

ENERGY III

INTERCONVERSION OF FORMS OF ENERGY

ENERGY CHANGES

We will consider first the interconversion of potential energy and kinetic energy. We will then consider the interconversion of different types of energy: mechanical energy, electrical energy, chemical energy, and so on.

Interconversion of potential energy and kinetic energy

We have already seen that one form of energy can change into another. We have seen, for example, that when a bowling ball is dropped its potential energy changes into kinetic energy. The slamming of a screen door is analogous: the potential energy of the open door with the stretched spring turns into the kinetic energy of the moving door as the door slams.

The swinging of a pendulum also exemplifies the interconversion of potential energy and kinetic energy. At the extremes of its arc the pendulum is at rest and its energy is entirely potential. At the lowest point of its arc the energy of the pendulum is entirely kinetic.

Conservation of energy

One of the greatest insights of science is that energy is neither gained nor lost; it just changes form. Energy, that is, is *conserved*. Considering the bowling ball story one might ask Where did the kinetic energy go when the ball hit the ground? Believers in the conservation of energy would say that most of that kinetic energy was converted to heat, and a little to sound. The ground and the ball were slightly warmed, and the air, and our eardrum, were slightly wiggled.

The screen door example could be considered in the same way, and the ultimate slowing and stopping of a pendulum would be accounted for by a slight resistance to the motion of the pendulum by the air, and by a small degree of friction at the point of suspension of the pendulum, air resistance and friction being mechanisms for conversion of the coherent motion (mechanical energy) of the pendulum to the random atomic and molecular motion (thermal, or “heat” energy) of the air and the support for the pendulum.

The idea that energy is conserved is one of the most powerful and useful insights of the human mind; it allows us to understand much that would

otherwise be incomprehensible.

Interconversion of other forms of energy

In all of the examples just presented the only energy considered was mechanical energy. The energy was either the coherent mechanical energy of a large scale object, a bowling ball, or a screen door, or a pendulum, or our eardrum, or the energy was the random kinetic energy of atoms and molecules, thermal energy.

Interconversion of mechanical energy and electrical energy

In earlier examples, however, we saw that mechanical energy can be converted to electrical energy by *generators*, and that the reverse, the conversion of electrical energy to mechanical energy, can be accomplished by *motors*.

Interconversion of chemical energy and electrical energy

We are also familiar with the effect of a *battery*, a device that converts chemical energy to electrical energy. For some batteries this is a process that cannot be reversed, but for others it can. Batteries for which the process can be reversed are called *rechargeable batteries*.

Fuel cells are similar to batteries in that they convert chemical energy to electrical energy. Fuel cells differ from batteries, however, in that the chemicals that are consumed by the fuel cell can be continually replaced while the device is in operation.

Interconversion of light energy and chemical energy

Most of us are familiar with devices that convert chemical energy to light energy, and that can convert light energy to chemical energy. The firefly, and other luminescent organisms, converts some chemical energy to light, so-called “cold” light, and every living plant converts light energy, sunlight, to sources of chemical energy, typically sugars and starches. The mechanism is the same for all plants, and it involves the green pigment chlorophyll. It is the chemical energy thus produced that provides us humans with the energy we need to stay alive. Yes; our diet consists exclusively of chemicals.

Interconversion of electrical energy and light energy

We all know about electric lights. One type of electric light is the *incandescent* light bulb. In this device the light is produced indirectly. The electricity heats a wire, the filament, to incandescence, a temperature at

which the filament glows “white” hot. An electric toaster or toaster-oven operates in the same way, but at a lower temperature, only “red” hot. Incandescent lights produce far more heat than light, and for that reason are said to be inefficient since the main purpose is to produce light.

Another type of light is the *fluorescent* light tube. In this device the light is also produced indirectly. The electricity pops electrons out of the gas atoms in the tube, and as the electrons, now high in potential energy, fall back to their ground state their excess energy is emitted as photons of light. In a fluorescent light a larger fraction of the electrical energy is converted to light energy, and for this reason fluorescent lights are said to be more efficient than incandescent lights.

Light energy can also be converted to electrical energy. In a “solar cell”, a photon of sunlight pops an electron up in energy, as in the photoelectric effect. These higher energy electrons can then be used to operate electrical devices. The problem is that the “higher energy” electrons have very little excess potential energy and so they are not very good at running motors or operating lights. It’s like trying to run a mill or generate electricity with a waterfall only 1 foot high. One foot high, even a mile wide, is not ideal.

Other interconversions of forms of energy

Almost any form of energy can be converted into another form of energy. Electrical energy and thermal energy can be interconverted by thermocouples, and mechanical energy and electrical energy can be interconverted by piezoelectric crystals.

Energy equivalence

As we have just seen energy in one form can be converted to energy of another form. We would now like to know how much of one form of energy will give how much of another form of energy. One problem in such comparisons is that the unit by which energy is measured for one kind of energy is generally not the same as the unit by which energy is measured for a different kind of energy. Mechanical energy is often reported in joules (J) while thermal energy is reported in calories (cal).

Units of energy

In addition to joules and calories, energy is also measured in British thermal units (Btu), million electron-volts (Mev), barrel-of-oil equivalents (BOE), and many other units depending upon the application and its history.

Units of mechanical energy

When a small apple, approximately 102 grams, is raised up 1 meter from the surface of the earth it has been moved by a force of 1 newton over a distance of 1 meter. The potential energy of the apple has been increased by 1 newton-meter, also called a *joule*. A 1-pound weight raised 1 foot has had its potential energy increased by 1 foot-pound, or 1.356 joules.

