CHAPTER 32

Solar Physics

INTRODUCTION 32.1

As you awake one morning, a cheery radio weather presenter announces:

> The weather forecast this morning is for moderate to high temperatures, sunlight early yielding 620 watts per square metre rising to 980 watts per square metre on the coast and 1100 watts per square metre inland. Those in southern regions will require battery reserves.

In the future, this scenario could prove true for communities that have their electrical power generation supplemented by solar energy. The Earth's star is a self-sustaining nuclear fusion reactor whose output is an incredible 4×10^{26} W, of which central Australia receives only about 1.0×10^{3} W m^{-2} on the ground. If the nuclear reactions in the Sun's core were to be switched off now, it would be 10 million years before the outer solar surface started to cool and before the Earth would feel the effects. Such is the power of the Sun!

Even animals are affected by solar processes. On 7 July 1988, 3000 homing pigeons were released from cages in northern France for their annual race back home towards southern England. Two days before, unusual solar flare activity had sent vast clouds of charged protons and subatomic particles into space, some of which disrupted the Earth's magnetic field patterns. In poor weather the pigeons used internal magnetic compasses to guide them. Misled by the solar disturbances caused to the Earth's magnetism, the pigeons flew way off course. Most of the 3000 never returned!

Solar physics is the study of the Sun's energy processes and the ways in which modern technology can use both its heat and its light. One of the best examples of solar technology assisting engineering was the feat of American aeronautical engineer Paul MacCready, who designed the famous *Solar challenger* human-powered aircraft. In July 1981, Steve Ptacek pedalled this aircraft, whose wings were covered with solar cells on their upper surfaces, over 262 km from Cormeilles en Vexin near Paris, across the English Channel to Manson in Kent.

In this chapter we will look at the Sun itself, the major methods of obtaining energy from the Sun, both passively and actively, as well as one of the main dangers to the health of all Australians, namely, ultraviolet radiation.

SOLAR RADIATION 32.2

The Sun as a star

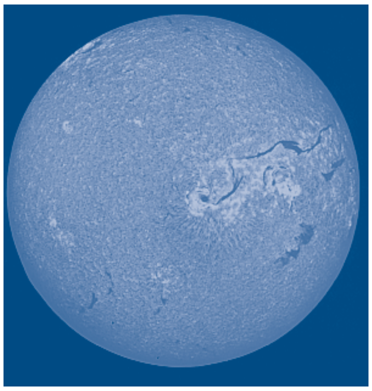
Our Sun, called *Sol*, dominates the planetary system that includes the Earth. The Sun provides the input energy for most of the food webs that make up our natural environment. The Sun radiates energy at the tremendous rate of 4.0×10^{26} W, of which the Earth receives approximately 1.8×10^{17} W at its outer atmosphere. About half of this actually reaches the ground and provides the driving energy for our climate and weather systems as well as the photosynthetic requirements of plants as the food chain producers.

The Sun has been studied scientifically since the time of Galileo (1611), who used the first telescopes to discover sunspots on its surface. Table 32.1 lists the physical data of the Sun. It is a very average star by comparison with those in the rest of the universe and is about half-way through its lifespan — middle-aged you might say, with only about 4.5 billion years left to keep radiating its energy. Our next nearest stellar neighbour is the bright star in the Centaur*us* (pointers) constellation called Alpha Centauri, at 4.3 light-years distance.

Table 32.1 SOLAR DATA

Diameter	1.39×10^9 m	Spectral type	G
Mass	1.99×10^{30} kg	Mean distance	149 597 000 km (8.3 light-minutes)
Specific gravity	1.409	Rotation period (equatorial)	25.38 days
Axial inclination	7° 15′	Absolute magnitude	+4.71
Effective temperature (black body)	5800 K	Escape velocity	617.5 km s^{-1}

Photo 32.1
Sun's surface features.



In 1814 the German physicist Joseph von Fraunhofer used a spectroscope to break the Sun's light radiation up into its component wavelengths and examined it carefully. Recall that Isaac Newton had also performed spectral dispersion with a prism as early as 1666. Fraunhofer's spectral analysis enabled an explanation of the solar atmosphere. He found that the continuous emission spectrum of the Sun was crossed by a complex set of dark lines. It was Gustav Kirchhoff in 1859 who showed that these dark **Fraunhofer lines** were actually absorption lines caused by atoms present in the low pressure solar atmosphere lying between the Sun's source of light, called the **photosphere**, and the experimental observer. By comparing these lines with the emission spectra of known elements on Earth, it was shown that the Sun itself contains most of the known elements. The inert gas helium was named because of this. In 1889 the American astronomer George E. Hale invented the spectroheliograph (Greek *helios* = 'Sun'), which enabled the Sun to be studied in the light emitted by one element alone, such as the light of hydrogen or calcium. Today, spectral filters can do much the same job.

Like all stars, the Sun is composed mostly of hydrogen, together with helium (27%) and other heavy elements (2%). At the core of the Sun, the temperature is 16 000 000 K and has a density about 150 times that of water. In these conditions hydrogen nuclei fuse to produce helium via reactions called **nuclear fusion**. The solar nuclear fusion process is actually a series of three collisions between atomic particles called the 'proton–proton cycle'. The three collision processes are not of equal probability but end up fusing four hydrogen nuclei (protons) into one helium nucleus. As the final helium nucleus is only 99.3% as massive as the original four protons the missing energy appears as gamma rays and a neutrino according to Einstein's $E = mc^2$ formula. The neutrino is totally unreactive and escapes the Sun very quickly, while the gamma rays may bounce around internally for millions of years. Even though the timescale for the proton–proton cycle is large, the staggering number of particles in the Sun means a massive amount of total energy is continuously released via gamma rays that radiate outward toward the convection layers of the Sun. It is in this outer one-third of the Sun's volume that large-scale convective turbulence not only reduces the temperature but produces most of the Sun's radiation energy. The photosphere is the top surface of these convection cells, which give it a mottled appearance called **solar granulation**. The granulated cells on the photosphere last typically for 5–15 minutes and are about 2000 km in diameter. The temperature of the photosphere is about 6000°C. The German-born American physicist Hans Bethe was awarded the 1967 Nobel prize for physics for his work on the fusion cycle reactions that are the source of the Sun's tremendous energy production.

