Chapter 14: Energy in Nature

Goals of Period 14

Section 14.1: To describe the Earth-Sun system
Section 14.2: To illustrate how the Sun powers the Earth
Section 14.3: To explain how the Earth is illuminated by the Sun
Section 14.4: To consider some non-solar energy sources

In this period, we define solar energy as energy from the sun and discuss the interaction between solar energy and our environment. We discuss how solar energy is used by nature to maintain an environment suitable for sustaining life. Specifically, we see how the atmosphere, climate, weather patterns and seasons are all powered by solar energy. Living things also derive their chemical energy from solar energy. Finally, for contrast, we mention other significant sources of energy not derived from solar energy. These non-solar sources include nuclear, geothermal and tidal energies. In Period 15 we will consider applications of solar energy for our use. However, throughout this period, keep in mind that solar energy is clean, plentiful and renewable.

14.1 The Earth-Sun System

The Sun is the star about which the Earth revolves. In order to visualize the relative sizes and separation of the Earth-Sun system we consider a scale model. If the distance from the Sun to the Earth is represented by the length of a football field, 100 yards or about 91 meters, how big are the Sun and the Earth? At one end of the field, the Sun is a relatively large ball with a diameter of 85 cm. At the other end of the field is a tiny ball with a diameter of about 8 mm representing the Earth. The Earth revolves around the Sun in a nearly circular orbit. In the model, how big and where is the moon? It is about 2 mm in diameter orbiting the Earth 23 cm away. In class, we will see a smaller scale model. Table 14.1 presents some data on the Earth-Sun system.

Table 14.1 The Earth-Sun System

Sun to Earth distance	1.50×10^{11} meters
Earth to Moon distance	3.82×10^{8} meters
Surface temperature of the Sun	6,000 ^{o}C
Power of the Sun	3.90×10^{26} watts
Solar insolation near Earth	1,340 watts/meter^2
Height of troposphere	1.25×10^{4} meters

	Sun	**Earth**	**Moon**
Mass (kilograms)	1.99×10^{30} kg	5.98×10^{24} kg	7.36×10^{22} kg
Radius (meters)	6.96×10^{8} m	6.37×10^{6} m	$1.74\ 10^{6}$m

Energy of the Sun

The Sun radiates great quantities of electromagnetic energy. Some of this energy reaches the earth where we experience it as warmth (infrared radiation), as visible light, and as the tanning of our skin (ultraviolet radiation). This electromagnetic energy originates in the center of the Sun when nucleons (protons and neutrons) fuse together to form helium nuclei. This reaction is strongly exothermic. When nucleons combine in nuclear fusion reactions, large quantities of energy are released.

To begin a nuclear fusion reaction, activation energy is required. We have seen this requirement in most chemical reactions. For example, to burn paper we apply the activation energy of a lit match. The high activation energy needed for nuclear fusion reactions in the Sun comes from the tremendous thermal energy in the Sun's core. The gravitational force of the Sun's mass acting inwards on its center heats the Sun's core to about 16 million degrees Celsius. This thermal energy provides the activation energy to begin nuclear fusion.

