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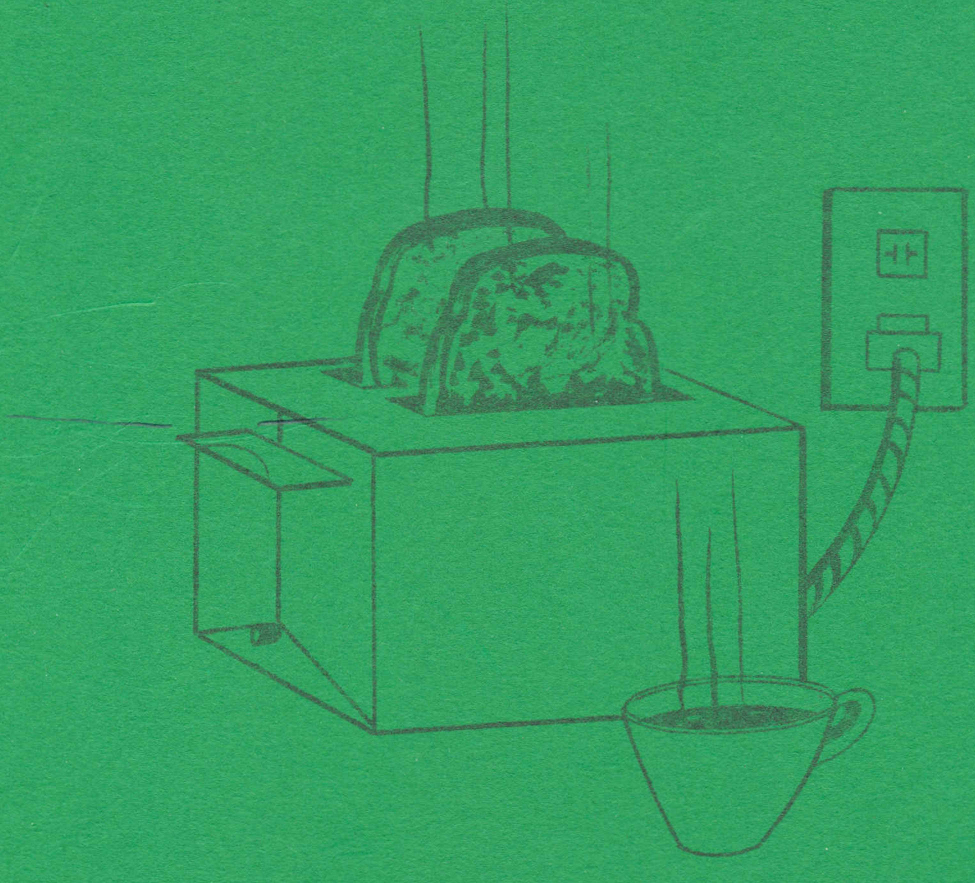
PHYSICS OF TECHNOLOGY — A Modular Approach

THE TOASTER

A MODULE ON HEAT AND ENERGY TRANSFORMATIONS



SUNY

State University of New York at Binghamton

oordinated by the American Institute of Physics

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THE TOASTER

A MODULE ON HEAT AND ENERGY TRANSFORMATIONS

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TOASTER MODULE

Introduction

In our technological society, there are many devices which use electricity for heating processes. You are probably most familiar with those which appear in the home, such as irons, water heaters, clothes dryers, hair dryers, coffee makers, ranges, and toasters. Although you may be less familiar with them, devices based on the same properties are common items in industrial manufacturing plants and research laboratories.

This module introduces the principles needed to understand the operation of such devices. We have chosen to use the toaster as an example. As you work through the module, you should try to reach the following goals:

1. Learn about processes that change electrical energy into heat.
2. Learn to identify the major forms of energy and to describe how one form changes into another.
3. Discover that materials expand when heated and use a formula that describes this effect.
4. Learn to describe one or two systems which are controlled by a thermal expansion device.

This list of goals should give you a general idea of the topics included in the module. More specific statements on what you will be expected to know and be able to do are provided by the following list of learning objectives.

Learning Objectives

This list of objectives indicates what you should be able to do after completing the study of this module:

1. Define in clear and precise sentences the following words: energy, power, specific heat, heat capacity, coefficient of linear expansion.
2. Determine the power delivered to a circuit by a battery by performing the following two steps within 15 minutes:

   a. Given a circuit diagram, a battery, hook-up wires, a resistor, an ammeter, and a voltmeter, measure the appropriate voltage and current.
   b. Calculate the power.
3. Determine the energy delivered to a resistor by performing the following two steps within 20 minutes.
   a. Given the same equipment as for the preceding objective plus a timer, measure the appropriate voltage, current and time interval.
   b. Calculate the energy in joules.
4. Given two of the following three quantities for an object, determine the third: heat capacity, temperature change, quantity of heat.
5. Convert energies from any one to any other of the following units: joules, calories, B.t.u.'s, kilowatt-hours. (A table of conversion factors will be provided.)
6. Determine experimentally within 30 minutes the heat capacity of an object by measuring the temperature rise for a measured input of electrical energy using the following apparatus: the object, material to insulate the object, a voltmeter, an ammeter, a clock, a thermometer, hook-up wires and a source of electricity.
7. Given an object made up of several different materials, determine an approximate value for the heat capacity of the object by estimating the masses of the different materials, looking up approximate values for specific heats of the materials, and performing the appropriate calculations.
8. Given a control system based on the thermal expansion of materials (such as in the toaster), describe the sequence of events by which the thermal control mechanism produces a desired result or prevents an undesirable one when energy is supplied to the device.
9. Given a process which involves the transformation of energy among several different forms and a list of energy forms, identify all forms of energy which change during the process and state which are increasing and which are decreasing during each stage of the process.
10. Given two of the following three quantities for an electric cir-

cuit, determine the third: voltage, current, power.

11. Given two of the following three quantities for a circuit, determine the third: time, power, energy.
12. An object is heated through a range in which the specific heat is constant. Given three of the following four quantities, determine the remaining quantity: heat, specific heat, mass, change in temperature.
13. An object is heated through a range in which the coefficient of thermal expansion is constant. Given three of the following four quantities, determine the remaining quantity: change in length, original length, coefficient of thermal expansion, change in temperature.
14. Given a bimetallic strip made of known metals and a table of coefficients of thermal expansion, determine which way the strip will curve when heated.
15. Given the appropriate formula, the dimensions and composition of a bimetallic strip, the coefficients of thermal expansion for both metals, and the temperature change from the situation in which the strip was straight, calculate the angle of curvature of the strip.
16. Given the appropriate formula, the dimensions and composition of a bimetallic strip, the coefficients of thermal expansion for both metals, and the temperature change, calculate the amount of movement of one end of the strip.

THE TOASTER

The toaster is a simple device to operate: you plug it in, put in the bread, lower the mechanism, and in a short time, up pops the toast.

There are several interesting aspects to the toaster which must be studied if the principles of operation are to be understood. An essential feature is that the toaster produces heat by using electricity. This is an example of a general process we see many times every day: energy changing from one form to another. This process and the laws of nature which govern it are of such great importance that we shall study them in some detail.

Before we discuss the process, the meaning of the word "energy" must be established. Energy is the capacity to do work. Since we have defined one scientific word, energy, in terms of another, work, we must be certain that we know the meaning of the word "work." If you push a hand lawnmower across the lawn, you do work. If you raise a book from the floor to a table top, you do work. The amount of work done by a force acting in the direction of motion is equal to the force multiplied by the distance moved. With that in mind, the definition should be more meaningful. A person (or an object) has energy if he (or it) has the capacity to do work. The best way to grasp the meaning of energy is to consider the various forms in which it appears.

Forms of Energy

One of the most obvious forms of energy results from the ability of a raised object to do work. In general, an object in a higher position can do work in the process of moving to a lower position. This type of energy, associated with the potential to do work as a result of the gravitational force, is called

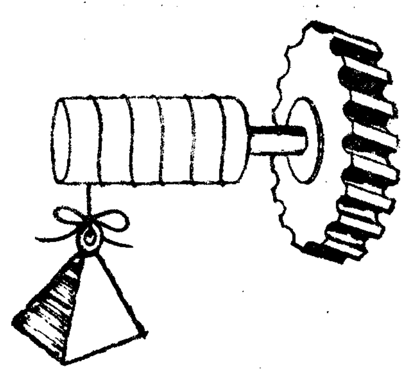


Fig. 1. As the weight falls it runs machinery which does work.

gravitational potential energy.

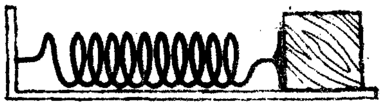


Fig. 2. A compressed spring can move objects, thereby doing work.

Another common form of energy is the result of forces produced in stretching, compressing, bending or twisting materials. Such forces are called elastic forces.

The potential to do work as a result of elastic forces is called elastic potential energy. Consider this example of elastic energy. When you lower the mechanism which carries the bread into the toaster, you compress a spring. Later, the elastic potential energy of the compressed spring does the work of "popping up" the toast.

If you have ever driven a nail with a hammer, you have used another form of energy, called kinetic energy. The work which can be done by a moving object in being brought to rest is called kinetic energy.

("Kinetic" refers to motion.)

We distinguish between the two types illustrated in Figure 3 by calling the first translational and the second rotational kinetic energy. If the motion is described by referring to the turning about some axis, it is called rotational motion.

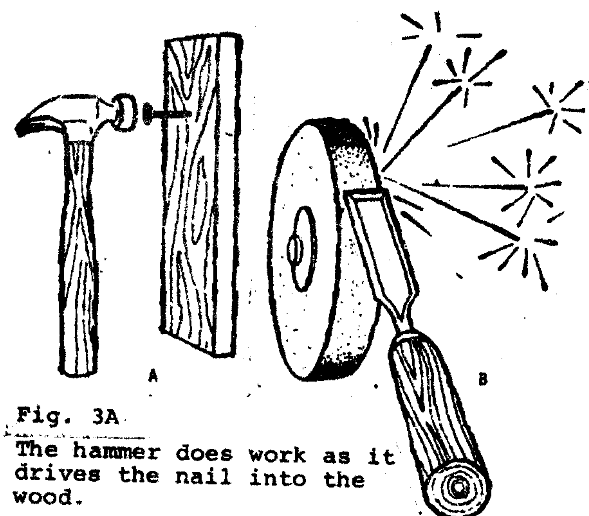


Fig. 3A
The hammer does work as it drives the nail into the wood.