Sunspots

Sunspots are smaller regions of the photosphere that are, on average, 2000°C cooler than their surroundings and depressed into the surface slightly. They tend to occur in pairs. In 1908 George E. Hale discovered that they contain very strong magnetic fields, with each pair containing magnetic flux that points in opposite directions, either into or out of the Sun's interior. A sunspot cycle occurs, in which the number of sunspots varies from a maximum to a minimum over an 11-year cycle. As a new 11-year cycle begins, the magnetic polarity of the leading sunspot of each pair in each hemisphere of the Sun's surface reverses. This represents a full solar cycle of 22 years. Sunspots forming early in the cycle in each hemisphere tend to start at higher latitudes (45°) than sunspots later in the cycle (10°). These cyclic changes seem to indicate a definite connection between the Sun's magnetic field, the convection zone in the Sun's outer layers, and the Sun's rotation period itself, which is faster at its equator than at its poles.

Solar flares and prominences

The Sun's **chromosphere** (Greek *chroma* = 'colour') rises to about 9600 km above the photosphere, with an average density about one thousand times less than the photosphere and a temperature of about 30 000 K. Elements in the chromosphere absorb light and produce the Fraunhofer lines in the Sun's emission spectrum. The upper layer is not uniform but produces **spicules** or high temperature gas plasma eruptions that are continuously penetrating the outer layer or **corona** (Greek *corona* = 'crown'). Because of the continuous agitation, plasma particles are being thrown off into space, causing the **solar wind**, which eventually reaches the Earth. Near sunspots the chromosphere radiation is more active, producing very rapid releases of magnetic energy and plasma particles called **solar flares**. Among the phenomena that accompany solar flares are intense X-rays, radio waves and other energetic particles that may also eventually reach the Earth to cause auroral displays and disrupt radio and telecommunications services.

The corona extends for several solar radii from the disc of the Sun itself. All the structural detail within the corona is due to the solar magnetic field. The corona is at a very high temperature of about 1 000 000°C indicating very high particle velocities. Occasionally, the corona traps low temperature plasma emissions on a large scale from the chromosphere. These produce **prominences**, which may extend out from the Sun's surface for hundreds of thousands of kilometres and are best seen during periods of solar eclipses at the edge of the Sun's disc. These prominences can also release tremendous numbers of particles into the solar wind. The largest recorded could have swallowed the Earth many times over.

Solar radiation at the Earth

The Earth receives a constant energy flow from the Sun of about 1.23×10^{17} W (122 500 TW). As the Earth gains thermal energy its temperature will rise but, like any hot body, its rate of energy emission also increases with temperature. If the received and emitted thermal energies were equal in wavelength this would lead to an average equilibrium temperature of about −17°C for the Earth. Fortunately, the Earth reradiates its thermal energy at much longer wavelengths, as shown in Figure 32.1. These longer wavelengths are absorbed by the atmospheric water vapour and carbon dioxide. This absorbed energy is reradiated with about 85% of it returning to further heat the Earth to an average global value of 15°C (288 K). This effect is called the **greenhouse effect** and without it most life forms on Earth would die. The commonly held view that the greenhouse effect is bad stems from a misunderstanding of the basic effect. Modern technology needs to be applied to reduce the emissions of greenhouse gases into the atmosphere. This will prevent an increase in the natural greenhouse effect, which would lead to a rise in average temperatures or **global warming**. The planet Venus has an atmosphere of dense carbon dioxide, which produces a surface temperature of 470°C through its natural greenhouse effect. Let us hope the Earth never gets to this point.

Figure 32.1
Solar and terrestrial energy emissions.

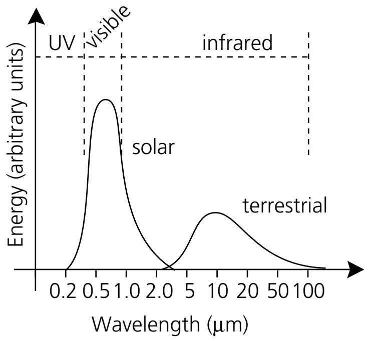
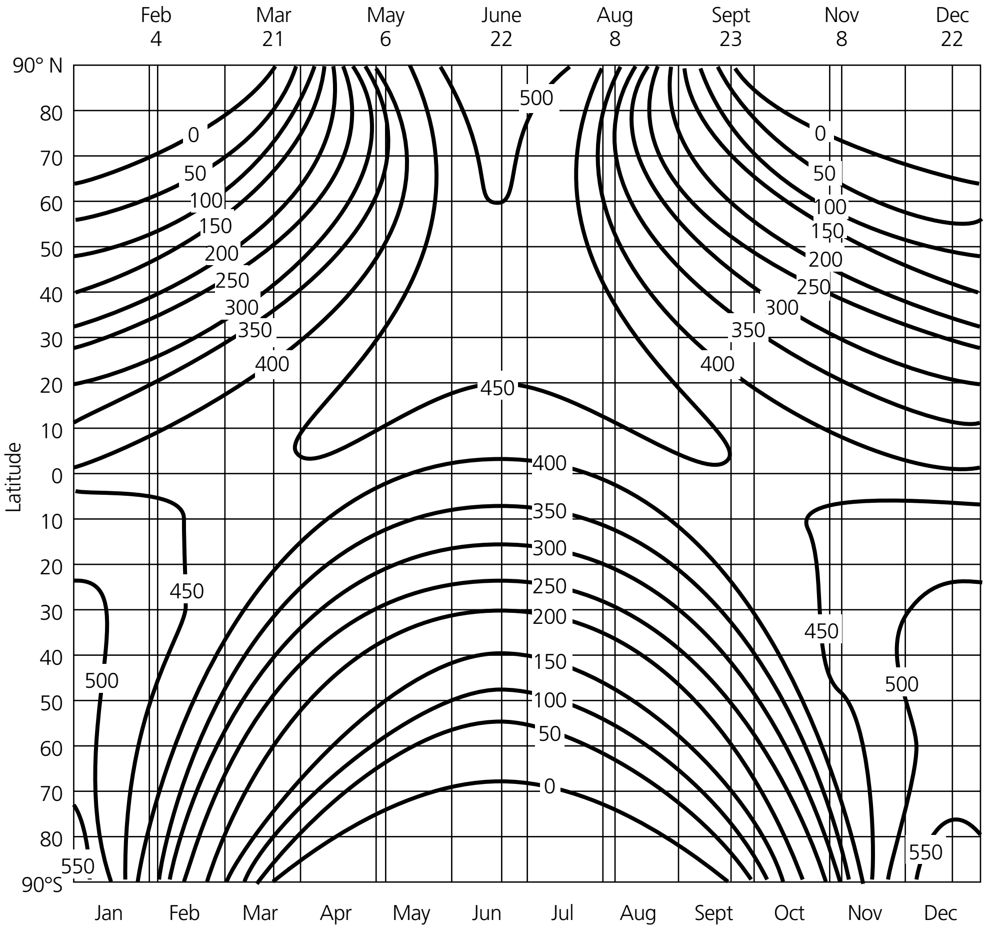


Figure 32.2
Variation of solar radiation.



