet.org/the-sun-as-a-source-of-energy/part-2-solar-energy-reaching-the-earths-surface/

Figure 8.1: The solar spectrum.

The earth's atmosphere reflects and absorbs solar radiation.

Certain molecular species in the atmosphere absorb at specific wavelengths.

Average insolation

The total radiation on the earth solar constant times the cross sectional area of the earth's disk

$$P_{\text{total}} = (1367\ \text{W/m}^2) \times 3.14 \times (6.371 \times 10^6\text{m})^2 = 1.73 \times 10^{17}\ \text{W} \qquad \textbf{(8.2)}$$

About half of this is absorbed or reflected by the earth's atmosphere.

The average (horizontal) insolation is the incident radiation arriving at the earth's surface divided by the total area of the earth

$$\frac{P}{A} = \frac{0.5 \times 1.73 \times 10^{17}\text{W}}{4\pi \times (6.371 \times 10^6\ \text{m})^2} = 168\ \text{W/m}^2 \qquad \textbf{(8.3)}$$

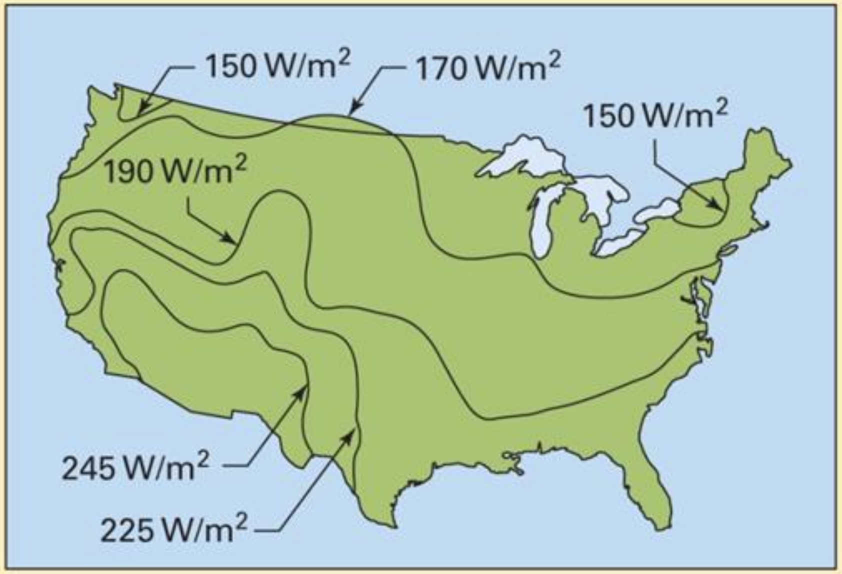
Distribution of insolation

The insolation at a given point on the earth's surface depends on factors such as

- The time of day
- The day of the year
- The latitude

The average insolation at a particular location also depends on average weather conditions

Average insolation in the United States



U.S. Department of Energy

Figure 8.2: Yearly 24-hour averages of insolation on a horizontal surface for the United States.

Yearly 24 hour average insolation in the United States

Heat transfer

In order to understand the design of solar collectors we need to understand how heat is transported.

Heat transport can be by

- Conduction
- Convection
- Radiation

Conduction

Heat transfer by conduction through a piece of material depends on

- The temperature difference across the material (T_h - T_c)
- The cross sectional are of the material *A*
- The thickness of the material *l*
- The thermal conductivity of the material *k*

$$P = \frac{kA(T_h - T_c)}{l} \qquad (8.4)$$

Units

In British units

T in °F
A in ft^2
l in inches
k in (Btu•in)/(h•ft^2•°F)

P in Btu/h

Metric (SI) units

T in °C or K
A in m^2
l in cm
k in $(\mathrm{W}\bullet\mathrm{cm})/(\mathrm{m}^2\bullet{}^\circ\mathrm{C})$