Fig. 3B.
The grinding wheel does work as the wheel slows down, even after the power is shut off.

A form of energy which may not be as familiar as the ones already mentioned is the energy associated with electricity. The energy associated with charged particles at rest or in motion is called electromagnetic energy. In everyday life, this energy is most often used in systems which have charged particles moving through wires. This kind of energy is often called simply electrical energy. Examples include the energy required to operate the toaster, electric motors, and electric lights.

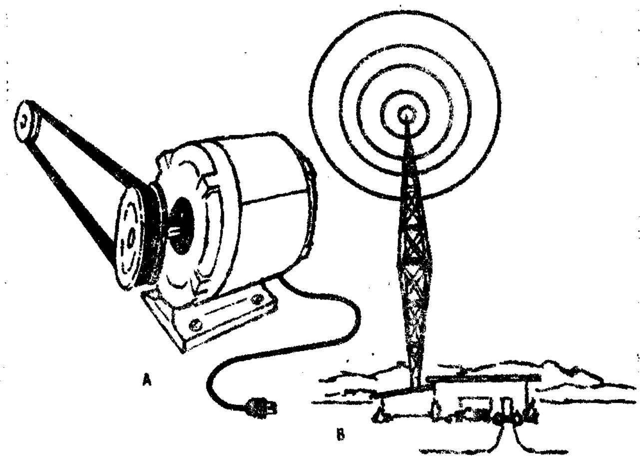


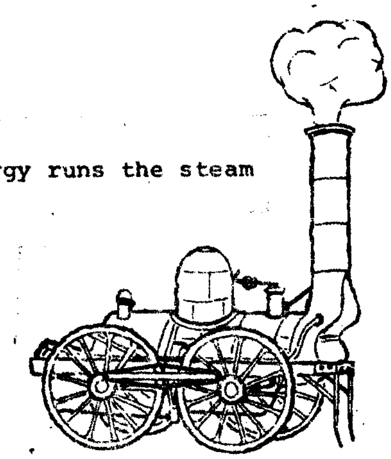
Fig. 4A.
Electricity runs the motor, which does work.

Fig. 4B.
Radio waves are capable of doing work.

Charges at rest sometimes contain a form of electromagnetic energy called electrostatic potential energy. If you rub a balloon on your hair on a dry day, the balloon acquires the ability to lift your hair, or other small objects, and thus do work. Moving storm clouds also become charged and clearly develop the potential to deliver large amounts of energy in the form of lightning bolts. The sudden light and sound is caused by a huge electric current, and it is an example of electrical energy which results in work being done. But even before the lightning strikes, the cloud has the capacity to deliver work, and thus we say it has electrostatic potential energy.

Electromagnetic energy also appears in the form of electromagnetic radiation. This includes radio and TV waves, light, X rays, and gamma rays (a gamma ray is electromagnetic radiation produced by nuclear effects).

Fig. 5.
Thermal energy runs the steam engine.



A form of energy which keeps us warm and does a variety of other things for us is called heat energy or thermal energy. Heat is the energy which is transferred from one object to another because of a temperature difference. Heat is usually involved in such processes as raising the temperature of an object, melting and boiling.

As you read and turn these pages, you are using a form of energy called chemical energy. Chemical energy is associated with all processes in which the atoms are rearranged to form different substances (chemical reactions). Examples of such reactions include burning, the production of electrical energy in a battery, and the production in a muscle of the energy needed to turn a crank.

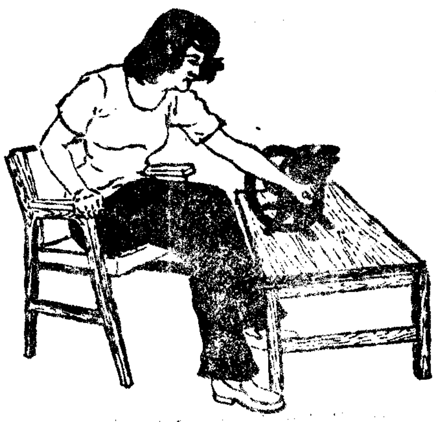


Fig. 6. The work done by the woman comes from the chemical energy in the food she ate.

The most recent form of energy to be used by man is nuclear energy. The energy which comes from the core, or nucleus, of the atom is called nuclear energy. Among our energy resources, only the light and heat radiation received from the sun is greater than the presently known sources of nuclear energy.

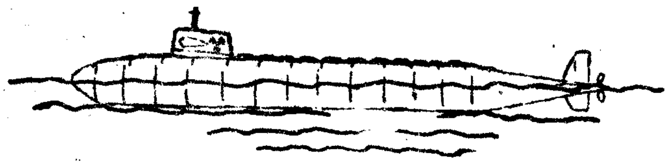


Fig. 7. Nuclear energy is changed to thermal energy and the thermal energy powers the submarine.

In summary, we identify the following forms of energy:

I. Mechanical energy
  (a) Gravitational potential energy
  (b) Elastic potential energy
  (c) Kinetic energy (rotational and translational)

II. Electromagnetic energy
  (a) Electrical energy
  (b) Electrostatic potential energy
  (c) Electromagnetic radiation

III. Heat energy

IV. Chemical energy

V. Nuclear energy

Transformations of Energy

It is possible to think of many different processes which involve changes from one kind to another among the different types of energy. For example, when using nuclear energy, heat is produced before the work is done. The main feature of the toaster is the changing of electrical energy to heat.

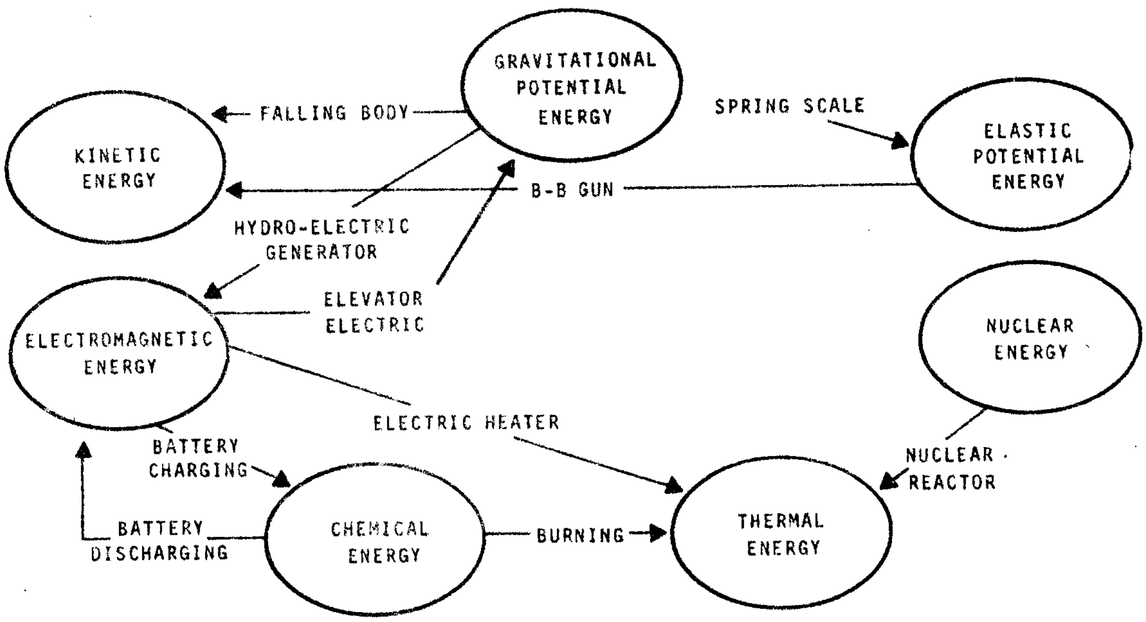


Fig. 8. A few of the many different energy transformations.

Let's look at some other situations which involve energy transformations.

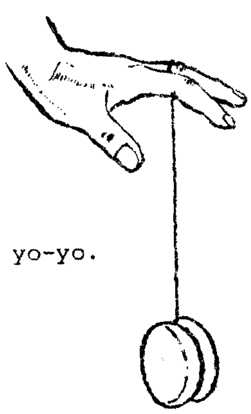


Fig. 9. The yo-yo.

As the yo-yo unwinds, it drops lower, thus losing gravitational potential energy. But as it moves down, it goes faster; therefore, the kinetic energy increases. Thus we have an example of the change of gravitational potential energy into translational and rotational kinetic energy. When the string is all unwound, it starts rewinding; the yo-yo climbs back up, transforming kinetic energy into gravitational potential energy.

You will find a clever example of energy transformation in the pop-up mechanism on some toasters. When you push down the handle to lower the elevator mechanism, it compresses a spring. When the toast is done, the elevator is released and the elastic potential energy is changed into other forms. Some goes into gravitational potential energy of the elevator and toast. Some goes into translational kinetic energy of the elevator and toast.

A difficulty appears when designing the elevator. If the spring is made strong enough to lift the heaviest slices of bread, it will be so strong it will throw the lightest slices into your corn flakes. When you examine the toaster in the laboratory, you will see how this problem is solved by causing some of the elastic potential energy to go into rotational kinetic energy.

In almost all processes involving energy transformation, some heat is produced whether you want it or not. In the two cases just discussed, the yo-yo and the toaster elevator, the rubbing of one surface on another produces heat energy (but not much). As another example, an electric motor gets warm while running because of friction in the bearings and because of resistance in the wires.

Discuss the energy transformations in the following devices or processes:

1) a flashlight
2) a wind-up clock
3) a car moving at constant speed
4) a car accelerating
5) a football thrown into the air

Conservation of Energy

Throughout the preceding discussion of energy transformations, we have hinted at an idea: Energy cannot be created or destroyed, although its form may be changed. This is a very fundamental law of nature and is called the law of conservation of energy.

In order to proceed with a meaningful discussion of the law, we must state how to assign numbers to various forms of energy. Descriptive terms are not sufficient; we need numbers. Although it is possible to do this for all the various forms of energy, we will concentrate on the two forms of central importance to the toaster: electrical energy and thermal energy.