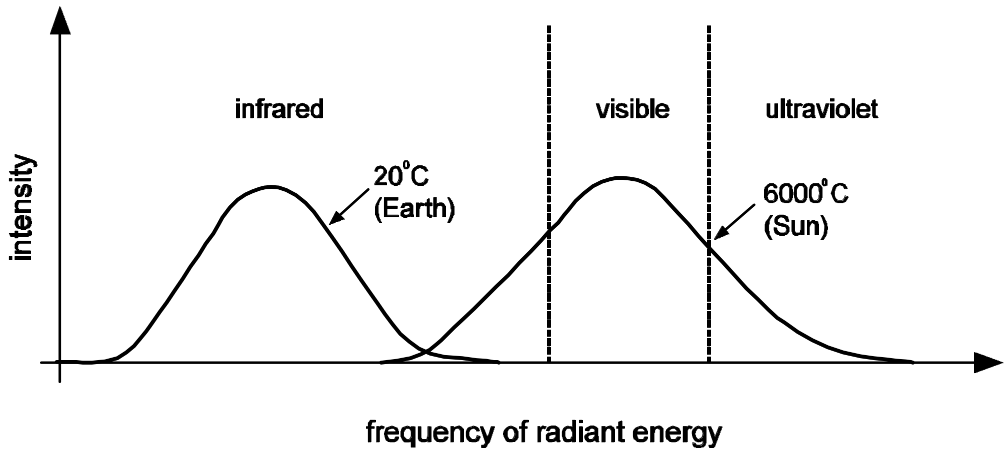
To continue a nuclear fusion reaction, matter must be confined so that the nucleons remain near one another. The gravitational force of the Sun's mass acting inward contains the fusion reaction in the core. A balance is reached between the inward force of gravity of the Sun's mass and the outward force of the nuclear reactions. Nuclear fusion in the Sun can be compared to nuclear fusion in a hydrogen bomb. However, without a force to contain the fused nuclei a hydrogen bomb, the exploding matter blows apart and the nuclear fusion reaction does not continue.

The nuclear energy released by the fusing nuclei is immediately converted into thermal energy that then makes its way to the surface. It may take several thousand years for the thermal energy to reach the Sun's surface. Once there, it heats up the outer layer of the Sun to about 6,000 ^{o}C (10,800 ^{o}F). This heated surface then radiates electromagnetic energy much the same way that the heated filament of an incandescent light bulb radiates electromagnetic energy as visible light and infrared radiation.

Radiant energy (light), not thermal energy, is radiated by the Sun. There is, however, a close relationship between the surface temperature of an object, such as a star or a heated filament, and the spectrum of the radiant energy (light) that is emitted by that object. Specifically, a heated object will emit radiant energy, most of which is confined to a range of frequencies; thus giving the heated object a characteristic spectrum, which depends primarily on the surface temperature of the heated object. The higher the surface temperature, the higher the frequencies of the spectrum. For the sun, the surface temperature is about 6,000 ^{o}C and the corresponding spectrum nearly coincides with the visible spectrum but extends into both the infrared and the ultraviolet. Since our eyes are sensitive to only the visible spectrum, we do not see the full spectrum of the Sun or any other heated object. Recall our discussion of the electromagnetic spectrum in Periods 2 and 3.

Figure 14.1 shows the spectrum of two objects each at a different temperature. Note how there is not a single frequency associated with a given temperature but rather a characteristic range of frequencies. The average surface temperature of the Earth is about 20 ^{o}C.

Figure 14.1 Temperature and Radiant Energy Frequencies



Do not confuse light reflected by an object and light emitted by an object. For example, the moon may be visible in the Earth's sky because sunlight is reflected by the moon's surface. The moon's cold and airless surface does not emit or radiate visible light.

The total power of the Sun is about 3.90×10^{26} watts. This energy is radiated uniformly in all directions from the Sun. The electromagnetic energy radiating from the Sun is called ***solar energy*** or ***solar radiation***. A very tiny fraction (4.5×10^{-10} or 0.000000045%) of the total energy radiated is actually intercepted by the Earth. Most of the radiant energy from the Sun misses the Earth and escapes to space since the Sun is uniformly radiating in all directions, not just in the direction of the Earth. Nevertheless, about 1.76×10^{17} watts of solar power is incident on the Earth. This amount of power is many thousands of times greater than our civilization's use of power.