P is in W

R-values

Power per unit area is expressed as

$$\frac{P}{A} = \frac{T_h - T_c}{R} \qquad (8.5)$$

where $R = l/k$ and has units

British system (h•ft^2•°F)/Btu
SI system (m^2•°C)/W

Thermal conductivities of some common building materials

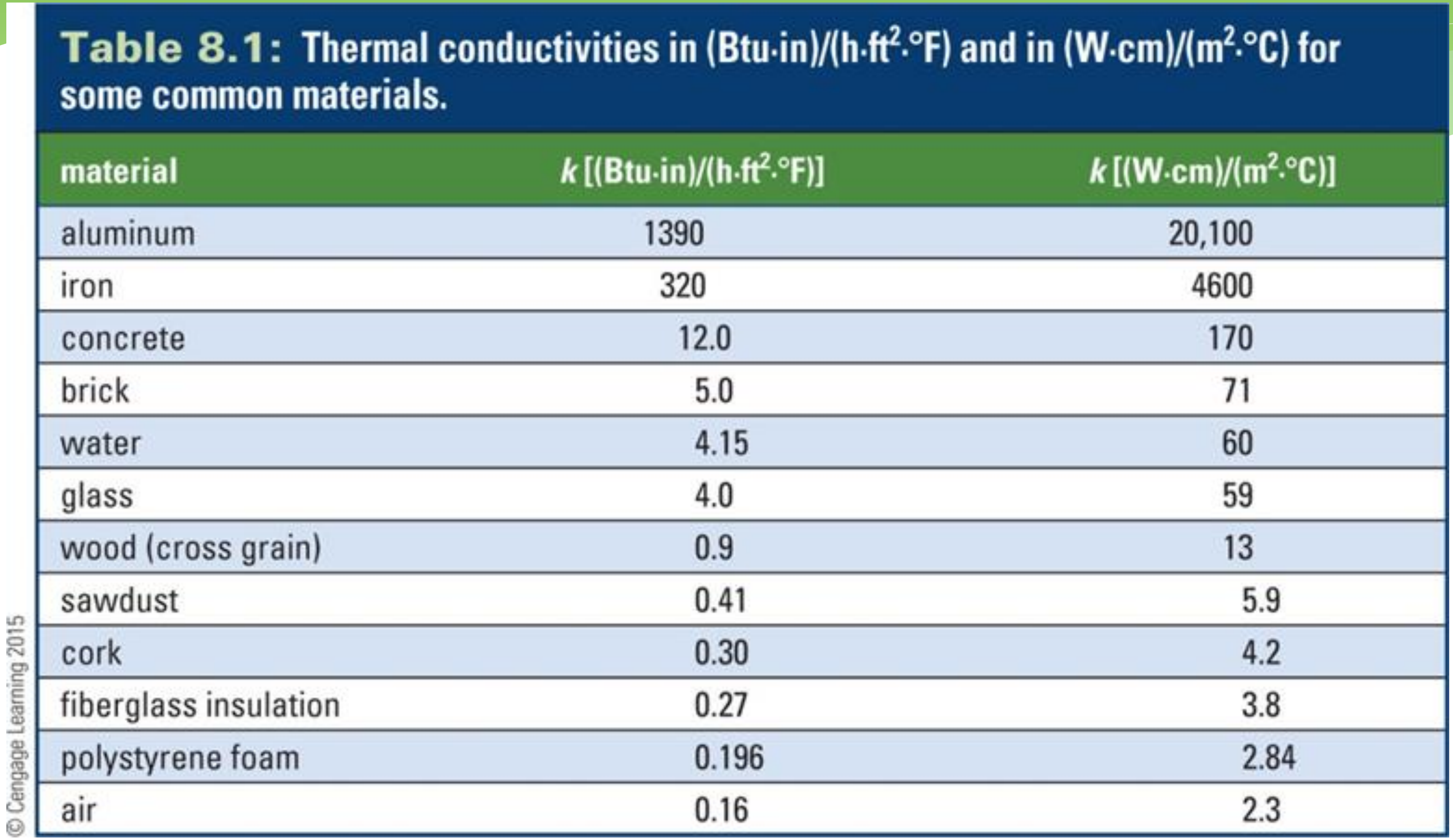


Table 8.1: Thermal conductivities in (Btu·in)/(h·ft^2·°F) and in (W·cm)/(m^2·°C) for some common materials.

material	*k* [(Btu·in)/(h·ft^2·°F)]	*k* [(W·cm)/(m^2·°C)]
aluminum	1390	20,100
iron	320	4600
concrete	12.0	170
brick	5.0	71
water	4.15	60
glass	4.0	59
wood (cross grain)	0.9	13
sawdust	0.41	5.9
cork	0.30	4.2
fiberglass insulation	0.27	3.8
polystyrene foam	0.196	2.84
air	0.16	2.3

© Cengage Learning 2015

Addition of *R*-values

R-values are additive for materials (i.e. walls) comprised of several layers

$$R_{\text{total}} = R_1 + R_2 + R_3 + R_4 + \ldots \tag{8.6}$$

Convection

Convection is the transport of thermal energy by air movement.

This is a very complex problem and is not considered quantitatively in this course.

Radiation

All objects at a temperature above absolute zero radiate energy according to the Stefan-Boltzmann law. For a perfect black body the total radiation is

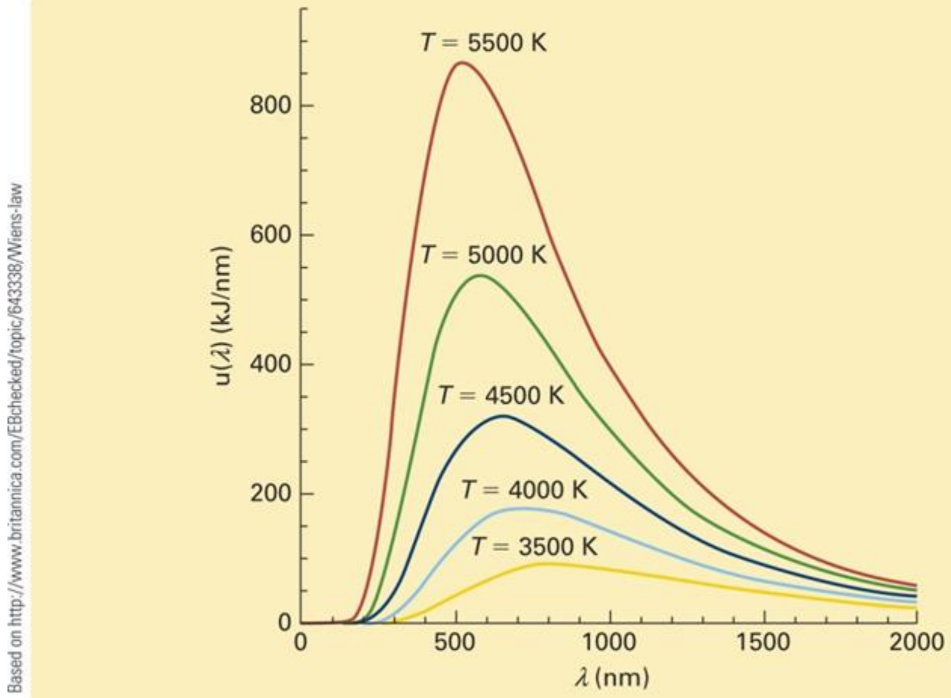
$$\frac{P}{A} = \sigma T^4 \qquad (8.7)$$

For an object that is not a perfect black body

$$\frac{P}{A} = \varepsilon\sigma T^4 \qquad (8.8)$$

Most common materials have emissivities of around $\varepsilon=0.9$.