ELECTRICAL ENERGY*

The amount of electrical energy delivered to or by a circuit element is determined by three things: the current, the voltage, and the time.

Current is the rate at which electric charge flows through a circuit. The common unit for current is the ampere. The device used for measuring current is called an ammeter. (The name "ammeter" comes from "ampmeter," but for some strange reason the "p" is left out.)

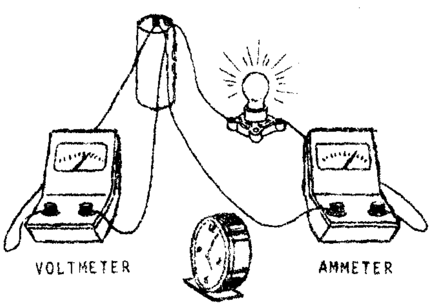


Fig. 10.

*This treatment of electricity is valid for all direct current circuits and for many alternating current devices, including the toaster.

The voltage between two points in an electric circuit is equal to the work done per unit charge as the charge moves from the first point to the second. Saying it another way, for simple circuit elements like heating coils, a larger voltage across the element causes a larger current to flow. The unit of voltage is the volt; an instrument that measures voltage is called a voltmeter.

The work that charges (electrons) do when they move through the wires of a toaster is to bump into atoms of the metal wire and cause them to vibrate. The energy of the vibrating atoms is the same energy we previously called heat energy or thermal energy. If a certain unit of charge produces 2 calories of heat energy when it flows through a resistor, and if 3 such units flow through the resistor every second, then the heat energy produced is 6 calories per second. (The calorie is a unit of heat. It will be defined later).

Since voltage is work per unit charge and the current is rate of flow of charge (charge per unit time), the product of the two is work per unit time:

$$\frac{\text{work}}{\text{charge}} \times \frac{\text{charge}}{\text{time}} = \frac{\text{work}}{\text{time}}$$

The rate of doing work (work per unit time) is called power. Thus we have:

voltage X current = power.

In terms of the common symbols for these quantities,

$VI = P$

If the voltage is expressed in volts and the current in amperes, then the power is in units called watts, one watt equals one volt-ampere. To give you some feeling for the size of a watt, a person running up a flight of stairs uses about 500 watts of power.

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NOW IS THE TIME TO DO EXPERIMENTS 1 and 2

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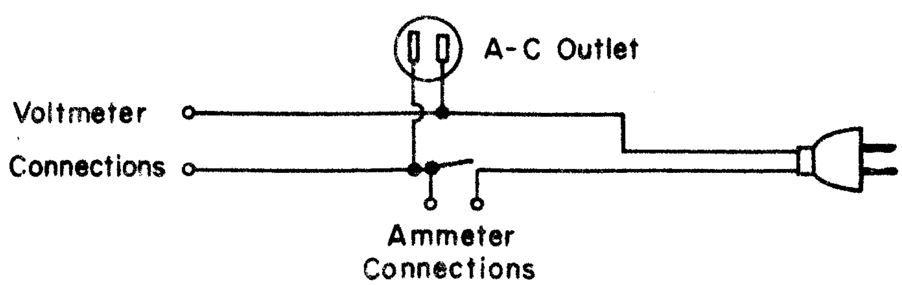
EXPERIMENT 1 - ELECTRICAL POWER - IMMERSION HEATER

In this experiment you will measure the electrical power delivered to an immersion heater and will compare the measured value with the manufacturer's rating for the device.

Since electric power is the product of current and voltage, it can be determined quite easily through use of an ammeter and voltmeter. To simplify the wiring, a transfer box is provided.

The immersion heater, voltmeter, and ammeter are all connected to this box.

CAUTION: Be sure the transfer box is not plugged in when you make your connections. Your instructor will plug it in



Transfer Box

after checking your circuit.

Place the heater in a cup of water before closing the circuit; it will burn out if provided with power when not in water. Complete the connections and ask your instructor to check the circuit.

Record the meter readings, then unplug the heater. Compute the power. Does it agree with the rated power stamped on the heater?

EXPERIMENT 2 - ELECTRICAL POWER - TOASTER

Use the procedure of Experiment 1 to determine the power delivered to the toaster. Compare with the manufacturer's rating.

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Example 1. Determine the power provided by a 6 volt battery to a circuit drawing 2 amperes.

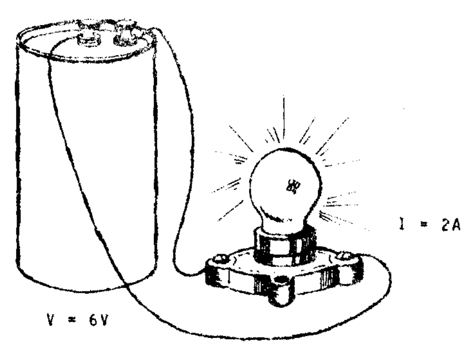

Fig. 11.

Solution:

$P=VI$

$= (6 \text{ volt}) \quad (2 \text{ amperes})$

$= 12 \text{ (volt X ampere)}$

$= 12 \text{ watts.}$

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Example 2. A light bulb is stamped "40 watts, 120 volts." How much current will it draw when connected to a 120 volt line?

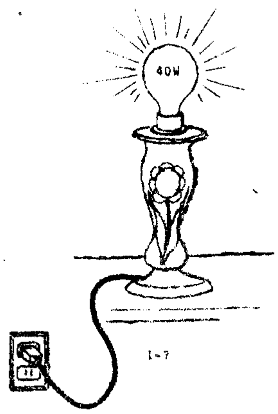

Fig. 12.

Solution: In this case the power and voltage are known and it is necessary to solve for current.

$P=IV$

$I= \frac{P}{V}$

$= \frac{40 \text{ watts}}{120 \text{ volt}}$

$= \frac{40 \text{ (volt x ampere)}}{120 \text{ volt}}$

$= \frac{1}{3} \text{ ampere.}$

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In many cases we will be interested not in the rate at which work is being done, but the amount of work done during some time. Since power is the rate at which work is done, just multiply by time to get the work, or energy:

$$W = Pt$$
$$= VIt$$

If the power is in watts and the time in seconds, then the work or energy is in watt-seconds. This combination of units appears so often we give it a name of its own; joule. That is, a joule is a watt-second. To give you a feeling for the size of a joule, it is approximately the energy needed to lift a hamburger three feet.

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Example 3. How much electrical energy is converted to heat and light if a 100 watt light bulb is left on for one hour?

Solution:

$$W = Pt$$
$$= (100 \text{ watt}) \quad (1 \text{ hour})$$
$$= (100 \text{ watt}) \quad (3600 \text{ sec})$$
$$= 360{,}000 \text{ joules}$$

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Although the joule is the unit of work and energy preferred by scientists, a more common unit when dealing with electricity is the kilowatt-hour, abbreviated kWh. It is the energy of a 1000 watt (one kilowatt) source run for a time of one hour. This is approximately the energy needed to lift a car to the top of the Empire State Building. The conversion between kilowatt hours and joules is easily established:

$$1 \text{ kilowatt hr} = 1000 \text{ watt hr}$$
$$= 1000 \text{ watt } (3600 \text{ sec})$$
$$= 3.6 \times 10^6 \text{ watt-sec}$$
$$= 3.6 \times 10^6 \text{ joules}$$

In circuit problems, it is convenient to compute the energy directly in units of kilowatt-hrs.

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Example 4. How much energy is required to make a slice of toast? The toaster is rated at 1200 watts, and the toasting time is one minute. Express the answer in kilowatt-hrs.

Solution:

$$W = Pt$$
$$= (1200 \text{ watts}) \quad (1 \text{ min})$$
$$= (1.2 \text{ kilowatts}) \quad (1/60 \text{ hr})$$
$$= 0.02 \text{ kilowatt-hr}$$

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Example 5. If electricity costs 2¢ per kilowatt-hr, for how many hours will 50¢ run a 1000 watt space heater?

Solution: At 2¢ per kilowatt-hr, 50¢ will buy 25 kilowatt-hr. Knowing the number of kilowatt-hr, we can solve for the time:

$$W = Pt$$

$$t = W/P = \frac{25 \text{ kw hr}}{1 \text{ kw}} = 25 \text{ hr}$$

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THERMAL ENERGY

Raising the temperature of an object by rubbing it is a simple experiment which shows that work and heat are somehow related.

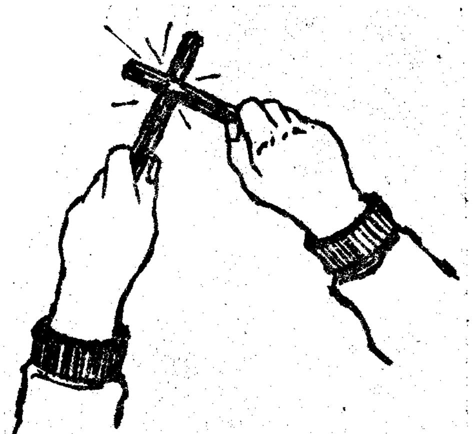

Fig. 13. Rubbing causes a temperature rise.

Indeed it was just this type of experiment which led to the identification of heat as a form of energy. Near the end of the eighteenth century Count Rumford noticed that during the drilling of cannon barrels, heat was produced for as long as the drilling continued. Later experiments proved that other forms of energy could be changed to heat, and vice versa. These observations led to the statement of the basic law of conservation of energy.

However, long before it was realized that heat is a form of energy, scientists had studied the effects of heat on such things as temperature, melting, and boiling. To explain their observations they assumed that a substance, which they called "caloric," flowed from one object to another during heating processes. Although we no longer believe the caloric theory, a souvenir remains in the name for a unit of thermal energy, the calorie. A calorie is the heat required to raise the temperature of one gram of water one centigrade degree.

If heat is applied to a sample of material, the temperature will rise. We find that the amount of heat required is proportional to the mass (m) of material and also proportional to the change in temperature (ΔT)*. That is,

$$Q = cm\Delta T$$

where Q is the amount of heat and c is a constant for a given material but has different values for different materials. The constant c is called the specific heat. Note that

*The symbol Δ, which is the Greek letter delta, indicates the change in a quantity.

from the definition of calorie, the specific heat of water is one calorie per gram-centigrade degree. If the specific heat of a substance is known, the amount of heat required to increase the temperature of a given mass of the material a given amount can be determined.