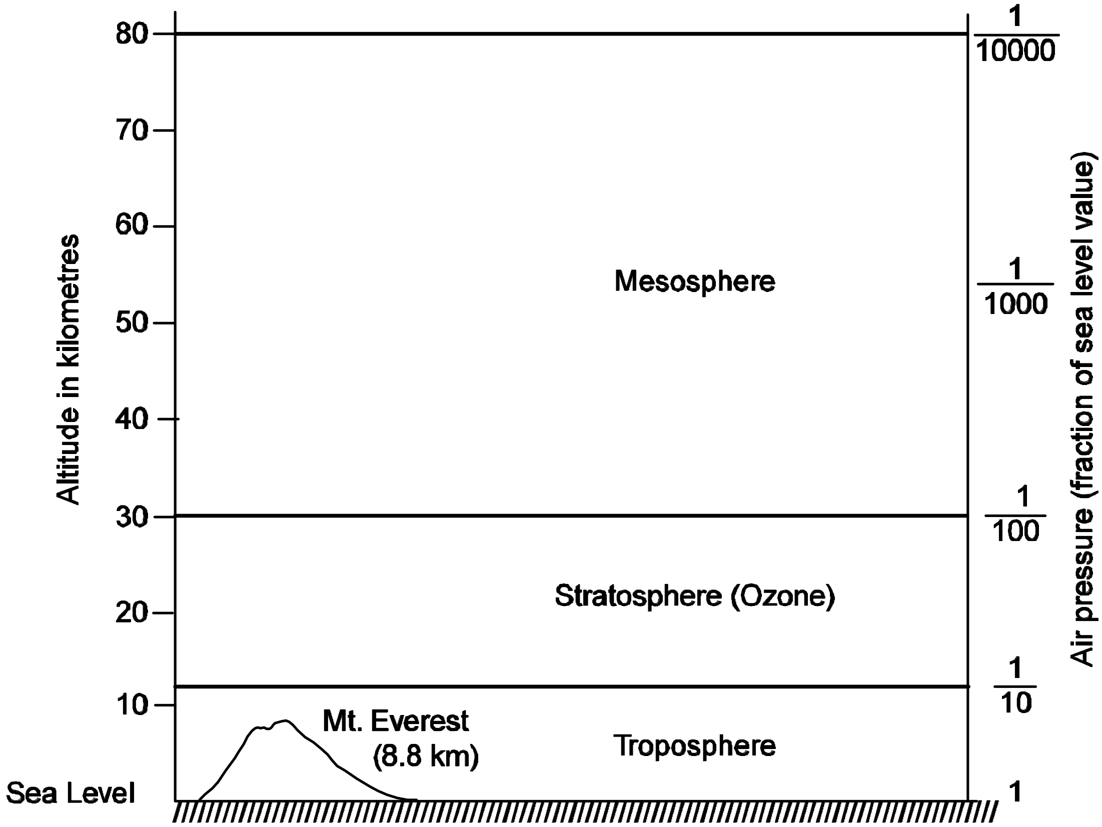
14.2 Powering the Earth

We now explore the complicated interaction between the 1.76×10^{17} watts of solar power incident on the Earth and the Earth's natural environment. We will see some aspects of how the energy is distributed and how it relates to everyday common experience. We will see how solar energy powers much of the Earth's natural environment such as the weather patterns and living things. An understanding of this material is essential for one to make intelligent decisions regarding our utilization of solar energy.

The Atmosphere

The atmosphere is a delicate blanket of air covering the Earth. The atmosphere does not end abruptly at a certain altitude; it gradually thins out with height. Air pressure is a measure of how much air there is. For example, the air pressure at the top of Mount Everest (altitude 8.8 km) is about one third the air pressure at sea level. However, there are several distinct regions of the atmosphere, each with its own respective properties. Figure 14.2 illustrates these regions.

Figure 14.2 Atmospheric Regions



The ***troposphere*** extends from sea level, or ground, to an altitude of about 12.5 km. It contains 90% of the air in the atmosphere and this is the region in which we live. No known life forms naturally exist above the troposphere. Familiar weather patterns, such as storms, are contained entirely within the troposphere. It is also within the troposphere that so-called greenhouse gasses, such as carbon dioxide (CO_2) and water vapor (H_2O), trap thermal energy.

Above the troposphere, from 12.5 km to 30 km, lies the ***stratosphere***. The ***ozone layer***, which filters harmful ultraviolet radiation, coincides with (or lies within) the stratosphere. The stratosphere contains about 9% of all the air in the atmosphere.

The Earth's atmosphere is composed primarily of nitrogen and oxygen. Table 14.2 lists the chemical content (by volume) of the atmosphere near sea level. The water vapor content is highly variable so it is excluded from the other gasses listed in the table. Note the relatively small amount of the notorious carbon dioxide.