Wavelength dependence of black body radiation



Based on http://www.britannica.com/EBchecked/topic/643338/Wiens-law

Figure 8.4: Wavelength dependence of black body radiation for surfaces at different temperatures. The vertical axis, u(λ), give the energy density as a function of wavelength.

Solar space heating

Solar space heating may be accomplished using

- an active system consisting of a solar collector which heats a working fluid which is circulated to heat a building

- a passive system which heats the interior of the building directly as a result of building design and placement

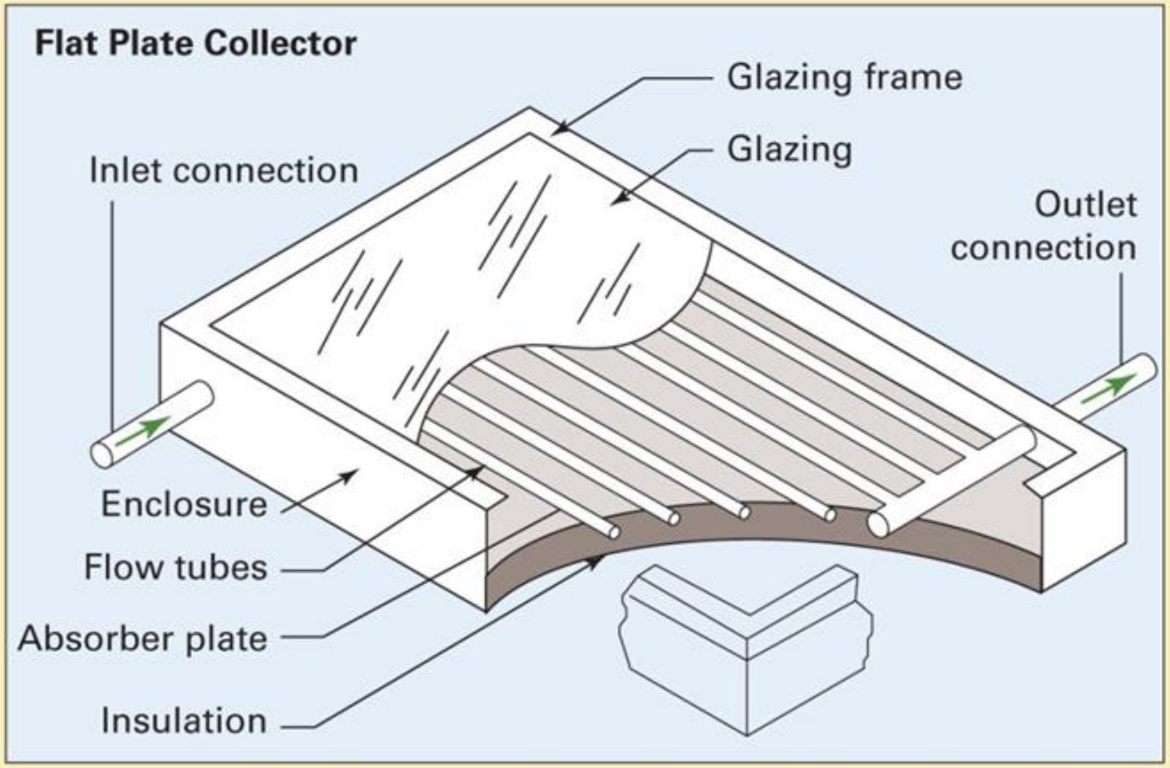
Solar collectors

Typical flat plate solar collector

Richard A. Dunlap

Figure 8.5: Flat plate solar collector installation.

Solar collector design



U.S. Department of Energy

Figure 8.6: Design of a flat plate solar collector.

Solar collector design

Features of a solar collector

- insulated box
- transparent cover
- absorbing plate
- pipes to carry working fluid

Principles of operation

Solar radiation enters through the transparent cover and is absorbed by the plate which heats and transfers heat to the working fluid.

Absorbed radiation is at short wavelength characteristic of the black body temperature of the sun (about 500 nm).

Energy re-irradiated from the plate is long wavelength characteristic of a black body at the operating temperature of the collector (about 8000 nm).

Minimizing energy loss

Energy loss is minimized by two mechanisms

- conduction is minimized by insulation behind the plate
- radiative losses are minimized if the transparent cover is transparent to short wavelength radiation and opaque to long wavelength radiation