Units of thermal energy

When a gram of water is raised in temperature by 1 °C its thermal energy has been increased by 1 *calorie*.

The mechanical equivalent of heat

As we mentioned earlier, the cannon-boring experiments of Benjamin Thompson indicated that what we sense as heat is the energy of motion, or kinetic energy, of atoms and molecules.

A natural question then arises: How many joules of mechanical energy does it take to provide a calorie of thermal energy? This question was first answered about 160 years ago by experiments of James Prescott Joule. He used a paddle wheel device, run by a falling weight, to stir water in an insulated container.

His initial experiments indicated that water falling 778 feet should be warmer by 1 °F after it hits the bottom of the falls . It was his intent to confirm this estimate while on his honeymoon in the Alps. At Chamonix he tested the water, using a huge thermometer that he had brought with him for the purpose. His efforts were frustrated, however, as the water did not fall through that distance, and the amount of spray that was produced spoiled the experiment.

The results of his more careful experiments, refined more recently, indicate that 4.18 newton-meters of mechanical energy is the equivalent of 1 calorie of thermal energy. The newton meter was renamed the joule in honor of Joule's work.

Some equivalencies

A Btu is worth 1055 joules, a kilocalorie, or "food" calorie is worth 4187 joules, a kilowatt-hour is worth 360,000 joules, and a therm is worth approximately 105 500 000 joules (105 million small apples lifted 1 meter).

What does it take to heat a cup of coffee?

If the water for a cup of coffee, 200 grams, is at 20 °C at the start and at 100 °C at the finish it should take 200 grams times 80 degrees C times 1 calorie per gram per degree = 16 000 calories, or 16 Kcal, of thermal energy to heat the water.

At about 4 joules, say, per calorie, the equivalent mechanical energy needed to heat the water would be about 64 000 joules, or 64 kjoules of mechanical energy.

We can estimate, then, that 16 000 small apples falling 1 meter, suitably connected to a propeller inside the cup, could do the job.

Two more equivalencies

An *electron-volt*, analogous to a foot-pound, or pound-foot, is the energy required to increase the potential energy of an electron by 1 volt. For just one electron this is very little energy, but for all the electrons, 6×10^{23} electrons, in a gram of hydrogen 96 000 joules would be needed.

Finally, the *chemical energy of one ton of TNT*, the unit often used to express the energy of a nuclear bomb, is about 4 billion joules. A *kiloton* of TNT would be worth 4 000 000 000 000 (*four trillion*) joules.

Efficiency of interconversion of energy

In our consideration of the conversion of one kind of energy into another kind of energy we have implied that the interconversion can be complete. One kind of energy can be completely converted into only one other kind of energy. That is, interconversion can be accomplished with an *efficiency* of 100%.

Interconversion of potential and kinetic energy

Sometimes the interconversion of potential energy and kinetic energy is almost 100% efficient. The interconversion of potential energy and kinetic energy during the swinging of a pendulum approaches an efficiency of 100%, but the pendulum ultimately comes to rest. Energy is still conserved, however; the “lost” energy is still somewhere, as heat.

Interconversion of mechanical and electric energy

Electric generators and electric motors are not 100% efficient as there are always losses to friction. Some of the mechanical energy put in to run the generator ends up as heat; some of the electrical energy put in to run the motor ends up as heat. Just feel an electric motor that is running; it is warm.

Interconversion of other forms of energy

While energy is always conserved, it is, in practice, impossible to convert all the energy of one type completely into just one other form -- other than heat. There will always be some *friction*; there will always be some *loss* to friction; there will always be some *conversion* to heat.

Conversion of other forms of energy to heat

This is the exception. It *is* possible to convert any form of energy entirely to heat. The conversion to thermal energy *can* be 100% efficient. There are no “losses” to friction; the goal in this instance is complete “conversion” to friction. Joule’s experiments to determine the mechanical equivalent of heat were of this nature.

Conversion of heat to other forms of energy

Heat cannot be *completely* converted to any other form of energy. This is a statement of experience. This is how the world works.

Heat engines

In the “steam” engines that were first used to drive the industrial revolution heat was used to produce and maintain the steam that did the actual pushing, or work. There were many different ways to do this, and so there were many different designs for steam engines. Some were more efficient than others, but none even approached an efficiency of 100%.

Thus the question naturally arose: what is the maximum possible efficiency of a “steam” or heat engine?

A heat engine cannot have an efficiency of 100%

It turns out that it is *impossible* to completely convert heat to any other form of energy. This has never been done, and the reasons that it will never be done are fully understood and accepted. Among the first to understand the impossibility of complete conversion of heat to any other form of energy was Sadi Carnot.

The limit to the efficiency of a heat engine is the subject of the next chapter.

Summary of Energy III; Interconversion of Forms of Energy

- Energy is conserved

- Mechanical energy and electrical energy are interconverted by generators and motors
- Chemical energy and electrical energy are interconverted by batteries.
- Fuel cells convert chemical energy to electrical energy
- Fireflies convert chemical energy to light energy
- Plants convert light energy to chemical energy
- Incandescent bulbs and fluorescent light tubes convert electrical energy to light energy
- Mechanical energy equivalent of thermal energy
- Units of energy: joule, calorie, Btu, electron-volt, Newton-meter, kilowatt-hour, kiloton of TNT
- Efficiency of interconversion of forms of energy: all forms of energy *except for thermal energy*, can be completely converted to any other form of energy. The rate of conversion, however, must be extremely low in order for the efficiency of the conversion to approach 100%. There must be no losses to friction.
- Heat cannot be *completely* converted to any other form of energy under any conditions.