The variation with latitude and time of year of the maximum amount of solar radiation (in kW m^{-2}) received on a horizontal surface at sea level

Figure 32.2 illustrates the variation with latitude and time of year of the maximum solar radiation received (kW m^{-2}) on a horizontal surface at sea level. The global average value is about 200 W m^{-2}. The lack of symmetry between the two hemispheres is due to the slight ellipticity of the Earth's orbit, which results in the shortest distance to the Sun (perihelion) occurring on 4 January and the greatest distance (aphelion) on 5 July. At any particular location the solar radiation flux is determined by the time of day, the season, and the geographical latitude. Weather provides an unpredictable element. Under clear skies the radiant energy will be mostly direct, with only about 15% being diffuse, while under overcast conditions, obviously 100% of the radiant energy is diffuse. Australia is particularly lucky, with its solar radiant energy flux being more direct and constant than most countries, with peak maxima rising as high as 1.4 kW m^{-2}.

In order to exploit solar energy, designers of solar devices must contend with several factors:

- relatively low power density available
- variation in the availability of solar radiation
- low efficiency of various conversion techniques to other energy forms such as direct thermal or electrical.

In the rest of this chapter, we will examine some of the ways in which solar energy can be converted into other forms. These will primarily be by **photothermal** techniques concerned with the active and passive collection of solar radiation as heat, and **photovoltaic** techniques concerned with the direct conversion of solar radiation into electricity.

Questions

1. If the average solar radiation at a Western Queensland location is 600 W m^{-2}, calculate the total solar collector area needed at this site to generate 100 MW, assuming solar–electrical conversion efficiency of 9%.
2. Explain the interaction of the solar radiation with the Earth's atmosphere that allows a global average temperature equilibrium of 15°C.
3. Greenhouse gases include carbon dioxide, methane, and nitrous oxide. Research their predominant sources, both artificial and natural, and comment on their effect on global warming.
4. List reasons for the fact that about 30% of incident solar radiation is reflected back into space from the Earth.
5. Discuss any link that exists between these three statements of fact:
   - The 1987 Montreal protocol called for a halving of chlorofluorocarbon (CFC) emissions by the end of the twentieth century.
   - Stratospheric ozone blocks incident ultraviolet solar radiation that is less than 300 nm in wavelength and dangerous to living organisms.
   - Since about 1975, marked ozone depletion has occurred in the stratosphere over Antarctica each spring — the 'ozone hole'.
6. Assume you are sunbathing at noon in summer when the direct solar radiation flux is 850 W m^{-2}. Estimate the total radiation incident on your body in 20 minutes. How would this change at a later time when the Sun is 50° above the horizon?
7. Using Figure 32.2, what is the difference in solar radiation received at a latitude of 60° on the date of 8 August in both hemispheres? What accounts for this difference?

PHOTOTHERMAL DEVICES

32.3

Architectural design

How often have you noticed the build-up of heat and general stuffiness of a closed room with sun shining into it through the windows? Have you ever used a magnifying glass to burn holes in paper? These two effects illustrate the **passive** and **active** aspects of solar heating. The term **photothermal** device is used to describe a device that passively or actively converts solar radiation into heat. Architects today are very interested in aspects of **passive solar design**, which uses the materials of the house itself as well as modifications to its surroundings to efficiently collect, store and distribute solar energy, thus allowing large electrical energy savings in the general heating and cooling systems. It represents a very natural approach.

Architects may also use **active solar design** systems, which typically use solar collectors for heating water, thermal masses such as rock-beds and Trombe walls, as well as forced ventilation of solar heated air. These will be discussed later in the chapter. The Australian CSIRO has been very active in solar design elements for general housing, as well as showing the way for larger industrial applications, such as hybrid solar/diesel power stations and solar power towers. At Highett, in Victoria, CSIRO maintains a low-energy-consumption home (LECH), which is used for solar principle demonstrations and practical research.

Consider Figure 32.3, which illustrates a range of passive solar design architectural aspects. Let us take each of the labelled parts in turn.

1 Considerably larger window area on the northern side This aims to catch sunlight in winter, and also, by incorporating verandahs, pergolas or overhang, to provide shade from the higher summer sun. In Queensland especially, even early colonial houses tended to have wide cooling verandahs. The roof design contains insulated fibreglass batts or loose fill in the ceiling with reflective aluminium foil against the undersides of the tiles. Note also the

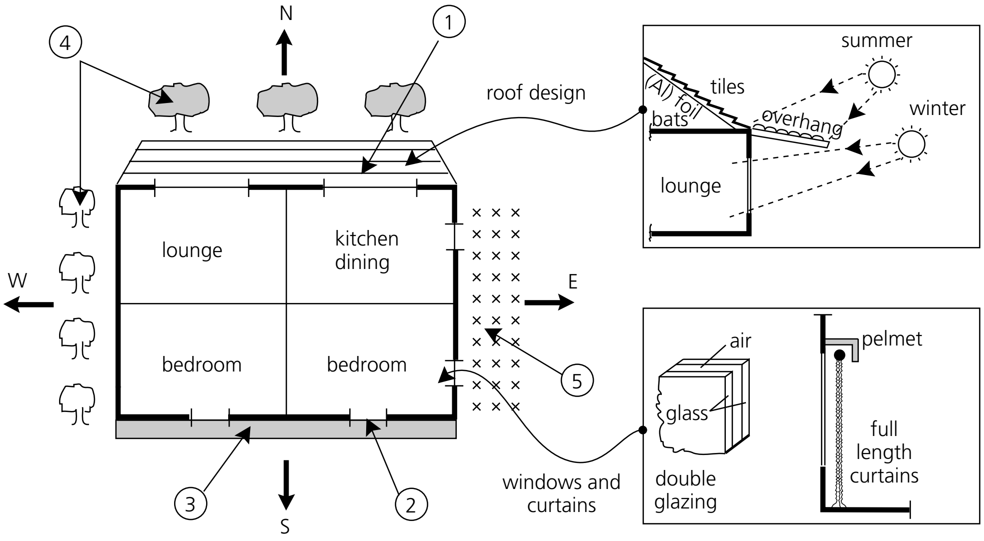


Figure 32.3
Passive solar design aspects for domestic housing.

general living areas of the house are on the northern side, while the bedrooms, for nightly warmth, are on the southern side.