Characteristics of a suitable glazing material

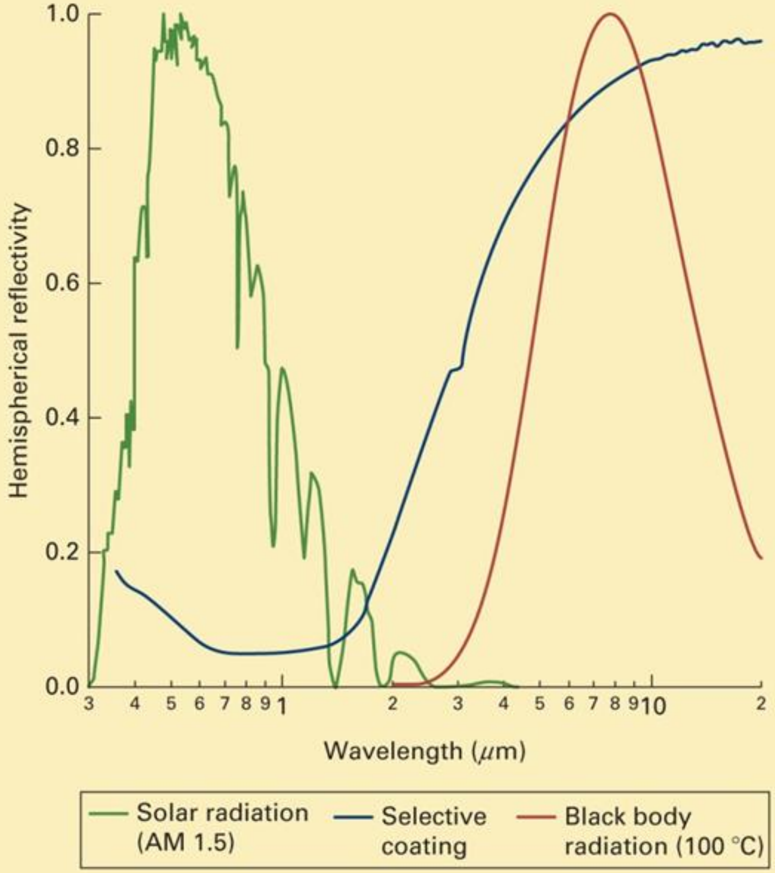


Figure 8.7: Measured reflectance of a suitable solar collector coating material relative to the solar spectrum (AM 1.5) and the black body curve at 100°C (373 K).

Based on P. Oelhafen and A. Schüller, "Nanostructured materials for solar energy conversion," Solar Energy 79 (2005) 110–121.

Availability of solar energy

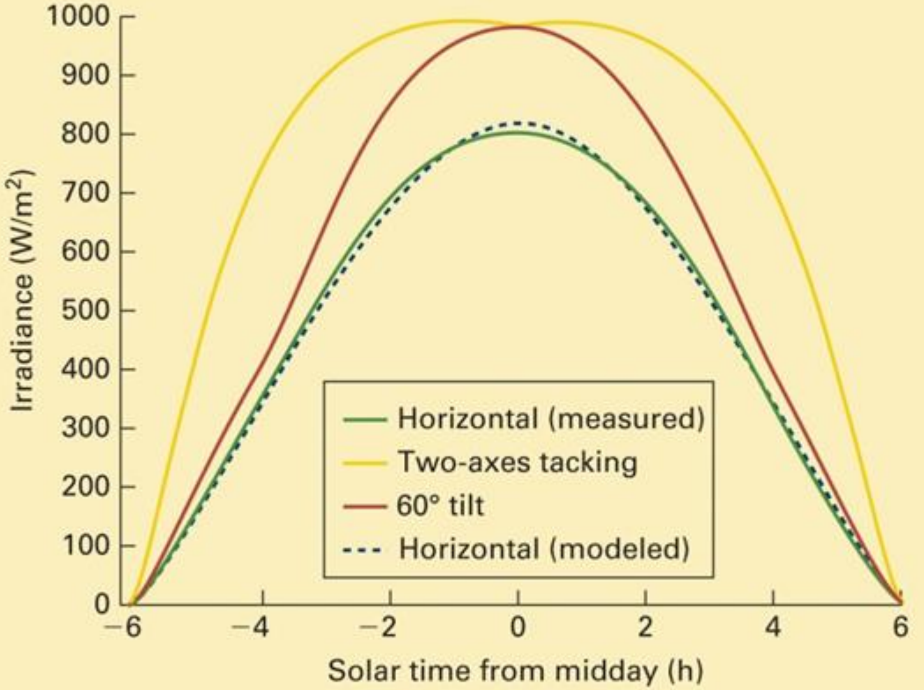
Available solar energy per unit collector area depends on

- Geographic location
- Time of year
- Orientation of the collector

Collector orientations

- horizontal
- vertical (facing south in Northern Hemisphere)
- tilted at optimal angle (facing south in Northern Hemisphere)
- tracking

Relationship of energy and collector orientation



Based on F. Cruz-Peragón, P.J. Casanova-Peláez, F.A. Díaz, R. López-García and J.M. Palomar, "An approach to evaluate the energy advantage of two axes solar tracking systems in Spain," Applied Energy 88 (2011) 5131–5142.

Figure 8.8: Power per unit area incident on a solar collector for different orientations.