The table below lists the experimentally determined values of specific heat for several common substances. (The values are the same in both the metric system of units and in the British system which will be described shortly.)

* *

TABLE I. Specific Heat

	cal/gmC° or B.t.u./lb F°
Aluminum	0.215
Bakelite	0.55
Copper	0.092
Glass	0.20
Iron	0.113
Lead	0.030
Water	1.00

* *

Example 6. How much heat is required to raise the temperature of 5 kilograms of iron six centigrade degrees?

Solution: Consulting the table above we find that the specific heat of iron is 0.113 cal/gm-C°.

$$Q = cm\ T$$
$$= (0.113\ \text{cal/gm C}^\circ\ (5000\ \text{gm})\ (6\ \text{C}^\circ)$$
$$= 3{,}390\ \text{cal}$$

Note that in using the formula $Q = cm\Delta T$, m must be expressed in grams if you want Q to come out in calories. Some scientists prefer to express m in kilograms and this will result in a value for Q expressed in kilocalories. This unit for energy, the kilocalorie, is the same amount of convertible energy contained by food when a dietician says the food contains one calorie. To say it another way, the "dietary calorie" is really a kilocalorie.

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NOW IS THE TIME TO DO EXPERIMENT 3

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EXPERIMENT 3 - CONVERSION OF ELECTRICAL ENERGY TO THERMAL ENERGY

In this experiment you will determine the electrical energy provided in heating a cup of water, and will compare it with the increase in thermal energy.

The electric energy provided is equal to the product of the power and the time. Therefore by adding a clock to the equipment used in Experiment 1, you will be able to determine the energy.

The increase in thermal energy, Q, is determined by the mass of water, m, the specific heat of water, c, and the change in temperature, ΔT:

$$Q = mc\Delta T.$$

Plan your experiment. We suggest that you start with cold tap water and heat it to about 80°C, inserting the heater nearly to the bottom of the cup. Stir gently but continuously. Before beginning, note which quantities must be measured in order to calculate the electrical energy and the thermal energy.

After completing your measurements, calculate the electrical energy provided in joules and the increase in thermal energy in calories. Compare the two by applying the appropriate conversion factor. How well do they agree? What factors could cause the two values to differ?

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Another heat unit frequently used in English speaking countries is the British thermal unit, abbreviated B.t.u. A B.t.u. is the amount of heat required to raise the temperature of one pound of water one Fahrenheit degree.

Calories and B.t.u.'s are different units for the same physical quantity, energy. So they must be related by a conversion factor. And they can both be related to the units for energy introduced earlier, joules and kilowatt-hrs. The conversion factors for these energy units are given in the table at the top of the following page.

TABLE II

Conversion Factors

one joule $= 2.78 \times 10^{-7}$ kwh

$= 0.239$ cal

$= 9.48 \times 10^{-4}$ B.t.u.

one calorie $= 1.16 \times 10^{-6}$ kwh

$= 4.18$ joule

$= 3.97 \times 10^{-3}$ B.t.u.

one kWh $= 3.60 \times 10^{6}$ joule

$= 8.60 \times 10^{5}$ cal

$= 3.41 \times 10^{3}$ B.t.u.

one B.t.u. $= 252$ cal

$= 1055$ joule

$= 2.93 \times 10^{-4}$ kwh

* *

Example 7. How much energy is required to raise the temperature of 10 lb of copper from 70° to 250°F? Express the answer in B.t.u.'s, calories, joules, and kilowatt-hrs.

Solution: We can apply the equation

$$Q = cm\Delta T.$$

Since the amount of material and the temperatures are expressed in English units, it will be convenient to do the calculation first in B.t.u.'s. Consulting the specific heat table we find the specific heat for copper.

$$Q = (0.092 \text{ B.t.u./lb-F}^{\circ})(10 \text{ lb})(180\text{F}^{\circ})$$

$$= 166 \text{ B.t.u.}$$

Now we can use the conversion factors in Table II to express the heat in other units.

$$Q = 166 \text{ B.t.u.} \left(\frac{252 \text{ cal}}{\text{B.t.u.}}\right) = 4.18 \times 10^{4} \text{ cal}$$

$$Q = 166 \text{ B.t.u.} \left(\frac{1055 \text{ joule}}{\text{B.t.u.}}\right) = 1.75 \times 10^{5} \text{ joule}$$

$$Q = 166 \text{ B.t.u.} \left(\frac{2.93 \times 10^{-4} \text{ kwh}}{\text{B.t.u.}}\right) = 4.86 \times 10^{-2} \text{ kwh}$$

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Example 8a. How many calories of thermal energy are produced by a 1200 watt toaster which stays on for one minute?

Solution: In Example 4 we calculated the energy for such a case:

$$W = Pt$$

$$= (1200 \text{ watt})(1 \text{ min})$$

$$= 0.02 \text{ kwh}$$

Applying the conversion factor from Table II

$$W = Q = 1.72 \times 10^4 \text{ cal}$$

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Example 8b. How much water can be heated from room temperature (20°C) to the boiling point (100°C) by the heat referred to in example 8a?

Solution:

$$Q = cm\Delta T$$

$$m = \frac{Q}{c\Delta T}$$

$$= \frac{1.72 \times 10^4 \text{cal}}{(1 \text{ cal/gmC}^\circ)\ (80\text{C}^\circ)} = 215 \text{ gm}$$

This is approximately one cup of water.

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Example 9. An electric heater is imbedded in a 2 kilogram piece of aluminum. The heater draws six amperes at 120 volts. If the temperature of the aluminum is initially 20°C, what will it be at the end of five minutes? (Ignore any heat losses to the surroundings.)

Solution: From the information on current, voltage and time, the amount of electrical energy can be calculated.

$$W = VIt$$

$$= (120 \text{ volt})\ (6 \text{ amp})\ (5 \text{ min})$$

$$= 3600 \text{ watt-min}$$

$$= 216{,}000 \text{ joule}$$

This energy appears as heat. For determining the temperature change, it is convenient to express this energy in calories.

$$W = Q = 216{,}000 \text{ joule } \left(\frac{1 \text{ cal}}{4.18 \text{ joule}}\right)$$

$$= 51{,}600 \text{ cal}$$

Now we can use the equation

$$Q = cm\,\Delta T.$$

Solving for ΔT,

$$\Delta T = Q/cm$$

$$= \frac{(51{,}600 \text{ cal})}{(0.215 \text{ cal/gmC}^\circ)\ (2000 \text{ gm})}$$

$$= 120\text{C}^\circ$$

$$T_{final} = 20^\circ + \Delta T = 140^\circ\text{C}$$

Therefore the temperature at the end of five minutes is 140°C.

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Another quantity often met in dealing with heat problems is the heat capacity, K, for an object. It is defined as the heat added to an object divided by the change in temperature resulting. For example, if 2000 cal. are required to change the temperature of some object by 10 C$^\circ$, the heat capacity is 2000 cal divided by 10 C$^\circ$, or 200 cal/C$^\circ$. Note that heat capacity is a characteristic of an <u>object</u> whereas specific heat is a characteristic of a <u>material</u>. If the heat capacity of an object is known, the heat required for a specified temperature change is readily determined:

$Q = K\Delta T.$

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Example 10. The heat capacity of a pot of beans is 1500 cal/C°. How much energy is required to raise its temperature from 20°C to 90°C?

Solution:

$Q = K\Delta T$

$= (1500 \text{ cal/C}^\circ)\ (70\ \text{C}^\circ)$

$= 105{,}000$ cal.

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For an object made up of several materials, the heat capacity can be calculated if the amount of each material and the specific heat for each material is known.

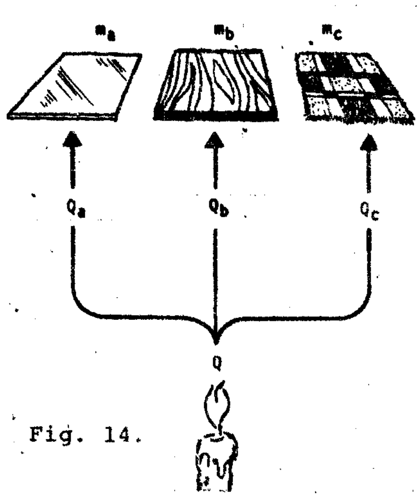

Fig. 14.

Suppose you have an object made up of three materials, a,b,c, with masses m_a, m_b, m_c, and specific heats c_a, c_b, c_c. To produce a temperature change ΔT in material a, the amount of heat required is

$Q_a = c_a m_a \Delta T.$

Similar expressions apply for materials b and c. The total heat needed to raise the temperature of the entire object is

$$\begin{aligned} Q &= Q_a + Q_b + Q_c \\ &= c_a m_a \Delta T + c_b m_b \Delta T + c_c m_c \Delta T \\ &= (c_a m_a + c_b m_b + c_c m_c)\Delta T \end{aligned}$$

This same total heat can be expressed in terms of K, the heat capacity:

$Q = K\Delta T.$

Comparing the two expressions, we see that the following must be true:

$K = c_a m_a + c_b m_b + c_c m_c.$

This procedure can be used no matter how many different materials are involved.

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NOW IS THE TIME TO DO EXPERIMENT 4

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EXPERIMENT 4 - HEAT CAPACITY

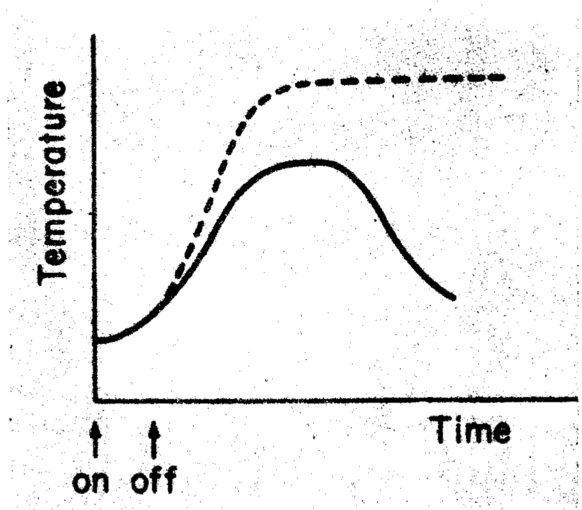
In this experiment you will experimentally determine the heat capacity of the toaster and will compare the result with a rough estimate based on the mass and specific heat of the materials in the toaster.