2 Minimum window area on the southern side This will reduce energy loss in winter. Windows are double glazed with the use of heavy curtains and pelmets to prevent direct air flow against the cold windows.

3 Heavy concrete base for thermal stability and mass storage Brick walls often with a cavity (double brick) for air insulation are used. The large base thermal mass heats slowly on hot days and will not lose heat quickly on cold nights. Ideally there are no windows at all on the western side to block entry of afternoon sun and cold winter winds. The flooring of most rooms should assist thermal insulation, especially in southern states, with thick underlay and carpets.

4 External planting of evergreen trees and shrubs on the western side This provides sun and wind-breaks. Deciduous trees provide shade in summer at the front of the house, but lose leaves in winter to let in the light and heat from the Sun.

5 Minimum window area on eastern side Pergolas or awnings are also used. Ground cover plants or grass, rather than reflective concrete, are used to prevent morning light reflection, especially during summer months.

Consider Figure 32.4, illustrating the principles of active solar design. In part **(a)**, the house design incorporates a large thermal mass rock-bed base down into which is fan-forced hot air from the roof-top solar collector. During cold nights the rock-bed slowly releases its stored thermal energy. In part **(b)**, the house design incorporates a **Trombe wall**, which can be thought of as a solar operated storage heater. A thermally massive blackened wall is placed behind glazing on the north-facing side of the house. The diagram shows how both cool and warm air circulate through the house via ducts and shutter flaps, depending on whether house cooling or heating is required. In some systems the Trombe wall is filled with water to achieve the same degree of thermal storage capacity.

Solar hot water systems

Most household solar heating is achieved with **flat plate collectors,** as shown in Figure 32.5 and Figure 32.6. A number of collectors are placed onto the roof (north-facing) and attached to the hot water plumbing system. The maximum operating temperature for these collectors is about 80°C. If it is made to operate at higher temperatures, radiation and convective losses increase dramatically. CSIRO developed a Teflon strip system to help to reduce convective losses in these flat plate collectors. In this system a series of parallel vertical thin strips of Teflon film run up and down the slope of the solar collector about 5 mm apart between the glass cover and the absorber. This addition increased operating efficiency considerably.

PHYSICS FACT

The Australian National University (ANU) hopes to build the world's largest combined solar hot water and electricity system for one of its own buildings, called Bruce Hall. In the developing system, built in conjunction with Rheem Australia-Solarhart, Sun-tracking parabolic mirrors concentrate sunlight by a factor of about 30 times and shine it onto thermal solar receivers mounted with solar cells that convert the sunlight directly into electricity with about 20% efficiency. The system is called CHAPS (combined heat and power solar) and will completely supply the building with electricity and hot water.

Figure 32.4
Active solar design: **(a)** solar air heating and rock-bed; **(b)** Trombe wall design.

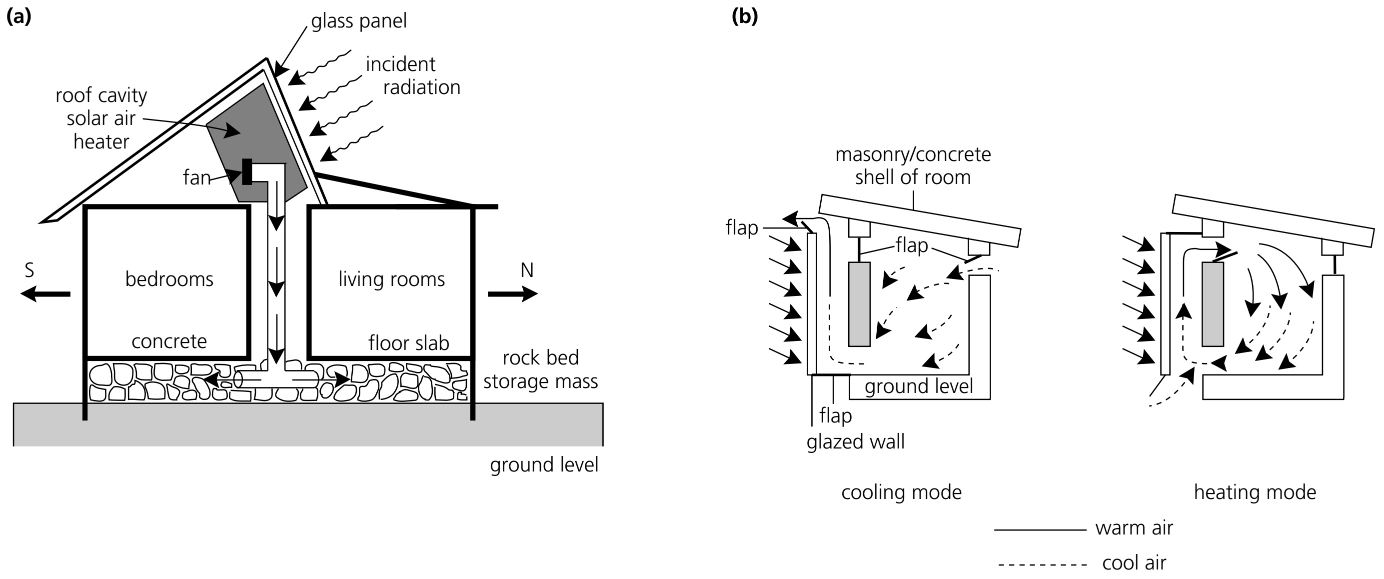


Figure 32.5
Flat plate solar collector — cross-section.