Daily insolation as a function of time of year and collector orientation

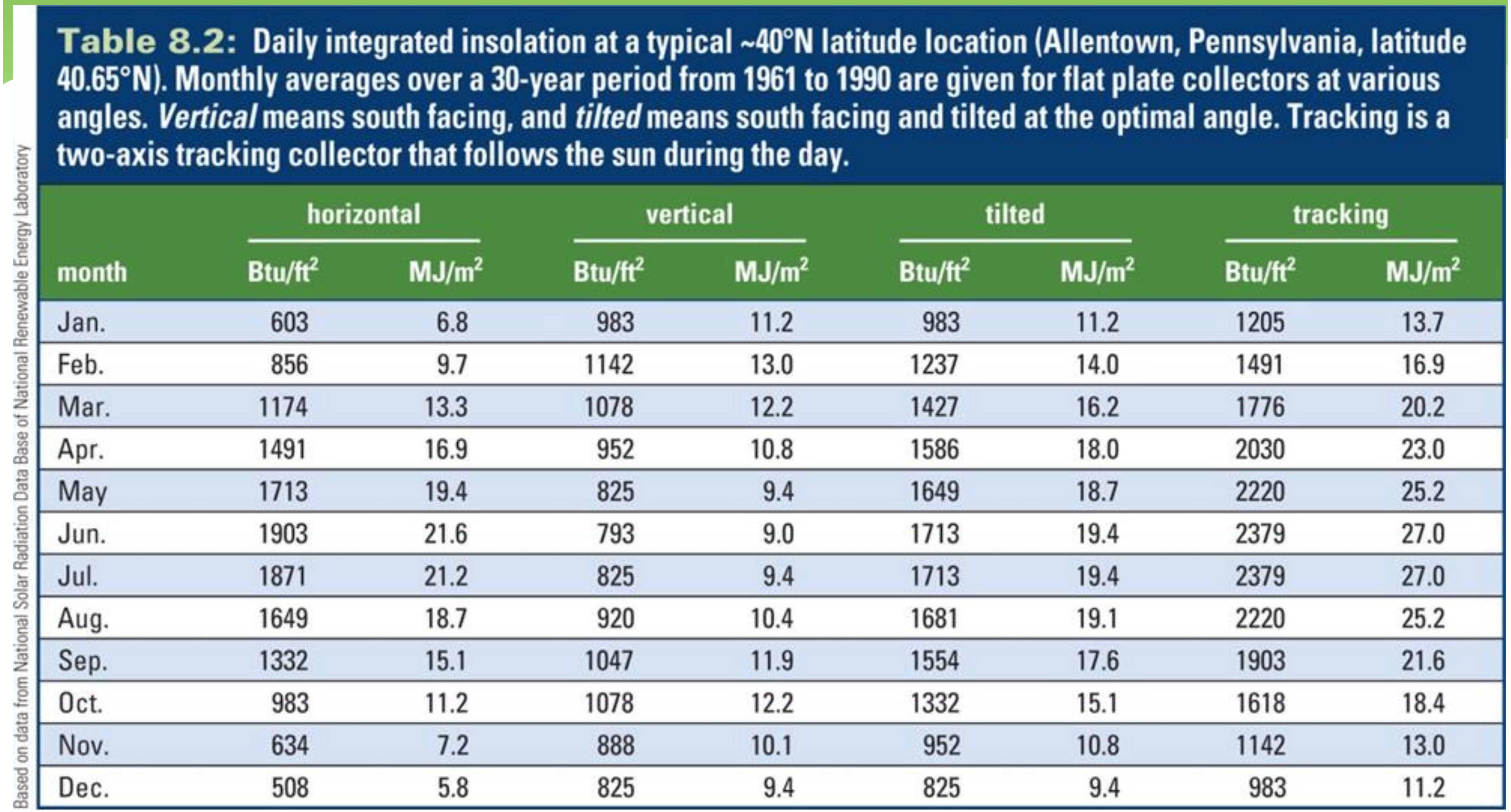


Table 8.2: Daily integrated insolation at a typical ~40°N latitude location (Allentown, Pennsylvania, latitude 40.65°N). Monthly averages over a 30-year period from 1961 to 1990 are given for flat plate collectors at various angles. *Vertical* means south facing, and *tilted* means south facing and tilted at the optimal angle. Tracking is a two-axis tracking collector that follows the sun during the day.

	horizontal		vertical		tilted		tracking	
month	Btu/ft^2	MJ/m^2	Btu/ft^2	MJ/m^2	Btu/ft^2	MJ/m^2	Btu/ft^2	MJ/m^2
Jan.	603	6.8	983	11.2	983	11.2	1205	13.7
Feb.	856	9.7	1142	13.0	1237	14.0	1491	16.9
Mar.	1174	13.3	1078	12.2	1427	16.2	1776	20.2
Apr.	1491	16.9	952	10.8	1586	18.0	2030	23.0
May	1713	19.4	825	9.4	1649	18.7	2220	25.2
Jun.	1903	21.6	793	9.0	1713	19.4	2379	27.0
Jul.	1871	21.2	825	9.4	1713	19.4	2379	27.0
Aug.	1649	18.7	920	10.4	1681	19.1	2220	25.2
Sep.	1332	15.1	1047	11.9	1554	17.6	1903	21.6
Oct.	983	11.2	1078	12.2	1332	15.1	1618	18.4
Nov.	634	7.2	888	10.1	952	10.8	1142	13.0
Dec.	508	5.8	825	9.4	825	9.4	983	11.2

Based on data from National Solar Radiation Data Base of National Renewable Energy Laboratory

Effects of climate on residential heating needs

The effect of climate is quantified by the use of degree days.

1 degree day is a period of 1 day during which the outside temperature is 1 degree lower that an established inside temperature.

- In British units degree days are measured on the Fahrenheit scale relative to 65 °F
- In SI units degree days are measured on the Celsius scale relative to 18.3 °C

Annual heating requirements are determined on the basis of the total number of degree days per year.

Example of degree days

If the average daily outside temperature is 10 °F, then that day would contribute