Table 14.2 Chemical Composition of the Atmosphere at Sea Level

Chemical	Symbol	Percent by Volume
Nitrogen	N_2	78.083%
Oxygen	O_2	20.947%
Argon	Ar	0.934%
Carbon dioxide	CO_2	0.033%
Other gasses		0.003%
Water vapor	H_2O	highly variable

The Solar Map and Solar Insolation

In the following discussion, we analyze in greater detail the way solar energy is actually distributed over the United States. Since solar energy is spread out over an area, a convenient way to refer to a quantity of solar radiation is to specify the amount of solar energy passing through a given area in a given amount of time. This quantity of solar radiation is the solar power per unit area and is called ***solar insolation***. (Do not confuse insolation with insulation. Insulation is material that slows the flow of something such as electricity (insulation on wires) or thermal energy (insulation of walls). Table 14.3 lists the seasonal averages of the solar insolation of selected locations measured in watts/meter^2. Also included in the table are the seasonably averaged temperatures at these locations.

Table 14.3 Solar Insolation at Selected Locations

Seattle, Washington (400 ft elevation, 48^o latitude)

	Spring	Summer	Autumn	Winter
Temperature (^oC)	9	17	11	4
Solar Insolation (W/m^2)	156	194	118	64

Minneapolis, Minnesota (800 ft elevation, 45^o latitude)

	Spring	Summer	Autumn	Winter
Temperature (^oC)	6	21	8	–9
Solar Insolation (W/m^2)	77	192	150	129

New York, New York (200 ft elevation, 41^o latitude)

	Spring	Summer	Autumn	Winter
Temperature (^oC)	11	23	14	1
Solar Insolation (W/m^2)	169	176	151	126

Columbus, Ohio (800 ft elevation, 40^o latitude)

	Spring	Summer	Autumn	Winter
Temperature (^oC)	10	22	12	–1
Solar Insolation (W/m^2)	159	181	147	97

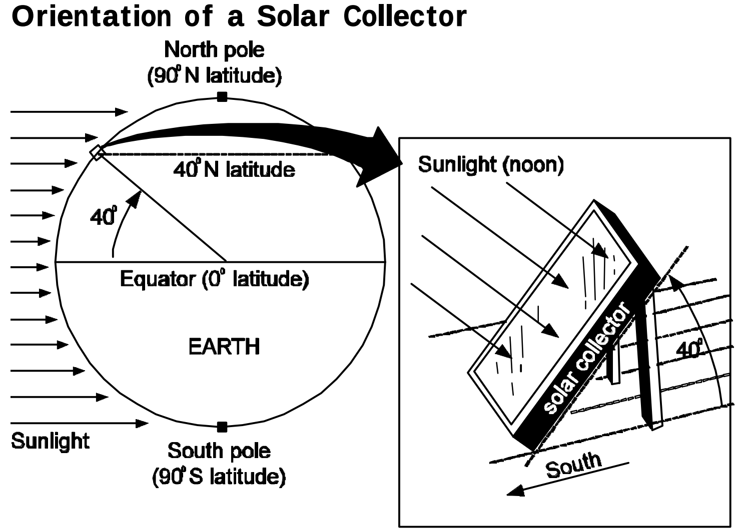
Table 14.3, Continued   Solar Insolation at Selected Locations

Albuquerque, New Mexico (5300 ft elevation, 35^o latitude)				
	Spring	Summer	Autumn	Winter
Temperature (^oC)	13	25	14	3
Solar Insolation (W/m^2)	267	256	257	235
Houston, Texas (100 ft elevation, 30^o latitude)				
	Spring	Summer	Autumn	Winter
Temperature (^oC)	20	28	21	12
Solar Insolation (W/m^2)	184	190	184	151
Miami, Florida (see level, 26^o latitude)				
	Spring	Summer	Autumn	Winter
Temperature (^oC)	24	28	25	20
Solar Insolation (W/m^2)	213	183	190	197

Just outside of the Earth's atmosphere, the value of the solar insolation is about 1340 watts/meter^2. As already described, this solar radiation is reflected and absorbed by things like the atmosphere and clouds, with the result that only some of this radiation reaches the ground as visible light. The actual values may be significantly less than 1340 W/m^2, such as the Columbus winter average of 97 W/m^2.