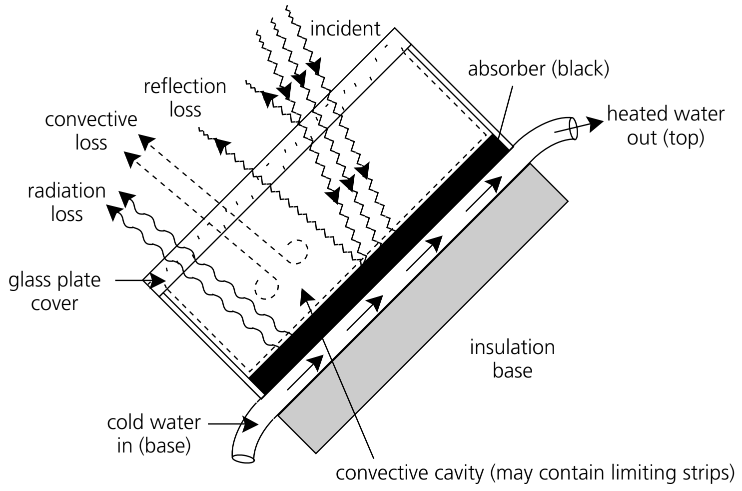
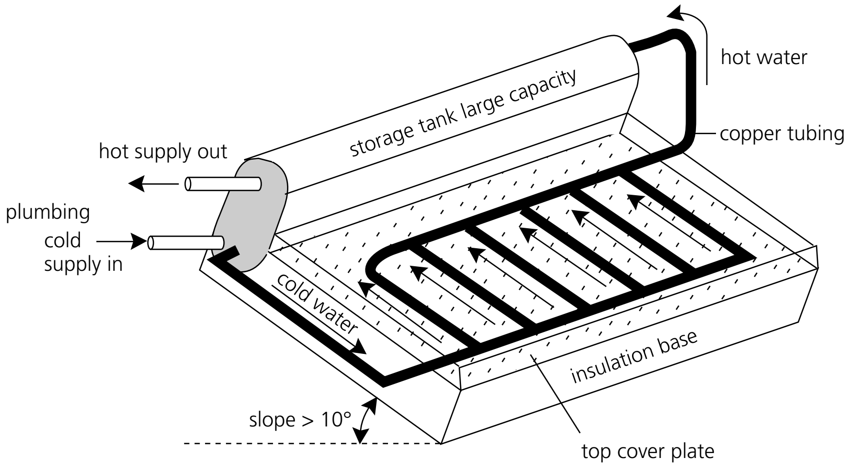


Figure 32.6
Thermosyphon solar water heater.



In Australia, the commonest design of solar hot water system uses the **thermosyphon** principle. A solar collector mounted on the roof is connected to a horizontal cylindrical storage tank. Cold water flowing into the collector pipes is heated and displaced upward by the cooler, more dense water. This natural convection flow produces a thermosyphon flow without the need for artificial pumps. The top of the collector sits below the bottom of the storage tank and the roof slope must exceed 10° for the thermosyphon effect to be efficient. In winter months a booster electric element situated in the top of the storage cylinder can be switched on to complete the heating of the top layers of water, if necessary. The solar collector should be angled to face the Sun. The angle is approximately equal to the latitude, so in Brisbane they are angled at 30°, while in Cairns the angle is 17°.

Although solar heating is becoming more efficient with design improvements, it is still only marginally economical in many countries where low levels of sunlight are received. Even in Australia, to power large systems with flat plate solar collectors is an unlikely future proposition. Larger industrial photothermal mechanisms that are in use in various parts of the world are called concentrating collectors and include power towers, solar farms, heliostat arrays and solar ponds. You might research some of the world's largest!

PHYSICS FACT — WORLD'S LARGEST SOLAR CELL

The Second World Conference on Photovoltaic Solar Energy Conversion, held in Vienna, July 1998, announced the production of the world's largest thin-film crystalline silicon solar cell.

It is manufactured by the Australian firm 'Pacific Solar' in conjunction with UNSW's Photovoltaics Special Research Centre.

Each solar module is 30 × 40 cm and has a planned efficiency of 15%, with an active cell thickness of 10 μm.

Pacific Solar hopes soon to be able to produce 1.0 m^2 solar cells.

32.4 PHOTOVOLTAICS

Probably the most efficient use of solar radiation is to convert it directly to electricity. Semiconductor materials can provide the direct conversion of the Sun's radiation to electrical energy under suitable conditions. **Photovoltaic cells** made from thin slices of silicon, gallium arsenide or other semiconductors were first developed in the 1950s for use in satellites as clean, lightweight, safe and reliable sources of electrical power. In 1954 the first 'solar battery', as it was called, was invented by D. M. Chapin, C. S. Fuller and G. L. Pearson, working as a team at Bell Laboratories in New Jersey, USA, as an extension of their work on transistors. Today, **solar cells**, as they are more commonly called, are manufactured by numerous companies and form the basis of many remote area electrical power installations.

Recall from Chapter 29 that the photoelectric effect required a vacuum tube and an external source of EMF in the photoemission circuit to allow the flow of a photocurrent. The advantage of the **photovoltaic effect** is that no vacuum environment is needed and the photovoltaic cell generates its own EMF. Early photographic light meters, such as the Weston cell, consisted of a selenium or cadmium sulfide layer deposited on metallic iron. Incident light photons passed through the selenium layer, promoting electrons from the iron metallic base into the selenium conductor and generating an EMF across the junction. The iron formed the positive electrode and the selenium formed the negative electrode of the photovoltaic cell. A sensitive galvanometer was used to display the electron current generated in the circuit and this was directly proportional to the intensity of the incident light. The galvanometer movement could be readily calibrated in terms of exposure values directly.

The silicon solar cell is the most widely used photovoltaic device today. Solar cells can be made in two ways. In one method, amorphous (solid) silicon is layered directly onto glass, with the rear being protected with a clear acrylic laminate. In the other method, monocrystalline silicon wafers are placed behind glass plates to protect them against physical shock as this form is particularly brittle. The amorphous type is more expensive but is more robust. The solar arrays used in the 1990 World Solar Challenge race by its eventual winner, the *Spirit of Biel Bienne* from Switzerland, were made of monocrystalline silicon cells developed by the Centre for Photovoltaic Devices and Systems at the University of NSW, Sydney, directed by Professor Martin Green. These 'green cells', made for the Spirit car, used laser grooved solar cells to maximise efficiency, which in the race peaked at 17%. In typical solar racing conditions the array averaged an output of 980 W, enabling the winning time from Darwin to Adelaide (3007 km) to be recorded at 46 hours 8 minutes.

On 22 August 1995, the Sandia National Laboratories in New Mexico confirmed that a 'thin' solar cell made at the University of New South Wales from crystalline silicon had achieved an efficiency of 21.5%. This was an improvement on the 1994 record of 17% set by

PHYSICS FACT

The University of New South Wales Photovoltaic Research Centre's recent work has led to development of the multilayer solar cell. This innovative cell structure has the potential to overcome the efficiency limits of amorphous solar cells while maintaining low processing costs. Such a development could make solar cells far more cost-competitive with conventional generators such as coal-fired power stations.