(65 °F - 10 °F) = 50 °F degree days

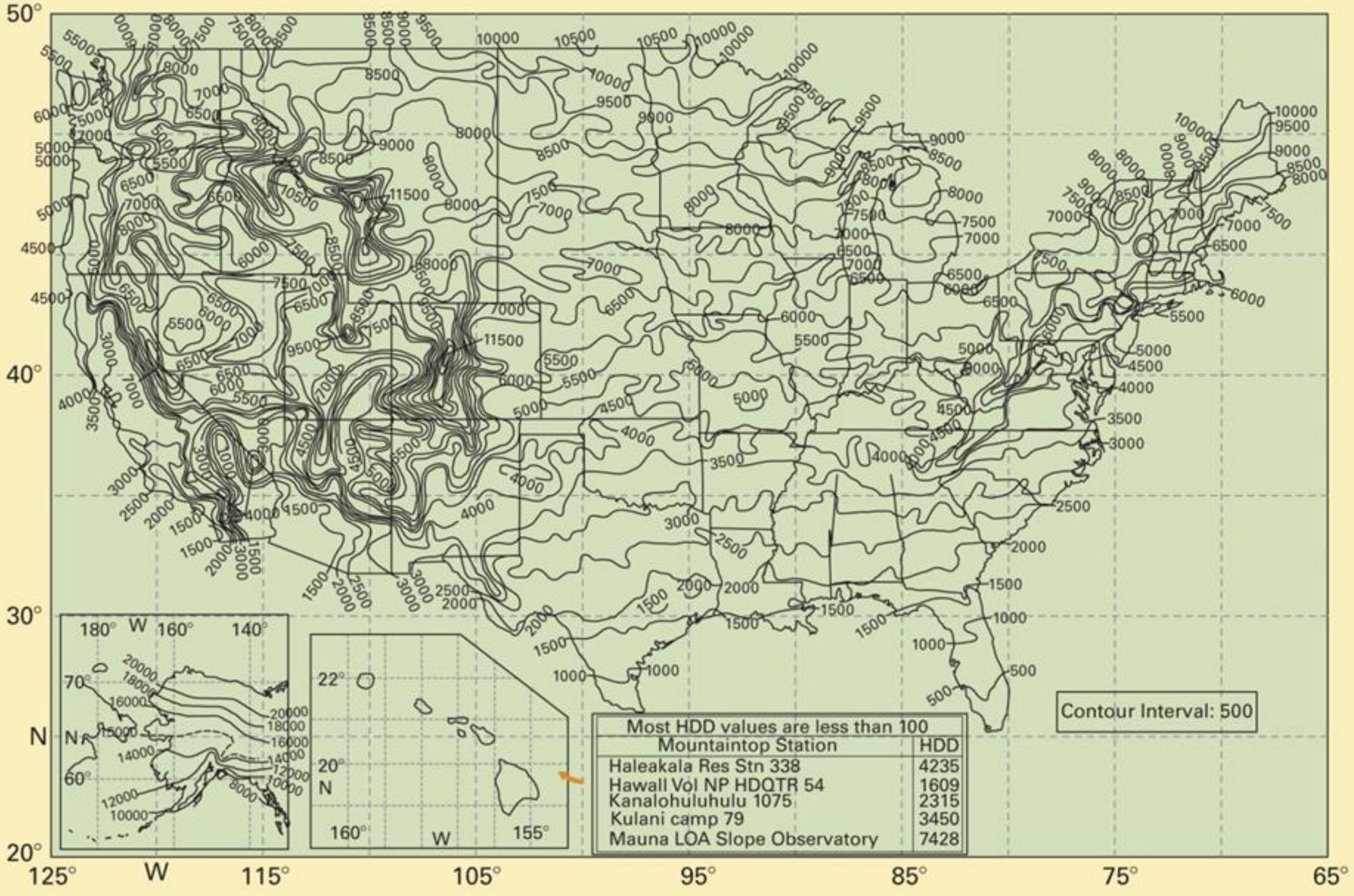
towards the yearly total.

If the average daily outside temperature is -5 °C, then that day would contribute

(18.3 °C - (-5 °C) = 23.3 °C degree days

towards the yearly total.

Degree days in the United States in °F

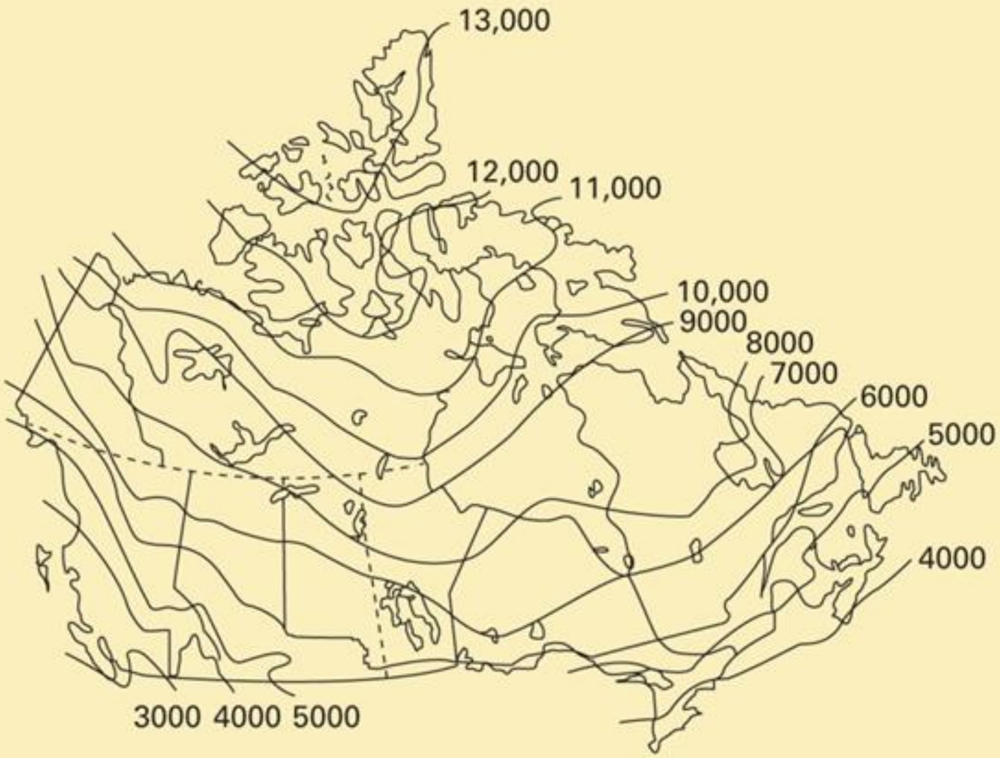


Most HDD values are less than 100 Mountaintop Station	HDD
Haleakala Res Stn 338	4235
Hawall Vol NP HDQTR 54	1609
Kanalohuluhulu 1075	2315
Kulani camp 79	3450
Mauna LOA Slope Observatory	7428

National Oceanic and Atmospheric Administration (NOAA)

Figure 8.9: Map of the United States showing the number of heating degree days (in °F) per year (average of period 1961–1990).