When interpreting the tabulated values of the solar insolation, it is important to know how the area through which the radiation passes is oriented. For example, is the area lying flat on the ground or is it aimed at the Sun? The convention we use is to face it south and orient it at an angle equal to the latitude as shown in Figure 14.3. With this convention, the solar collection will be aimed at the Sun only around noon when the sun is high in the sky. Columbus, Ohio, is at 40^o N latitude, so the area is oriented at an angle of 40^o. The orientation of a solar energy collector is very important to make it effective.

Figure 14.3 Orientation of a Solar Collector



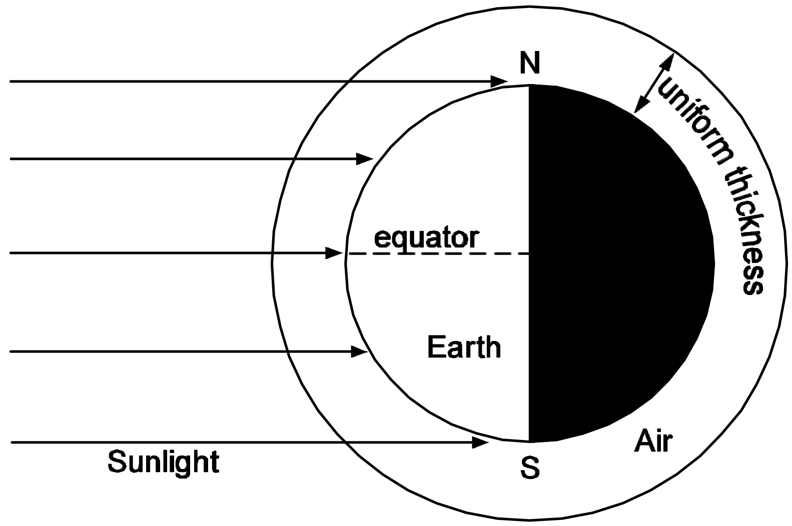
The Solar Insolation Map shown in Figure 14.4 groups regions of the United States with similar average values of solar insolation. Notice that there is a latitude dependence. This should be familiar since we know that the southern regions are generally warmer than northern regions. However, note that the regions are somewhat complicated in shape. This is because there are other factors such as cloud cover that are important. For example, the desert southwest is relatively cloudless and dry and so the solar insolation is greater than at regions at the same latitude to the east.

Figure 14.4 U.S. Solar Insolation Map

Why is there a latitude dependence in the climate? One important factor is that sunlight must pass through the atmosphere, which absorbs and reflects solar energy. Although the atmosphere is rather uniform around the Earth, sunlight must pass through more of it when the Sun is not high in the sky. Figure 14.5 on the next page, which is not drawn to scale, illustrates this. Note that the amount of atmosphere through which the sunlight must pass increases as one moves from the warm equatorial region to the cold polar regions.

The elevation above sea level is also important in determining the climate. At relatively high altitudes, the temperature is typically cooler. This is partly because there is less air and clouds to retain the solar energy. Another factor is that since cold mountain tops might be covered with snow even near the equator, much of the incident solar radiation is simply reflected back into space.

Figure 14.5 Latitude Dependence in Climate



14.3 How the Earth is Illuminated by the Sun

In class, we use a globe model to see in more detail how the Earth is illuminated by the Sun. The model is, of course, limited because it does not show many important features such as how solar energy is absorbed and reflected by the air and clouds. However, we will see the familiar day-night cycle and how the light is spread out. We will also discuss the seasons. These effects are important from a practical point of view. In the following, we shine a light on an ordinary Earth globe and make a few observations.

Day-Night Cycle

Only half of the globe is illuminated by the lamp at any time. The illuminated side is in day while the dark side is in night. Since the Earth is spinning (rotating) on its axis, while it revolves around the sun, a given place on the earth alternately experiences day and night. This we call the day-night cycle. All places on the Earth have the same total number of day-lit hours for each year, however, not all places receive the same amount of solar energy as we will see next.