A conventional solar cell is 350 μm thick and consists of just one layer of P-type silicon and one layer of N-type silicon sandwiched together to form a PN junction. (A human hair is about 50 μm wide.) A multilayer solar cell only 15 μm in width, however, consists of up to 10 very thin alternate layers of P-type and N-type silicon deposited onto glass to give several PN junctions. It is this multilayer structure that enables moderate efficiencies to be achieved with low-quality material, since each light-generated charge carrier does not have very far to travel to reach a PN junction.

researchers at the Australian National University. To qualify as a thin device, the cell had to be less than 50 µm thick — about the thickness of a human hair. The record-breaking solar cell tested in New Mexico was about 47 µm thick. The UNSW team also holds the current record for the most efficient conventional solar cell at 24%. At over 400 µm thick, however, these cells require nearly 10 times as much silicon as the 25% 'thin' type.

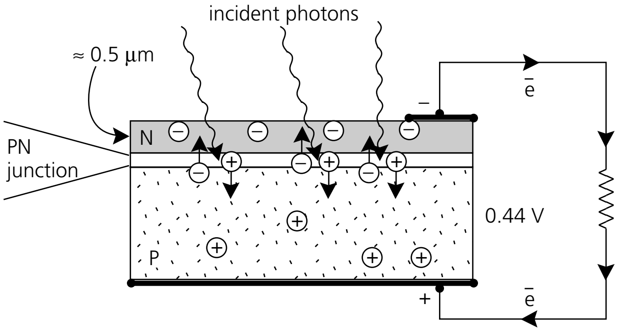
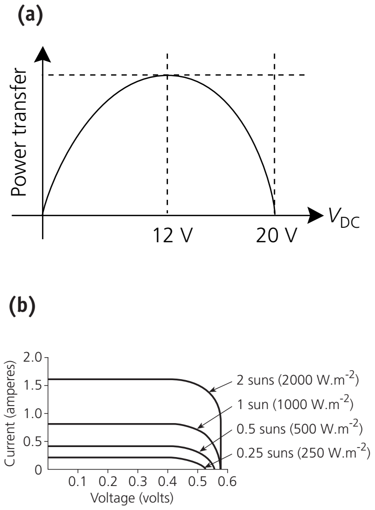


Figure 32.7
Action of a silicon solar cell.

Refer to Figure 32.7, illustrating the typical photovoltaic action in a silicon solar cell. It represents a PN junction with an external circuit connected across it. Silicon atoms require incident photon wavelengths in the near infrared region of the spectrum ($\lambda = 10^{-6}$ m) to dislodge electrons in the crystal lattice. When light is incident on the exposed thin N-type surface, most pass through into the PN junction layer. The photon energy is transferred to the electrons that are dislodged from the atoms, producing electron-hole pairs in the junction region. The electric field in this region forces uncombined electrons into the N-type layer and equivalent holes are left in the P-type layer. This generates the EMF source of 0.44 V, which produces an electron flow in the external circuit. It should be noted that the layers of N-type and P-type semiconductor in the diagram could be reversed and the cell would operate just as efficiently.

Figure 32.8
(a) Solar cell power curve.
(b) Current and voltage output of a single solar cell under varying light levels.



A typical single-crystal silicon PV cell of 100 cm^2 will produce about 1.5 W of power at 0.5 V DC and 3 A under full summer sunlight (1000 W m^{-2}). The power output of the cell is almost directly proportional to the intensity of the sunlight. (For example, if the intensity of the sunlight is halved, the power will also be halved.) Figure 32.8**(b)** shows the current and voltage output of a solar cell at different light intensities.

An important feature of PV cells is that the voltage of the cell does not depend on its size, and remains fairly constant with changing light intensity. However, the current in a PV device is almost directly proportional to light intensity and size. When people want to compare different-sized cells, they record the current density, or amps per square centimetre of cell area.

Solar cells of this type can be constructed in panels that can be connected together in series to increase available voltage, as well as in parallel to increase the current capability. Practical solar panels are manufactured with useful voltage and power ratings. The power rating of a solar panel is directly related to its physical size. The rated voltage of a solar panel is not its open circuit voltage, however. For example, a 12 V panel usually has an open circuit voltage of between 18 V and 23 V, but delivers its output power most efficiently at 12 V (Figure 32.8**(a)**). If you search various electronics stores you'll find that most solar panels are rated at either 6 V or 12 V. The company BP Solar Australia, which sells solar cells to the biggest user in the world, Telstra, makes available a range of solar panels for serious electrical energy applications, such as the 32 cell 12 V 5.5 W unit through to the 36 cell 12 V 60 W unit covering 0.6 m^2. These panels, coupled with DC regulators, make ideal auxiliary charging systems for batteries in domestic, automotive and boating applications.

Questions

8 Explain the difference between a photothermal device and a photovoltaic device. Give an example of each.

9 Consider Figure 32.3. Explain any advantages or disadvantages of planting trees across the rear of the house.

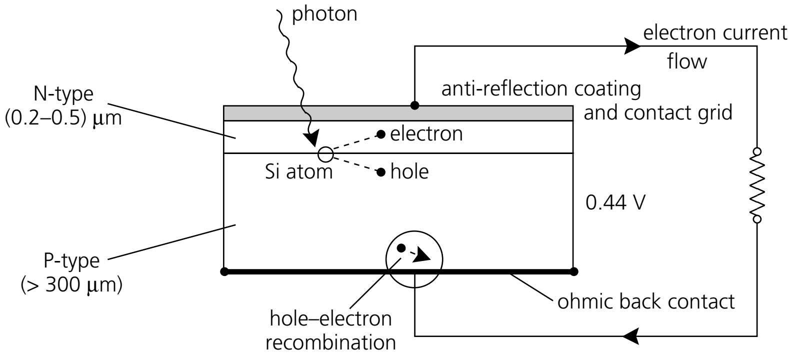


Figure 32.9
For question 10.

10 Figure 32.9 represents a cross-sectional diagram of an actual NP silicon solar cell. Explain each of the diagram labels shown in order to illustrate the principles of operation.

11 Photovoltaic action is a type of photoelectric effect. How do the two actions differ?

12 You are designing a solar car with a total roof area for solar cells of 6.4 m^{-2}. Calculate the electrical power available, assuming total cell efficiency of 17% and a constant solar flux of 980 W m^{-2}. Explain how this calculated power would vary in the actual operation of your car. What advantage would using the latest ‘thin’ cells provide?