Degree days in Canada in °C



From Hunt, Energy, Physics and the Environment, 3E. © 2007 Cengage Learning.

Figure 8.10: Map of Canada showing the number of heating degree days (in °C) per year.

Degree days for North American cities

city		heating degree days per year	
		(ºF)	(ºC)
Miami	FL	155	86
San Francisco	CA	2614	1452
New York	NY	4735	2635
Philadelphia	PA	4759	2644
Vancouver	BC	5267	2926
Boston	MA	5630	3128
Denver	CO	6127	3404
Toronto	ON	7319	4066
Minneapolis	MN	7882	4379
Winnipeg	MB	10,399	5777
Anchorage	AK	10,471	5817

Residential heating requirements

U.S. Federal Housing Authority (1972) established a benchmark for heating requirements

$$1\ \text{Btu/ft}^3 \text{ per degree day } (°\text{F})$$

or

$$67\ \text{kJ/m}^3 \text{ per degree day } (°\text{C})$$

Annual heating requirement example

Heating requirements for a 2600 ft^2 home with 9 ft ceilings in Philadelphia

Volume of house $(2600\ ft^2)\times(9\ ft) = 23{,}400\ ft^3$

Number of degree days in Philadelphia 4759 degree days (°F)

Heating requirements

$(1\ Btu/ft^3)\times(23{,}400\ ft^3)\times(4759) = 1.11\times10^9\ Btu$

Daily heating requirements example

Daily heating requirements for a 2600 ft^2 home with 9 ft ceilings for an outside temperature of 20 °F

Volume of house: $(2600\ ft^2)\times(9\ ft) = 23,400\ ft^3$

Daily heating requirement:

$(1\ Btu/ft^3)\times(23,400\ ft^3)\times(65\ °F - 20\ °F) = 1.05\times10^5\ Btu$

Solar collector requirements

To collect (say) 60% (about 600,000 Btu) of the daily energy as above with an optimally tilted collector for a home located at 40° in February, the collector requirements are as follows:

The daily insolation is about 1200 Btu/ft^2 and a typical collector efficiency is about 50%, so the required collector would have an area of

$$\frac{6.0 \times 10^5\ \text{Btu}}{1200\ \text{Btu/ft}^2 \times 0.5} = 1000\ \text{ft}^2 \qquad (8.10)$$

Heat storage

As solar radiation is not consistent throughout the day heat must be store to make the most effective use of this energy source.

Material may be heated during the day and heat extracted from that material during the night.

Heat available is

$$Q = Cm(T_\mathrm{i} - T_\mathrm{f}) \tag{8.11}$$

Thermal properties of some common materials

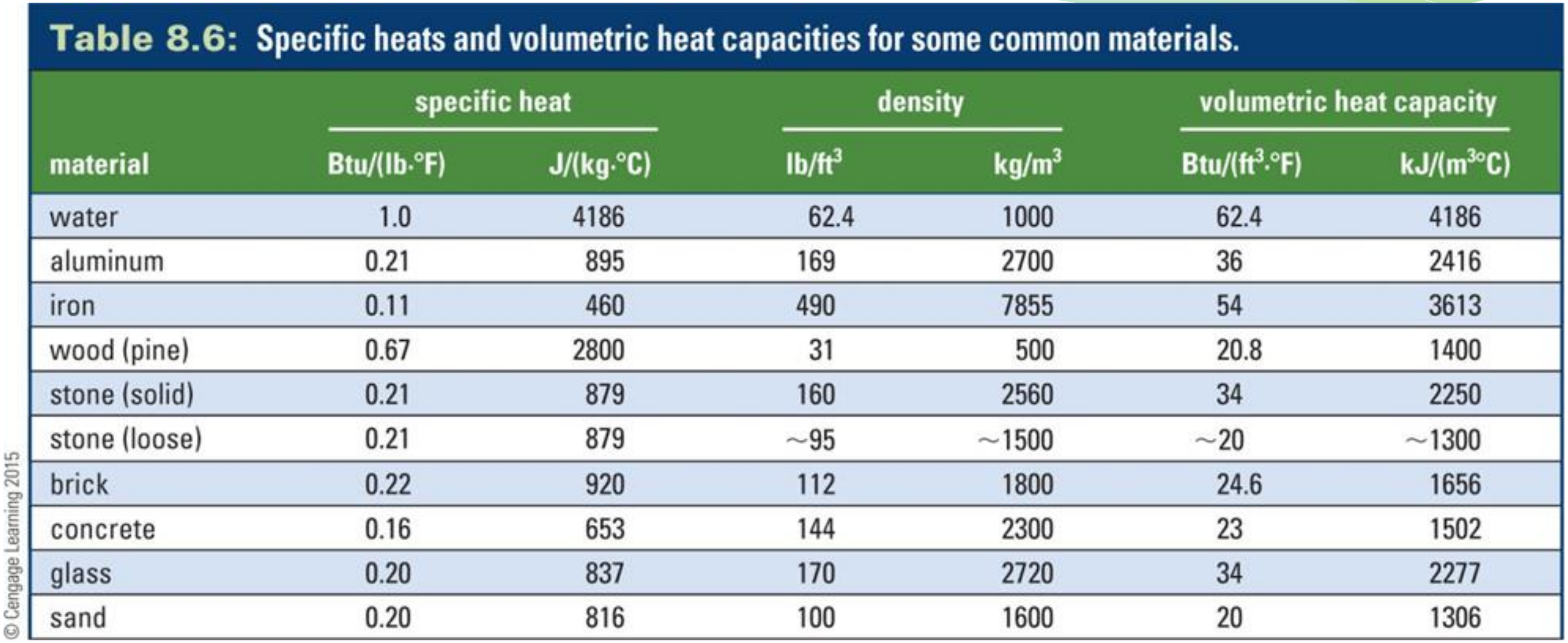


Table 8.6: Specific heats and volumetric heat capacities for some common materials.