Recall the definition of heat capacity; the heat capacity of an object is the heat required to produce some temperature change.

The amount of heat is equal to the electrical energy delivered to the toaster. It can be determined by measuring the power for the toaster and the time during which that power is applied. Since heat is customarily expressed in calories, it is appropriate to convert the energy in joules to energy in calories by applying the appropriate conversion factor.

The change in temperature can be determined by attaching a thermometer to the toaster. However there are some complications. The heating occurs in the heating elements within the toaster, and it takes some time for this heat to be distributed so that the toaster will have a uniform temperature. (In Experiment 3 you could keep the water temperature uniform by stirring; unfortunately you cannot stir the toaster.) While you are waiting for a uniform temperature, there will be considerable heat loss to the surroundings. This effect can be reduced by placing an insulating box over the toaster, but the losses are still appreciable. Fortunately there is a way to approximate the effect of these losses and adjust your data accordingly.

Suppose that you plugged in the toaster, left the power on for a minute or so, and then removed the plug. You then record the temperature as a function of time, taking readings every 30 seconds both while the power is on and for 20-30 minutes after the power is turned off. Don't stop until the temperature reaches the value it had when the power was turned off. If you plotted these data, the graph would look like the solid line in the graph below:



The temperature will rise only slightly during the short time that the toaster is on because very little of the heat will have reached the location of the thermometer. If there were no losses, the temperature curve would follow the dotted line, approaching some final temperature as the heat gets distributed throughout the toaster. The effect of the losses is to cause the temperature to follow the solid line. By noting the temperature loss per unit time during the cooling part of the curve, you can obtain an approximate value for the temperature loss during the rising portion of the curve. To do this, pick a time when the temperature of your toaster was just beginning to fall. Pick a later time at which the temperature had fallen to a value equal to what it was when the power was turned off. Divide this temperature difference by the elapsed time in minutes. The number you get is the average number of degrees the temperature fell each minute over this temperature range. Multiply this number by the number of minutes the temperature of the toaster was rising. Since the toaster presumably "lost" this many degrees while it was heating, this number should be added to the total observed increase to obtain the increase we would have observed for the same energy input if there had been no heat losses to the surroundings.

With the toaster unplugged and set for "light" toast, attach the thermometer to the end with the tape provided, and lower the elevator. Carefully place the insulating box over the toaster, guiding the thermometer through the hole in the box. Wait a few minutes to be sure the temperature is steady. Use the time to plan your measurements and prepare your data sheet. You must record the current, voltage, and the time the toaster stays on after plugging it in. Temperature should be recorded every 30 seconds during the early part of the run. Later, when the temperature is changing more slowly, the measurements can be less frequent.

Calculate the heat capacity of the toaster from the experiment data.

For a comparison with the experimental value, a rough estimate of the specific heat can be calculated from the mass and specific heat of the materials in the toaster. To do this it helps to have the toaster partly taken apart. (Check with the instructor before doing this.) This provides you with three components whose contribution to the heat capacity can be computed separately; the steel case, the "guts," and the end caps. The mass of each of these can be determined with a beam balance.

The contribution from the steel case can be determined easily by multiplying the mass by the specific heat of steel (about 0.1 cal/gm C^o).

The material in the end caps is either bakelite or a similar material. If you check tables of specific heat for such materials, you find that they all have a value of about 0.5 cal/gm C^o. Thus the contribution from the end caps can be estimated.

The contribution from the remainder of the toaster presents a problem because there are many different materials. However, if you check the specific heat for any of the materials which appear in significant quantity, you find that they vary between 0.1 and 0.2 cal/gm C^o. Therefore if you use a value of 0.15 cal/gm C^o, your result should be accurate to within about 25%.

From these three contributions obtain your rough estimate of the heat capacity and compare with the value determined from the heat and temperature measurement. Do they agree as well as you might expect?

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Example 11. An object consists of 2 kilograms of iron, 0.6 kilograms of aluminum and 0.4 kilograms of bakelite. What is the heat capacity of the object?

Solution:

$$\begin{aligned} K &= (0.113 \text{ cal/gmC}^o)(2000 \text{ gm}) \\ &\quad + (0.215 \text{ cal/gmC}^o)(600 \text{ gm}) \\ &\quad + (0.5 \text{ cal/gmC}^o)(400 \text{ gm}) \\ &= (226 + 129 + 200) \text{ cal/C}^o \\ &= 555 \text{ cal/C}^o \end{aligned}$$

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THERMAL EXPANSION

The preceding discussion has provided the basis for an understanding of the energy transformation (electrical to thermal) which occurs in the toaster. Another important feature of the toaster is the control system, the mechanism for shutting off the current at the right time. Could this be a simple clock timer? No; it takes less time for the second batch than it does for the first because the toaster is "pre-heated." The control system must somehow be based on heat and temperature, not time. To understand how this is accomplished, it is necessary to begin by studying a physical property called thermal expansion.

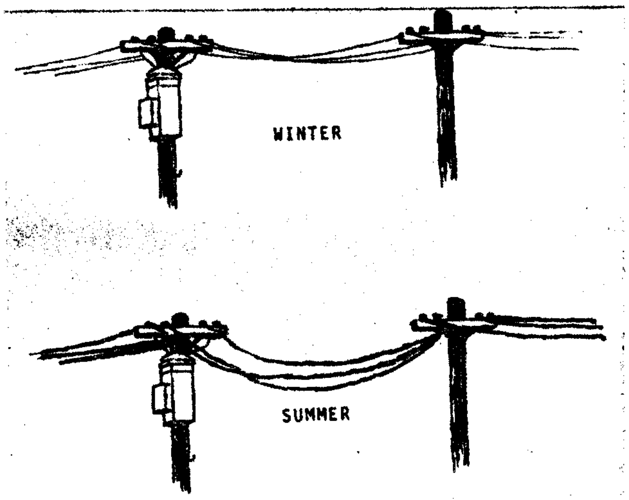

Fig. 15.

Have you ever noticed that electric power lines sag more in summer than in winter? This occurs because the wires expand when heated; this is called thermal expansion.

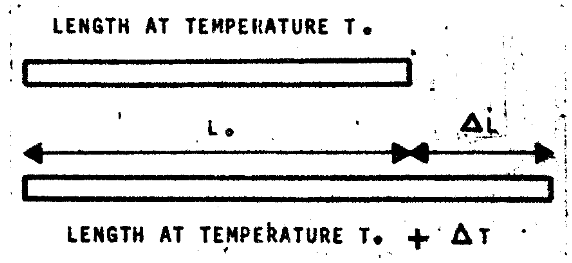

Fig. 16. In this figure the amount of thermal expansion is greatly exaggerated.

Experiments show that the change in length; ΔL, is proportional to the original length, L_o, and to the change in temperature, ΔT:

$$\Delta L = \alpha L_o \Delta T.$$

The constant of proportionality, α, is called the coefficient of linear expansion and its value depends on the material. Table III gives the experimentally determined values of this coefficient for several materials.

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TABLE III

Coefficients of Linear Expansion

	per C^o	per F^o
Aluminum	23×10^{-6}	13×10^{-6}
Brass	19×10^{-6}	11×10^{-6}
Glass (Pyrex)	3.2×10^{-6}	18×10^{-6}
Invar	0.8×10^{-6}	0.4×10^{-6}
Iron	12×10^{-6}	6.6×10^{-6}
Copper	17×10^{-6}	9.2×10^{-6}

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Example 12. Determine the change in length of a copper wire, originally 150 feet long, if the temperature is changed from $10^\circ F$ to $90^\circ F$.

Solution: From Table III, α for copper is $9.2 \times 10^{-6}/F^\circ$.

$$\Delta L = \alpha L_o \Delta T$$
$$= (9.2 \times 10^{-6}/F^\circ)\ (150\ ft)\ (80F^\circ)$$
$$= 0.110\ ft = 1.3\ in$$

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This dependence of size on temperature can be used in devices that measure temperature, and in devices that control temperature, such as the control mechanism in a toaster. Because the change in length is very small, many of these devices use two different materials in a clever way which has the effect of magnifying the movement. The arrangement is called a bimetallic strip.

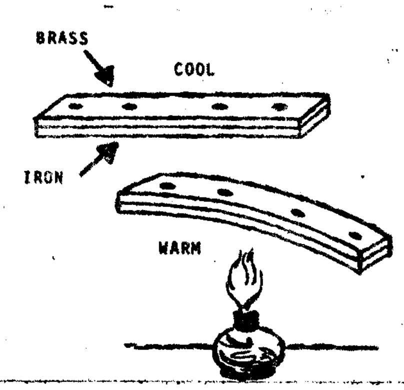

Fig. 17. A bimetallic strip curves when heated.

Figure 17 shows such a strip. The device consists of a thin strip of iron attached to a thin strip of brass. If the temperature of the strip is increased, both the iron and the brass will expand. However, the brass will expand about 1½ times as much as the iron because of its greater coefficient of expansion. How can the two have different lengths and still remain fastened together? The strip must curve, as shown in Figure 17.

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OPTIONAL DERIVATION

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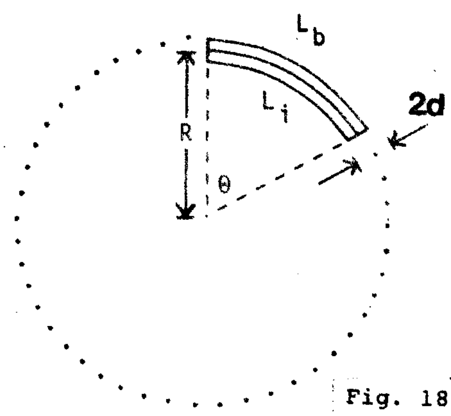

Fig. 18.

Figure 18 shows an idealized "model" of what happens when a bimetallic strip is heated. For our model we are assuming that the strip curves so that it is simply an arc of a circle whose radius is R. The angle θ is a convenient quantity to use as a measure of the curvature. Our task now is to predict θ ; that is, to find an expression for θ in terms of the original length, L_o, the change in temperature, ΔT; the two coefficients of expansion, α_b and α_i, and the thickness of each strip, d.