32.5 ULTRAVIOLET RADIATION

UV spectrum

Australia has one of the world’s highest potentials for the use of solar energy, but in recent years the abundance of this energy has led to concern over its medical problems as well. **Ultraviolet radiation** (UV) is electromagnetic energy that has wavelengths stretching from 400 nm, the wavelength of violet visible light, through to 1.0 nm, the wavelength of long X-rays. UV radiation can be harmful to living things, especially at wavelengths shorter than 300 nm. Ultraviolet sterilisation of surfaces uses wavelengths less than 310 nm because it kills bacteria and viruses. In humans, unprotected exposure to UV radiation can cause sunburn and eventually skin cancer, but it is not entirely harmful, as a large proportion of the necessary vitamin D that we need for good health is produced by skin irradiated with ultraviolet rays. Tanning of the skin is produced by gradual UV exposure. Delayed tanning is a result of melanin production in the skin as a response to UV radiation exposure. Photodamage, including premature wrinkling and aging of the skin, is a result of chronic exposure to UV radiation. No amount of tanning, however, will decrease the possibility of skin cancers developing, which is a common misconception held by the so-called ‘bronzed Aussie’ brigade.

Ultraviolet radiation is also used to erase programmable (EPROM) chips in computers as well as cause certain dyes and inks to fluoresce in applications such as ‘black light’ signature readers in banks and special effects lights at the local disco. Ultraviolet radiation is produced artificially mainly by vapour discharge tubes or electric arc lamps, whereas the major source of natural UV radiation is, of course, the Sun.

In terms of the solar spectrum, ultraviolet radiation is classified as:

- soft or **UV-A** radiation with wavelengths between 400 nm and 315 nm
- hard or **UV-B** radiation with wavelengths between 315 nm and 290 nm
- **UV-C** radiation with wavelengths less than 290 nm.

Although UV-B radiation is the most dangerous ionising form, as it can strip electrons from atoms in its path, it is generally considered today that both UV-A and UV-B can contribute to sunburn and more harmful skin cancer development. Hence, the development of 'broad-spectrum' sunscreens that will effectively block both bands for a given period of time under the right conditions. Ordinary window glass is opaque to a large portion of the UV spectrum, particularly short wavelengths. Special UV glass is transparent to the longer wavelengths.

The Earth's atmosphere protects living organisms from the majority of solar UV radiation. The **ozone layer** of the atmosphere absorbs most of the incident wavelengths, especially the shorter band. Ozone is a colourless gas present in the upper atmosphere. Although scientists are concerned about the ozone hole in the Earth's atmosphere, the gas itself is far less welcome at ground level. Ozone arises artificially from the interaction of vehicle exhaust gases, such as nitrogen oxides, hydrocarbons and carbon monoxide, with sunlight. Ozone can be detected by humans at about eight parts per billion (8 ppb), and it smells like weak chlorine. At 50 ppb it causes headaches, while above concentrations of 120 ppb, eye and mucous membrane irritation develops. Ozone is a very strong photochemical oxidant and it attacks and damages many materials including rubber, cellulose, dyes and organic paint binders. The US Environmental Protection Agency states that humans should not be exposed to ozone levels greater than 120 ppb (averaged per hour). Ozone levels often exceed 200 ppb, however, in many of the world's largest cities.

Ultraviolet monitoring

The monitoring and experimental analysis of incident solar UV radiation can be carried out with simple photodiode detectors such as the Vital Technology **BW-10 monitor**, which formed the basis of an Australia-wide monitoring network set up by the University of Canberra. Table 32.2 lists the instrument specifications.

Table 32.2 SPECIFICATIONS OF THE BW-10 MONITOR

Size	2.35″ × 3.5″ × 0.9″ outside dimensions
Weight	195 g
Battery life	8000 hours typical (9 V alkaline)
Frequency response	Weighted 290 nm to 365 nm (CIE human skin response)
Dynamic range	0.1 to 9.9 AES skin damaging UV units (CIE weighted)
LCD display type	2 digit transreflective — twisted nematic
A–D converter	Auto zero, temperature coefficient (1 ppm/°C)
Detector–diffuser	Extended range photodiode, Teflon diffuser

This simple device is calibrated in atmospheric environmental skin damaging units on a range of 0.0 to 9.9 with the highest corresponding to an incident UV radiation of 250 mW m^{-2}. The scale units can be converted using the figures in Table 32.3 after readings have been taken. Data collected on a permanent basis can be collated and examined for long-term trends over a wide area of Australia. A typical set of monitoring results is shown in Table 32.4, obtained by high school students in Wynnum, Queensland (latitude 27° 30′ S, longitude 153° E, elevation 20 m). Notice that combined UV, indirect UV, cloud cover and other atmospheric data are valuable in this type of research. Not only can this type of instrument be used for general UV monitoring but it can also form the basis of experimental design into such research topics as sunscreen testing, surface reflectivity, efficiency of sunglasses and effects of UV radiation on plant growth. Refer to the suggested activity and check with your teacher whether your school has a UV monitor.

Table 32.3 BW-10 CONVERSIONS

In the table below: Type I skin = Fair. Type VI = Olive-Dark. E.g. if the meter reads 5.0, a safe exposure time in the sun is 21 minutes for Fair, and 75 minutes for Dark skin.

AES	MINUTES BY SKIN TYPE						mW/m^2
#	I	II	III	IV	V	VI	
0.2	520	700	960	1167	1427	1880	5
0.4	260	350	480	583	713	940	10
0.6	173	233	320	389	476	627	15
0.8	130	175	240	292	357	470	20
1.0	104	140	192	233	285	376	25
1.2	87	117	160	194	238	313	30
1.4	74	100	137	167	204	269	35
1.6	65	88	120	146	178	235	40
1.8	58	78	107	130	159	209	45
2.0	52	70	96	117	143	188	50
2.2	47	64	87	106	130	171	55
2.4	43	58	80	97	119	157	60
2.6	40	54	74	90	110	145	65
2.8	37	50	69	83	102	134	70
3.0	35	47	64	78	95	125	75
3.2	33	44	60	73	89	118	80
3.4	31	41	56	69	84	111	85
3.6	29	39	53	65	79	104	90
3.8	27	37	51	61	75	99	95
4.0	26	35	48	58	71	94	100
4.2	25	33	46	56	68	90	105
4.4	24	32	44	53	65	85	110
4.6	23	30	42	51	62	82	115
4.8	22	29	40	49	59	78	120
5.0	21	28	38	47	57	75	125
5.2	20	27	37	45	55	72	130
5.4	19	26	36	43	53	70	135
5.6	19	25	34	42	51	67	140
5.8	18	24	33	40	49	65	145
6.0	17	23	32	39	48	63	150
6.2	17	23	31	38	46	61	155
6.4	16	22	30	36	45	59	160
6.6	16	21	29	35	43	57	165
6.8	15	21	28	34	42	55	170
7.0	15	20	27	33	41	54	175
7.2	14	19	27	32	40	52	180
7.4	14	19	26	32	39	51	185
7.6	14	18	25	31	38	49	190
7.8	13	18	25	30	37	48	195
8.0	13	18	24	29	36	47	200
8.2	13	17	23	28	35	46	205
8.4	12	17	23	28	34	45	210
8.6	12	16	22	27	33	44	215
8.8	12	16	22	27	32	43	220
9.0	12	16	21	26	32	42	225
9.2	11	15	21	25	31	41	230
9.4	11	15	20	25	30	40	235
9.6	11	15	20	24	30	39	240
9.8	11	14	20	24	29	38	245
9.9	11	14	19	24	29	38	248