If we mask the globe with cardboard with holes, light shines through the holes and shows up as spots of light on the globe. The holes on the mask form a regular pattern, however the spots of light on the globe follow a different pattern. When the spots are relatively close together, the light is more intense than otherwise.

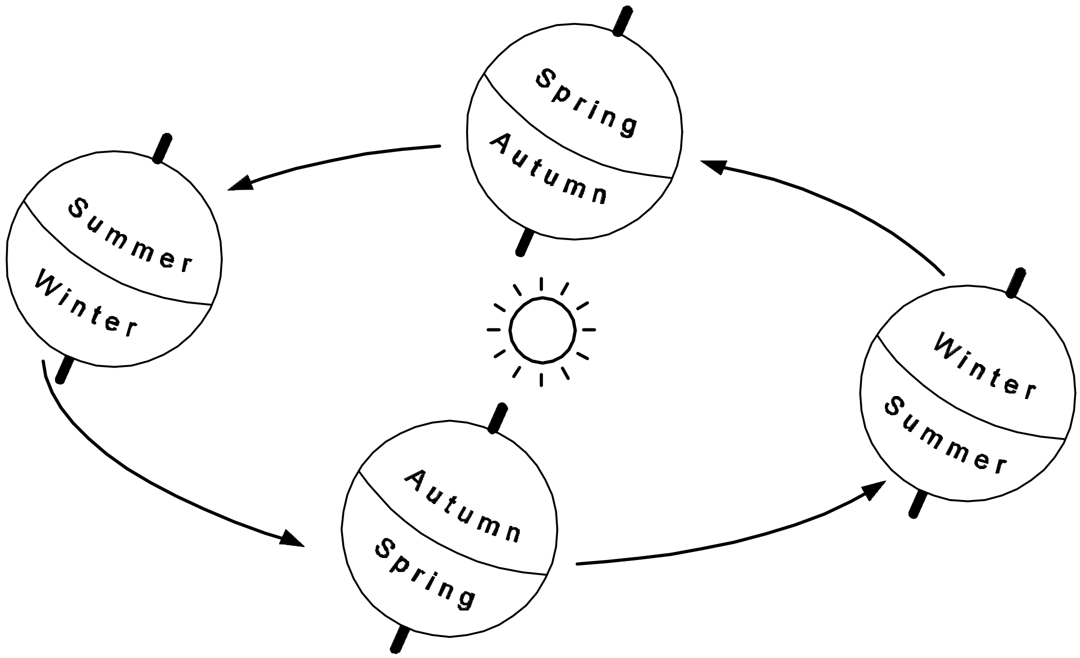
The relative spacing of the spots shows how sunlight is distributed according to how high the Sun is in the sky. When the Sun is high in the sky, the sunlight is generally more intense. When the Sun is low in the sky, that is, at dawn or dusk and in the polar regions, the sunlight is relatively less intense. We can see this effect by observing the overall spacing of the spots on the globe and as illustrated in Figure 14.6. The reason for this effect, of course, is that light is incident on the curved surface of the globe at different angles. For glancing rays, the spots of light are relatively far apart so the light is less intense.

Figure 14.6 Intensity of Light on a Globe

The Seasons

Besides spinning on its axis, the Earth is revolving in a nearly circular orbit around the Sun. It takes one year (about 364 days) for each revolution. The plane defined by the orbit of the Earth is called the ***ecliptic***. The axis about which the Earth rotates is tilted relative to ecliptic by constant 23.5 degrees. Ordinary globes of the Earth usually illustrate this tilt by the way they are mounted on their stand. The Earth's axis is considered to be this axis about which it rotates. On its journey around the Sun, the Earth's axis points in the same direction, that is, it maintains its orientation relative to the distant stars. These effects cause the seasons as shown in Figure 14.7 on the next page.

Figure 14.7 The Seasons



Notice that the northern and southern hemispheres have seasons opposite to each other. For example, when the southern hemisphere is experiencing winter, the northern hemisphere is experiencing summer. The temperate regions have more pronounced seasons. Specifically, there is the familiar annual cycle of winter, spring, summer, and autumn.