First let us find θ in terms of the length of the brass strip, L_b, and the length of the iron strip, L_i. Note that L_i is a certain fraction of the circumference of a circle; the fraction is $\frac{\theta}{360^o}$. Therefore

$$L_i = \frac{\theta}{360^o} \text{ times circumference}$$

$$= \frac{\theta}{360^o} 2\pi R \text{ where}$$

R is the average radius of the iron strip. We can write down the corresponding expression for the length of the brass strip, noting that the average radius for the brass strip is greater than that for the iron by an amount equal to the thickness, d;

$$L_b = \frac{\theta}{360^o} \; 2\pi (R + d).$$

Subtracting,

$$L_b - L_i = \frac{\theta}{360^o} \; 2\pi \; (R + d) - \frac{\theta}{360^o} \; 2\pi R$$

$$= \frac{\theta}{360^o} \; 2\pi d.$$

Solving for θ ,

$$\theta = \frac{360^o}{2\pi} \left(\frac{L_b - L_i}{d} \right)$$

Now we can write expressions for the lengths of the two strips in terms of their lengths when they were straight (which were equal), their coefficients of thermal expansion, and the temperature increase which caused the strips to curve.

$$L_b = L_o + \Delta L_b$$

$$= L_o + \alpha_b L_o \Delta T.$$

Similarly,

$$L_i = L_o + \alpha_i L_o \Delta T$$

Subtracting,

$$L_b - L_i = \alpha_b L_o \Delta T - \alpha_i L_o \Delta T$$

$$= (\alpha_b - \alpha_i) L_o \Delta T$$

Inserting this in the expression for θ ,

$$\theta = \frac{360^o}{2} \quad \frac{(\alpha_b - \alpha_i) L_o \Delta T}{d}$$

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Example 13. A bimetallic strip, made of iron and brass strips each 0.01 inches thick, is straight and three inches long at 10^oC. Determine the amount of curving at 80^oC, by specifying θ .

Solution:

$$\theta = \frac{360^o}{2} \; \frac{(19 \times 10^{-6} - 12 \times 10^{-6}/C^o \;\; (3in)(70}{0.01 \text{ in.}}$$

$$= \frac{360^{\circ}}{2\pi} \quad \frac{(7 \times 10^{-6}/C^{\circ})\ (3\ in)(700^{\circ})}{0.01}$$

$$= 8^{\circ}$$

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When designing a bimetallic strip for use in a thermometer or control device, the quantity of interest is usually the travel at the end, Δs, rather than the angle θ.

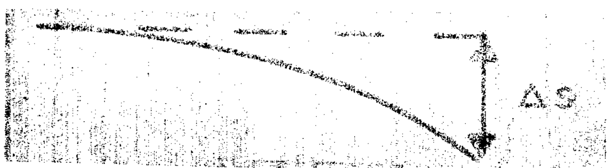

Fig. 19.

We will not derive the expression for Δs, but will simply state it:

$$\Delta S = \frac{2d}{(\alpha_b - \alpha_i)\,\Delta T} \sin^2 \frac{\theta}{2}\,.$$

It is possible to write a simpler, approximate expression which can be used in most cases:

$$S = \frac{L_o^{\,2}}{2d} \quad (\alpha_b - \alpha_i)\,\Delta T$$

This expression is quite accurate for cases where θ is no larger than 30°, which corresponds to Δs no greater than one fourth of L_o.

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NOW IS THE TIME TO DO EXPERIMENT 5

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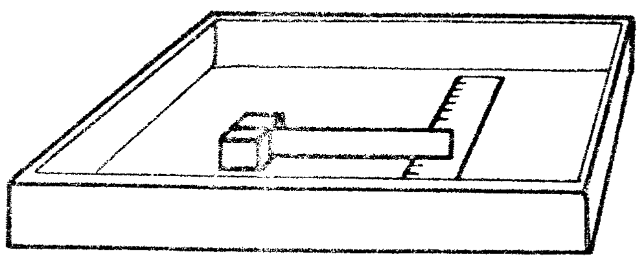
EXPERIMENT 5 - THE BIMETALLIC STRIP

In this experiment you will measure the movement of the end of a bimetallic strip made of brass and invar as the temperature changes, and will compare your experimental results with the relationship introduced in the text:

$$(1) \qquad \Delta S = \frac{L_o^{\,2}}{2d} \quad (\alpha_b - \alpha_i)\,\Delta T$$

where the symbols have the following meanings:

- ΔS: distance traveled by free end of strip
- L_o: length of strip
- $2d$: thickness of strip
- α_b: coefficient of linear expansion for brass
- α_i: coefficient of linear expansion for invar
- ΔT: change in temperature



With this apparatus you will be able to vary the temperature of the water, and measure the position of the free end of the strip as a function of temperature.

Procedure:

1. Measure the length of the strip, from the scale to the point where it enters the support clamp.
2. Measure the thickness of the strip at several points and obtain the average. (Note that this thickness is 2d.)
3. Fill the tray to within about one centimeter of the top with cold water.
4. Allow several minutes for the system to come to equilibrium, then record the temperature and the position of the end of the strip.
5. Immerse the immersion heater in the water and plug it in for about two minutes. Stir gently after removing the power.
6. Wait for about two minutes while stirring for the system to come to equilibrium, then record the temperature and the position of the end of the strip.
7. Repeat 5 and 6 until the temperature has reached approximately 50°.

You now have data on position versus temperature. Plot these data on a sheet of graph paper. Do the points fall approximately on a straight line? Should they, according to equation (1)?

From your graph, determine your experimental value for the change in position per unit temperature $\frac{\Delta S}{\Delta T}$. Using this value and equation 1, determine $\alpha_b - \alpha_i$. How well does this agree with Table III? The agreement may not be exact because the coefficient for invar goes up considerably for small changes in its composition.

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Example 14. A bimetallic strip, made of iron and brass strips each 0.01 inch thick, is straight and three inches long at 10°C. If one end is clamped in a fixed position, how much will the other end move if the temperature is increased to 80°C?

$$\Delta s = \frac{L_o^{\,2}}{2d} \left(\alpha_b - \alpha_i\right) \Delta T$$

$$= \frac{(3\text{ in})^2}{(0.02\text{ in})} (6.6 \times 10^{-6}/C^{\circ})(70C^{\circ})$$

$$= 0.21\text{ in.}$$

Since the result is much less than $L_o/4$, it is not necessary to use the more exact expression.

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THE BIMETALLIC STRIP AS A THERMOSTAT

The bimetallic strip is frequently used in electric circuits to turn the current on and off as the temperature changes. In the simplest application its purpose is to keep the temperature constant, or static, hence the name thermostat.

The figure below illustrates a simple thermostat circuit. The insulating material in the base of the thermostat cannot conduct a current. Therefore there will be a current in the heater only when the free end of the bimetallic strip touches the contact point at the right end. If it is touching, the heater will be on.

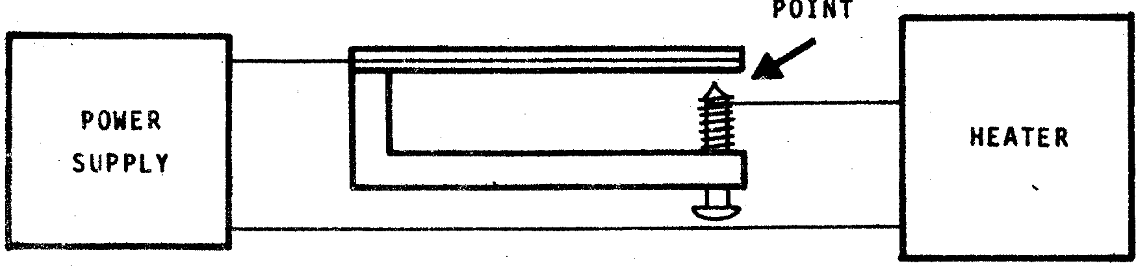

Fig. 20. A simple thermostat circuit.

This causes the surroundings, including the bimetallic strip, to heat up. As the strip gets hotter, it curves away from the contact point, thus breaking the circuit and turning off the heater. As the temperature goes down, the strip moves back to the contact point and the cycle repeats itself. A well-designed system of this type can hold the temperature variation to less than a degree.

In the above example the heat source is an electric heater. In a home furnace system, the circuit is used to start and stop the furnace.

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NOW IS THE TIME TO DO EXPERIMENT 6

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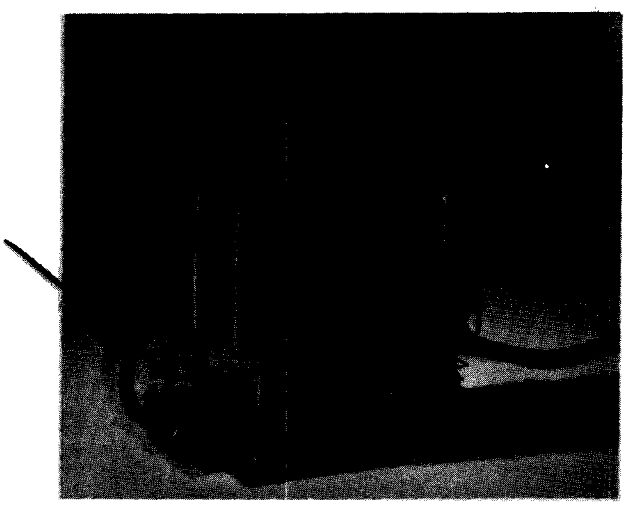
EXPERIMENT 6 - THE TOASTER CONTROL SYSTEM

In this experiment you will examine the mechanism which "decides" when the toast is done and then shuts off the power and pops up the toast.

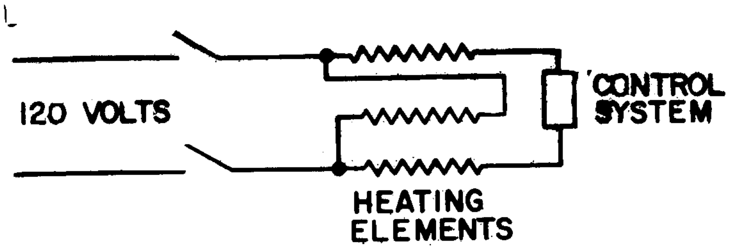
Although the operation is not terribly complicated, without some guidance it would probably take you a few hours to figure it out, largely because some of the important parts and important movements are difficult to see. The suggestions below are intended to guide you through the operation in a logical order.