Table 32.4 UV MONITORING DATA

MARCH 1993	MON.	TUES.	WED.	THURS	FRI.	SAT.	SUN.
Time of day	noon	noon	noon	noon	noon	noon	noon
Combined UV (meter display)	5.9	5.4	5.7	6.3	5.5	5.6	4.8
Combined UV (mW m^{-2})	147.5	135	142.5	157.5	142.5	140	120
Indirect UV (meter-shade)	1.9	1.7	2.2	0.9	2.2	1.5	1.4
Indirect UV (mW m^{-2})	47.5	42.5	55	22.5	55	37.5	35
Cloud type (cumulus = 1 stratocumulus = 2)	1	nil	2	2	nil	1	1
Cloud cover northern (%)	25	0	20	30	0	50	25
Cloud cover southern (%)	75	0	20	10	0	50	80
Temperature °C	28	32	31	28	25.5	28	29
Relative humidity (%)	50	45	50	62	62	52	46
Pressure (hPa)	1026	1015	1013	1013	1012	1019	1022
Wind speed (km h^{-1})	4	8	9	6	<4	<4	<4
Wind direction	SW	W	SW	ENE			

Activity 32.1 USING THE UV MONITOR

Design an experiment, making use of a typical UV monitor, to gather conclusive data in order to answer any of the following questions:

1. Does the direct UV level (DUV) change more during the day in summer or winter?
2. How does the type of reflective surface affect the amount of UV radiation received by a person, for example? What is the difference between grass, concrete, asphalt or sand?
3. Do fluorescent lights pose a greater UV threat than incandescent lighting?
4. How does the screening effectiveness of materials such as shade cloth, polycarbonate sheeting, fibreglass sheeting compare as roofing cover on pergolas?
5. Is an SPF 15$^+$ sunscreen more effective than an SPF 5$^+$ sunscreen?
6. Does the degree of darkening of photochromic sunglasses have an effect on their ability to screen UV radiation?

Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Review — applying principles and problem solving

***13** Explain the following terms related to solar physics: nuclear fusion; solar flux; corona; global warming; active solar design; Trombe wall; thermosyphon; flat plate collector; solar cell; soft UV rays; ozone.

***14** Explain why reflective foil insulation on the ceiling is better at reducing energy gain in summer than reducing energy loss in winter.

****15** Electric cars can be run off solar energy converted directly to electricity to run the electric motors and to be stored in batteries for later use.

- **(a)** If the solar cells are only about 15% efficient, where does all the remaining energy go?
- **(b)** Why do solar racing cars require very efficient battery systems?
- **(c)** What does it mean to say that the electric motor has an efficiency of 95%?
- **(d)** What maximum current is drawn from a solar array providing 65 V if the electric motor is rated at 1.2 kW DC?

***16** List the advantages and disadvantages of solar ultraviolet radiation for living organisms.

****17** Research five important skin cancer facts that all Australians should be aware of.

****18** Use Figure 32.8 to compare the open circuit voltage of a silicon solar cell array with its rated output voltage and power.

****19** Using the data of Tables 32.3 and 32.4, try to answer the following:

- **(a)** Check the conversions from meter display to readings in mW m^{-2}. Are they all correct?
- **(b)** List all meteorological features on the day of highest direct UV reading.
- **(c)** List all meteorological features on the day of lowest direct UV reading.
- **(d)** Does the incident UV reading appear to be influenced by cloud cover?
- **(e)** What are the limitations of this table of monitored data?

Extension — complex, challenging and novel

*****20** The CSIRO low energy consumption home (LECH) has a total solar air heater area of 19 m^2. (Refer to Figure 32.4.) If solar energy falls on this house at an average rate of 12 MJ m^{-2} per day. Calculate:

- **(a)** the total energy received per day;
- **(b)** the energy transferred to circulating air, assuming transfer efficiency of 65%;
- **(c)** the energy stored in the rock-bed during the day, assuming air transfer efficiency of 90%.

*****21** A solar hot water system receives solar energy at the rate of 10.5 MJ m^{-2} per day. If the collector area is 4.8 m^2, collector efficiency is 0.7 and the water volume is 325 L,

- **(a)** calculate the total water energy gain per day;
- **(b)** estimate the temperature rise of the water in the tank during the day.

*****22** Calculate the extra tilt support bracket length, l, that would be needed on a north-facing roof with a 15° pitch for a solar hot water system collector plate. Assume the house location is in Rockhampton, Qld (latitude 23°S) and the collector plate is 1.8 m long, with the tilt bracket at right angles to the roof.

*****23** Using Table 32.3, plot a curve of BW-10 AES reading versus exposure in minutes for skin type III. Can you deduce a formula linking these variables?

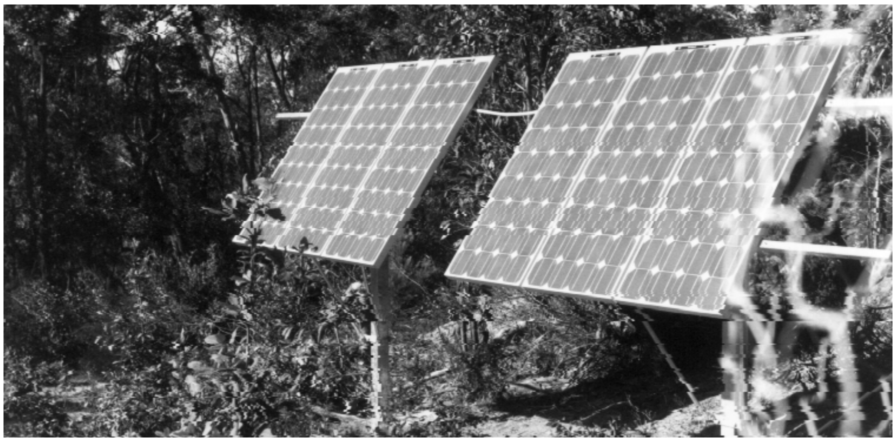


Photo 32.2
These solar modules are used to power a small house.