The polar regions, typically much cooler than other areas, receive sunlight only at very oblique or grazing angles. As shown in Figure 14.6 above, the atmosphere through which the sunlight passes is also significantly greater near the poles. Contrast this with the equatorial region, which is typically warm. The seasons in these regions are not very pronounced; the poles have a winter-like climate while the equator has a summer-like climate.

A common misconception is that the seasons arise because of a varying distance between the Sun and the Earth. The orbit of the Earth is not exactly circular meaning that there is a varying distance, however, it is too small to cause the seasons. When the northern hemisphere is experiencing summer, the Earth is actually slightly farther from the Sun than during the winter six months later.

14.4 Non-Solar Energy Sources

We next consider several important energy sources that are not derived from solar energy – nuclear, tidal, and geothermal energy. Since fossil fuels (oil, natural gas, and coal) are derived from ancient biomass, and thus from solar energy, they are excluded from this discussion.

Nuclear Energy

We previously discussed the energy released from nuclear fusion reactions when individual nucleons fuse into helium nuclei. The opposite reaction, called fission, occurs when atomic nuclei break apart, releasing matter and energy. In Period 17 we will look in depth at nuclear fission reactions as a source of energy in nuclear power plants. Nuclear fission reactors use as their fuel radioactive materials, such as uranium and plutonium.

Radioactive materials are examples of non-solar fuel sources. Uranium and deuterium, an isotope of hydrogen used in hydrogen bombs, occur naturally on Earth and were probably present when the Earth was formed. Plutonium is derived from uranium in a breeder reactor in a process we will discuss in Period 17.

Tidal Energy

Another example of a non-solar energy is ***tidal energy***. There is a familiar periodic rise and fall of the sea level called the tide. The cycle time for a tide is about 12 hours; there are two high-tides every day. It requires energy to effect the tides; a rising water level implies an increase in gravitational energy of the water. From where does the tidal energy come?

The tidal energy comes from the gravitational interactions between the Earth, moon and Sun. This gravity causes the oceans, which are an easily deformed fluid, to form two bulges, one on either side of the Earth. As the Earth spins on its axis, land bordering the oceans (the shore) passes through both bulges each day; thus the familiar cycle of the tides. Tidal energy does not come from solar energy. Next, we ask: How can such energy be utilized?

Consider what happens in a harbor when the tide is rising; water enters the harbor from the ocean. That is, there is a flow of water from the ocean to the harbor. Obviously, there must be a flow of water from the harbor back to the ocean when the tide is ebbing. If the harbor is large enough, there can be a significant flow of water throughout the day. Now, if the opening of such a harbor is dammed, water entering or leaving the harbor may be diverted to a water turbine to generate electricity. This method has been used in France but seems to be not very popular elsewhere. The technology involved in harnessing tidal power is very similar to that involved in harnessing water power provided by rivers. Note that one major adverse affect of harnessing tidal energy by damming a harbor is that it disturbs the local ecology.

Geothermal Energy

The interior of the Earth is very hot as evidenced by volcanoes, geysers or hot-springs. Actually, most of the Earth consists of molten rock; only a relatively thin crust has cooled and solidified. This thin crust, only few miles thick, is very effective in insulating us from the hot molten rock or ***magma***. Only in geologically active areas does magma come close to the surface or, in the case of volcanoes, reach the surface. Nevertheless, the interior of the Earth is a great reserve of thermal energy. This thermal energy is popularly called ***geothermal energy*** and is not of solar origin. Can geothermal energy be put to practical use?

In some places, such as Iceland, geothermal energy provided by natural hot-springs is used to generate electricity using steam turbines and to heat homes and other buildings. Geothermal energy seems to be very successful; it is readily available and its use reduces demand on fossil fuels. One drawback, however, is that some gasses such as sulfur dioxide, which smells like rotten eggs, are released in such operations. Extensive use of geothermal energy is still a thing of the future.

Period 14 Summary

14.1: We experience the Sun's electromagnetic energy as warmth (infrared radiation), as visible light, and as the tanning of our skin (ultraviolet radiation).