CAUTION: Before beginning your inspection of the system, be sure the toaster is unplugged.

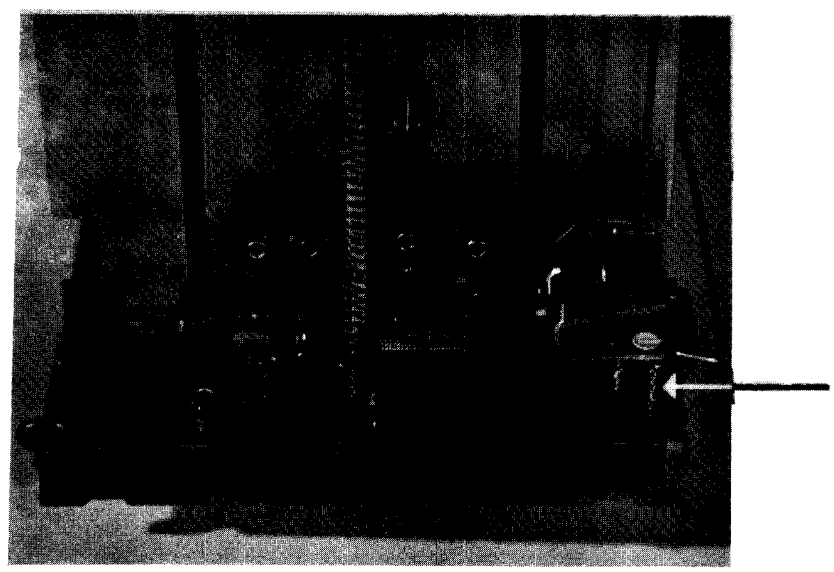
Lower the elevator and note that this action closes the main switch on the toaster.



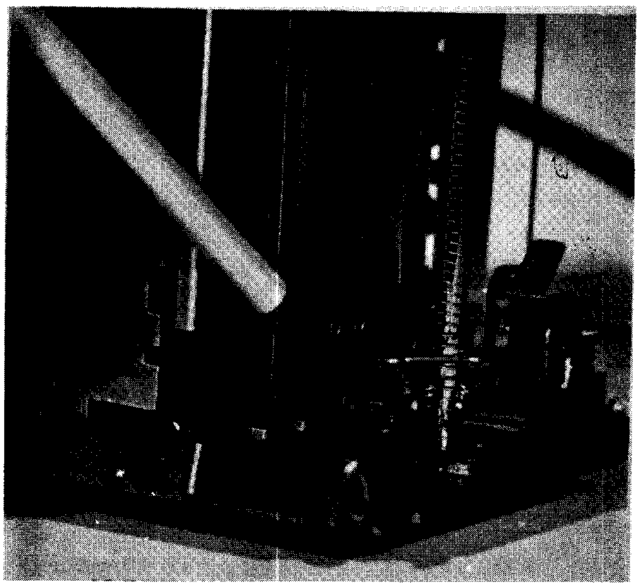
With the main switch closed, current can flow in the heating elements, and in the control system.



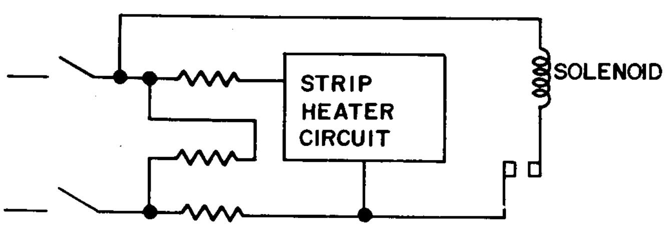
It is now clear that lowering the elevator starts the cycle. What ends it? When the elevator pops up the main switch will open, ending the cycle. Therefore you should seek the mechanism which releases the elevator so that the spring can push it up. Note the solenoid in the photograph.



A solenoid is an electromagnet which, when activated, pulls in a plunger. In the toaster, this action releases the elevator. Demonstrate this by pushing down on the plunger with your finger. The next obvious question is: what causes the solenoid to be activated? If you examine the circuit for the solenoid, you will find that the only thing preventing a current in the solenoid is the gap between the contact points indicated in the photograph.



The electrical hook-up for the solenoid can be represented by the schematic diagram below.



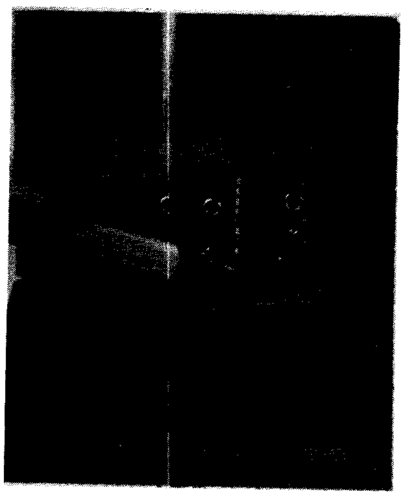
What makes the contact points close? At this point it is valuable to see the control circuit in actual operation. In order to do this without exposing you to dangerous temperatures or dangerous voltages we have made modifications in the toaster. These modifications allow the control system to operate in its usual way, but the main heating elements are by-passed, and the voltage is reduced to a safe level.

<u>First</u>, <u>be sure that the power supply is not plugged in</u>. Your instructor will plug it in after he has checked your circuit.

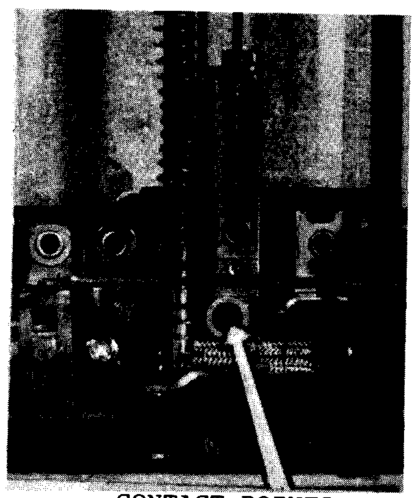
Connect the toaster as indicated in the photograph below, then ask the instructor to check it.

Lower the elevator to start the cycle, and watch what happens. (Because of the modifications, the toaster will not get hot; otherwise the events will be the same as in normal operation.) In particular watch the contact points which, when closed, activate the solenoid.

What causes the motion which results in the closing of the contacts? If you suspect a bimetallic strip, you are right. What heats the strip? The photo below points out an insulating "stocking" which covers a small heating element wrapped around the bimetallic strip. Although the stocking hides some of the detail, you can see one end of the heating element entering the stocking. The other end is connected to the strip. You might think that this heater would be on all during the cycle, and simply cause the strip to curve until the solenoid contacts are closed thereby completing the cycle. However, the operation is not that simple, as you will soon discover. Try to determine the circuit for the strip heater, with particular attention to the two pairs of contact points whose location is indicated by the photograph below. (To aid in locating them, a red spot has been painted on top of one pair and a green spot on top of the other.)

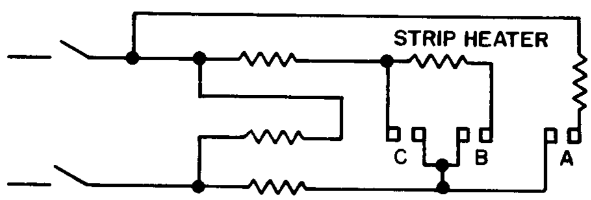


HEATER



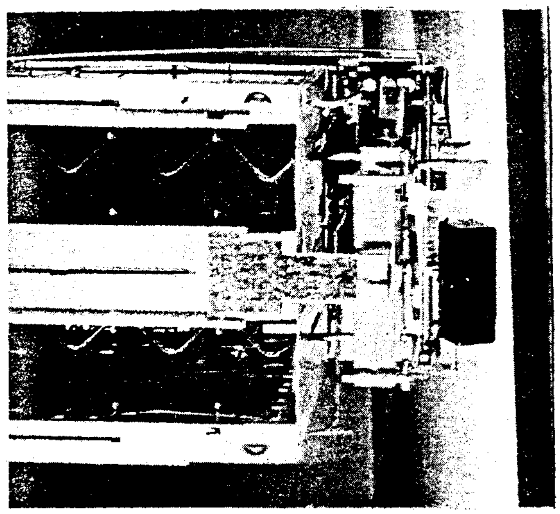
CONTACT POINTS

The electrical hook-up for the strip heater can be represented by the schematic diagram as shown in the right column.



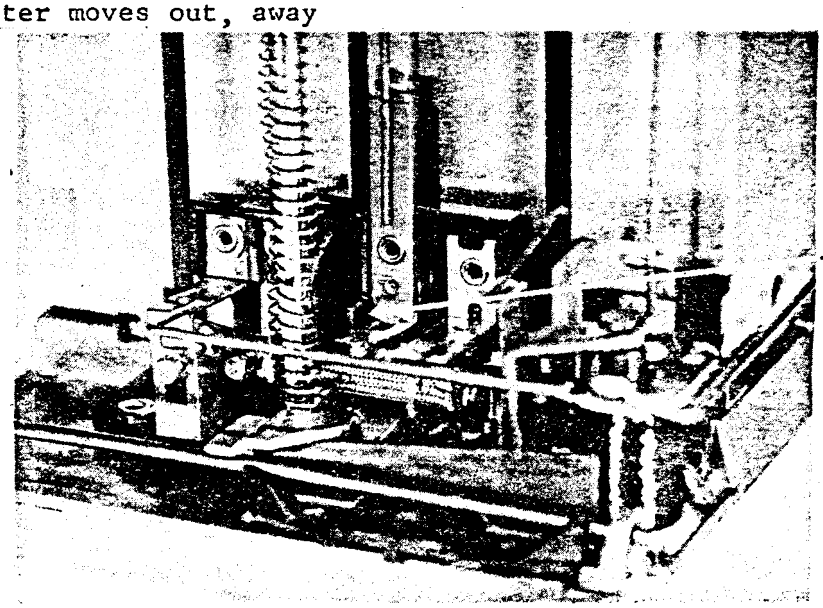
A: CONTACT POINTS FOR ACTIVATING SOLENOID.
B: CONTACT POINTS WHICH ARE OPENED TO BREAK THE STRIP HEATER CIRCUIT.
C: CONTACT POINTS FOR BY-PASSING STRIP HEATER.