	specific heat		density		volumetric heat capacity	
material	Btu/(lb·°F)	J/(kg·°C)	lb/ft^3	kg/m^3	Btu/(ft^3·°F)	kJ/(m^3°C)
water	1.0	4186	62.4	1000	62.4	4186
aluminum	0.21	895	169	2700	36	2416
iron	0.11	460	490	7855	54	3613
wood (pine)	0.67	2800	31	500	20.8	1400
stone (solid)	0.21	879	160	2560	34	2250
stone (loose)	0.21	879	~95	~1500	~20	~1300
brick	0.22	920	112	1800	24.6	1656
concrete	0.16	653	144	2300	23	1502
glass	0.20	837	170	2720	34	2277
sand	0.20	816	100	1600	20	1306

© Cengage Learning 2015

Daily heating requirements

Calculate the energy required to heat a home of 575 m^3 when the average outside temperature is -10 °C

(18.3 °C - (-10 °C)) = 28.3 degree days (°C)

Heating requirement

$(67\ kJ/m^3)\times(575\ m^3)\times(28.3) = 1.09\times10^9\ J$

Heat storage requirement

To store the energy calculated above in water with maximum and minimum temperatures of 65 °C and 35 °C (respectively) requires a mass of

$$m = \frac{Q}{c\Delta T} \qquad (8.13)$$

or

$$m = \frac{1.09\times10^{9}\ \mathrm{J}}{(4186\ \mathrm{J/(kg\cdot{}^{\circ}C)})\times(35{}^{\circ}\mathrm{C})} = 7.4\times10^{3}\ \mathrm{kg}.$$

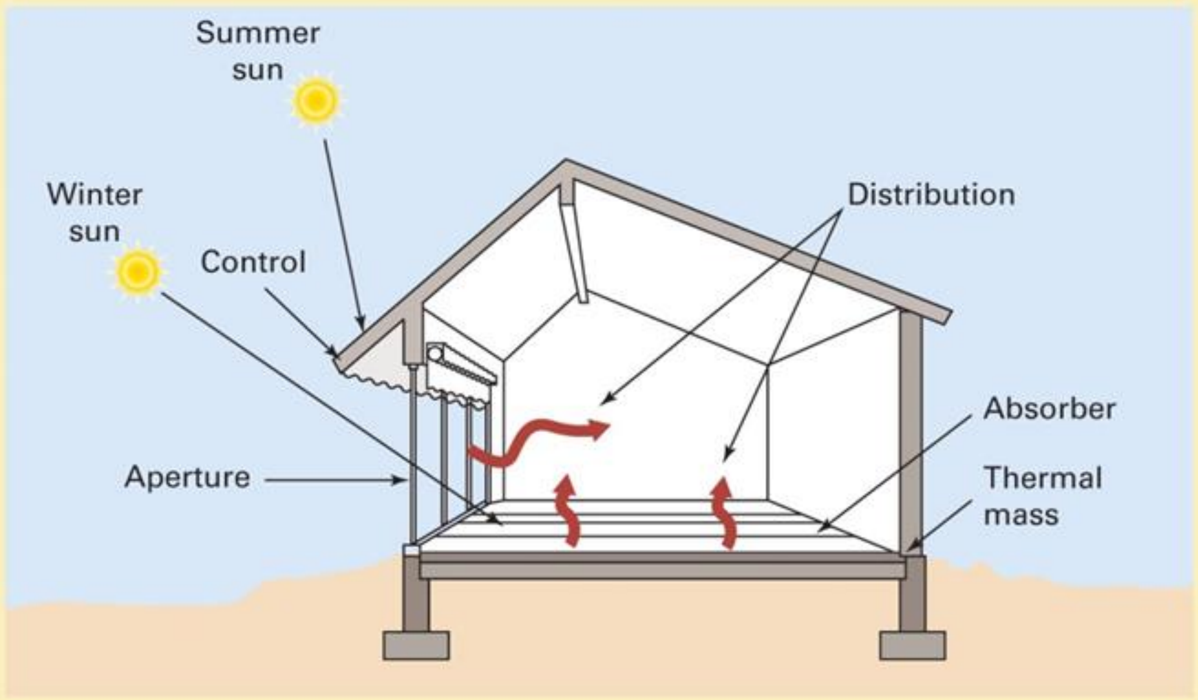
Passive solar heating

Building design incorporates large windows oriented to optimize insolation.

May also include floors or other building components to optimize absorption of radiation during the day and re-irradiation during the night.

Building geometry may also optimizes heating during the winter and minimized heating during the summer.

Passive solar heating building design



Based on http://www.energysavers.gov/your_home/designing_remodeling/index.cfm/mytopic=10270

Figure 8.12: Method of utilizing solar heating during the winter and reducing solar heating during the summer.

Summary

- Average horizontal insolation on the earth is 168 W/m^2
- Conductive heat transfer is described in terms of the *R*-value of the material
- Radiative heat transfer is described by the Stefan-Boltzmann law
- Solar space heating may be active or passive
- Typical active solar heating system utilizes a flat plate collector
- Heating requirements are determined by building characteristics and climate
- The effects of climate are quantified using degree days
- The periodic nature of sunlight requires a heat storage system to optimize the use of solar heating
- Passive solar systems require appropriate building design and orientation