This electromagnetic energy originates in the center of the Sun when protons and neutrons fuse together to form helium nuclei. This reaction is strongly exothermic.

Heated objects emit radiant energy. The frequencies of this radiation depend primarily on the surface temperature of the heated object. The higher the surface temperature, the higher the frequencies of the spectrum.

14.2: The Earth's atmosphere consists primarily of nitrogen and oxygen gases.

The troposphere extends from sea level to an altitude of 12.5 km. It contains 90% of the air in the atmosphere. No known life forms naturally exist above the troposphere.

The stratosphere lies from 12.5 km to 30 km above the Earth. The ozone layer, which filters harmful ultraviolet radiation, lies within the stratosphere.

The amount of solar insolation striking the Earth depends on

1) the season of the year. Due to the tilt of the Earth's axis, the northern hemisphere receives more insolation during the summer.

2) the latitude. Higher latitudes near the poles receive less insolation, the equator receives more.

3) the amount of radiation that passes through the atmosphere and reaches the Earth's surface. The amount of cloud cover and pollution in the air affects the amount of radiation striking the surface.

14.3 Seasons are caused by the tilt of the Earth's axis (23.5 degrees). In summer, the sun shines more directly on the Northern hemisphere. In winter, the sun shines more directly on the southern hemisphere.

Seasons are **NOT** caused by differences in the distance between the Earth and the Sun. In fact, the Earth is closest to the Sun during the winter (in the northern hemisphere).

Period 14 Summary, Continued

14.4: Some important non-solar energy sources include nuclear, tidal, and geothermal

Nuclear energy is released during nuclear fusion reactions when individual nucleons fuse into helium nuclei and during fission occurs when atomic nuclei break apart.

Tidal energy comes from the gravitational interactions between the Earth, moon and Sun. This gravity causes the oceans to form two bulges, one on either side of the Earth. As the Earth spins on its axis, land bordering the oceans passes through both bulges each day causing tides. Tide water flowing into a harbor can be used to turn electric generator turbines.

Geothermal energy taps thermal energy from the hot interior of the Earth.

Period 14 Exercises

E.1 Solar energy originates deep within the Sun as

a) nuclear fission energy.
b) nuclear fusion energy.
c) chemical energy.
d) gravitational energy.

E.2 The surface temperature of the sun is about

a) 60 ^{o}C
b) 600 ^{o}C
c) 6,000 ^{o}C
d) 1,000,000 ^{o}C
e) 16,000,000 ^{o}C

E.3 The percent of solar energy incident on the Earth, relative to the total amount of solar energy emitted by the Sun, is about

a) 50%
b) 14%
c) 1%
d) 0.000000045%

E.4 About 1.52 x 10^{22} joules of solar energy is incident on the Earth each day. Of this large amount of energy, how much escapes back into space as either visible light or infrared radiation?

a) none (0%)
b) about 30%
c) about 50%
d) about 70%
e) all of it (100%)

E.5 Which of the following pair of gasses is most abundant in the Earth's atmosphere?

a) oxygen and carbon dioxide
b) oxygen and nitrogen
c) ozone and nitrogen
d) carbon dioxide and nitrogen

E.6 The protective ozone layer lies within which region of the atmosphere?

a) Troposphere (up to an altitude of about 12.5 km)
b) the Stratosphere (between 12.5 km and 30 km)
c) the Mesosphere (between 30 km and 80 km)
d) There is no ozone layer.

E.7 Which of the following sources of energy are **NOT** derived from solar energy?

a) wind power
b) water power
c) geothermal power
d) All of the above are **NOT** derived from solar energy.

Period 14 Review Questions

R.1 We experience the Sun’s energy as infrared, visible, and ultraviolet radiation. How would this change if the Sun’s surface temperature was hotter? If the surface temperature was cooler?

R.2. Why does the amount of solar insolation striking the Earth change with changes in latitude?

R.3 What causes the seasons?

R.4 What are the advantages and disadvantages of using tidal energy?

R.5 What are the advantages and disadvantages of using geothermal energy?