Now you should observe the motion of the entire strip during a complete cycle. The best view for the first part of the cycle, until you hear a click, is straight down from the top, as in the photograph below.



Can you figure out what is happening? You will probably want to watch through several cycles, since each cycle lasts for only about a minute.

Perhaps you noticed that during the first part of the cycle, the strip curves in such a direction that the center moves out, away from the body of the toaster. When it clears the white block (pointed out in the next photo), it moves up. This upward motion opens one pair of contacts, breaking the circuit for the strip heater. It also closes another pair, thereby by-passing the strip heater.



With no current in the heater, the strip cools, and it begins to straighten. The block prevents the center from moving back in, therefore the free end moves out, eventually closing the solenoid contacts and thereby completing the cycle.

Why is the control system this complicated? Why not simply have the strip directly activate the solenoid, and omit the part of the cycle which causes the strip heater to be by-passed? Hint: What would happen if you tried to make a second batch of toast immediately after the first?

Here are some other questions you should consider:

1. During the cycle the strip clears the block and moves up. How does it get back under the block?
2. How does the "Light-Dark" control function?
3. There are two adjustment screws near the left side of the control system. What role do they play?
4. When the elevator pops up, a wheel spins. What purpose does this wheel serve?

* * * * * * * * * * * * * * * * *

Example 15. In the system shown below, should the material in the top of the bimetallic strip be the one with the higher or the lower coefficient of thermal expansion? To lower the temperature in the room should the adjustment screw be moved up or down?

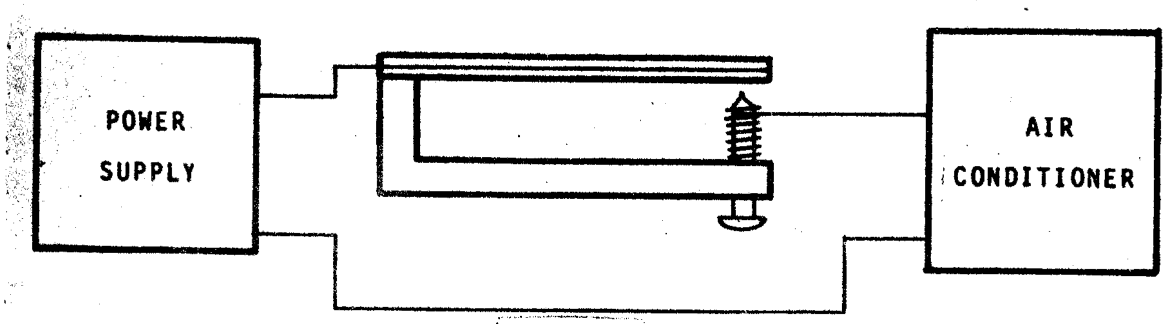


Fig. 21.

Answer: The material on top should have the higher coefficient of expansion. To decrease room temperature the screw should be moved up.

SUMMARY

The transformation of electrical energy to heat energy in the toaster is an example of conservation of energy; although the form of the energy is changed, the amount of energy is constant.

In an electric circuit, the power is the product of the voltage and the current. A unit for electric power is the watt, which is the same as a volt-ampere.

Power is the rate at which work is done, and the work done by the charges in a curcuit is equal to the amount of energy delivered. Thus the energy delivered by an electric circuit is the power times the time, or the product of the voltage, the current, and the time. If the power is given in watts and the time in seconds, the energy is in units of joules. Another energy unit commonly used in connection with electrical problems is the kilowatt-hour, which is simply 1000 watt-hours.

The two most common units for thermal energy are the calorie and the B.t.u. (British Thermal Unit). A calorie is the heat required to raise the temperature of one gram of water one centigrade degree. A B.t.u. is the amount of heat required to raise the temperature of one pound of water one Fahrenheit degree.

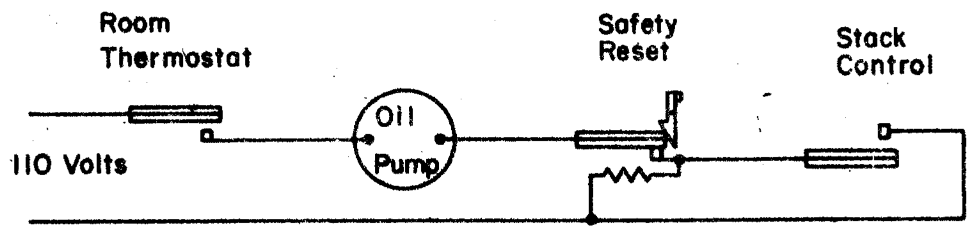
Different materials need different amounts of heat to raise the temperature of equal masses by the same amount. This property is specified by stating the specific heat: the specific heat of a material is equal to the heat added to a sample of the material divided by the product of the mass of the sample and the change in temperature.

Heat capacity is a characteristic of an object, not a material. It is equal to the heat added to the object divided by the change in temperature. Its value can be calculated from the masses of the materials in the object and the specific heats of the materials.

Most materials expand when heated, but different materials expand different amounts for equal increases in temperature. Because of this, a bimetallic strip will curve when heated. This effect is utilized in control circuits, such as that in the toaster, to open and close electrical switches.

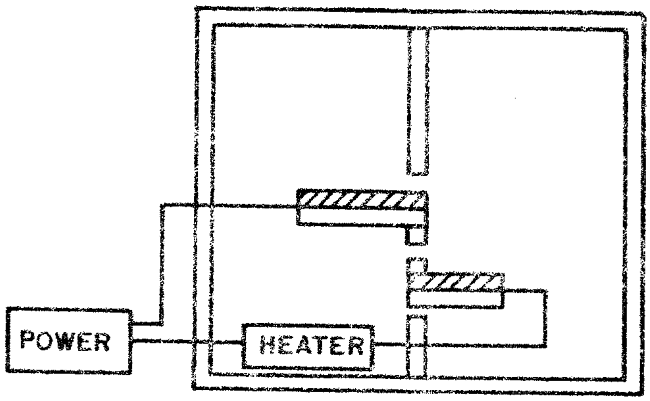
PROBLEMS

1. A flashlight is powered by two dry cells which provide three volts. If the current is five amperes, what is the power rating, in watts, for the bulb?
2. A 300 watt heater is designed to draw 25 amperes. What is the design voltage?
3. A certain car battery has the capacity to provide 0.84 kilowatt-hours of electrical energy. For how long can it run a 12 volt motor which draws 300 amperes?
4. An iron frying pan has a mass of three kilograms. How much energy is needed to raise its temperature from $20^{\circ}C$ to $220^{\circ}C$? Express your answer in calories, joules, kilowatt-hours, and B.t.u.'s.
5. For a particular thermos bottle 10,000 calories are required to raise the temperature of the inside bottle from $20^{\circ}C$ to $70^{\circ}C$. What is the heat capacity of the inside bottle?
6. A pound of water has an initial temperature of $176^{\circ}F$. What is the temperature of the water after losing 10,000 calories of thermal energy to the air?
7. A 200 watt immersion heater is used to heat an insulated container of water. The amount of water is 400 grams. Assuming that all the energy goes into heating the water, determine the rate at which the temperature increases.
8. Determine the heat capacity of the following system: An electric skillet consisting of 1.5 kilograms of aluminum, 0.6 kilograms of glass, and 0.4 kilograms of miscellaneous materials with an effective specific heat of 0.3. Inside the skillet is a stew consisting of 1.5 kilograms of water and 2.5 kilograms of meat and vegetables having an effective specific heat of 0.8.
9. Determine the change in length of an aluminum wire originally 200 feet long if its temperature is changed from $0^{\circ}F$ to $100^{\circ}F$.
10. You have a strip of metal one meter in length. It is known to be either iron or invar. You find that when you change the temperature by $100^{\circ}C$ the length changes by an amount somewhere between one-half and one-and-a-

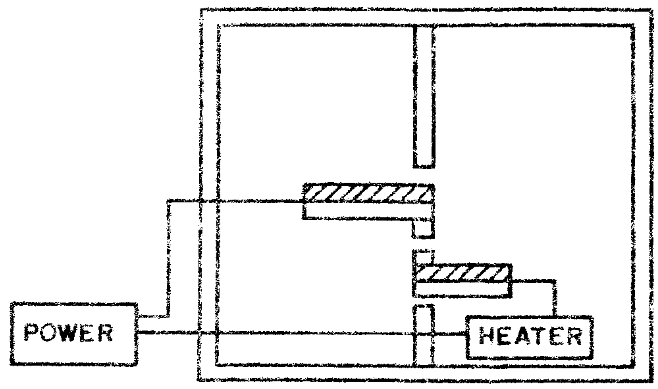


NOTE: **If the fuel ignites, the heat going up the stack causes the stack control to close, shorting the heater in the safety-reset circuit. Otherwise the safety-reset circuit will open and will be held open by the latch until manually reset.**

16. A container is divided into two parts by a verticle partition. A fixed temperature difference between the two parts is to be maintained by means of a control system based on bimetallic strips. In the diagrams below, the shaded part of each bimetallic strip is brass and the clear part is invar. In each case the strips make contact when they are at the same temperature. Determine which ones will produce the desired result.



(A)



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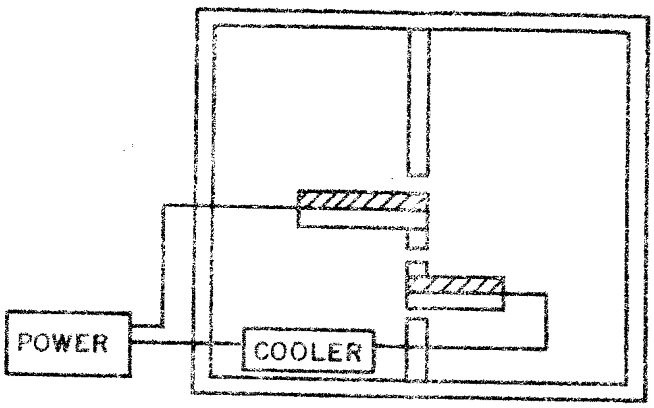

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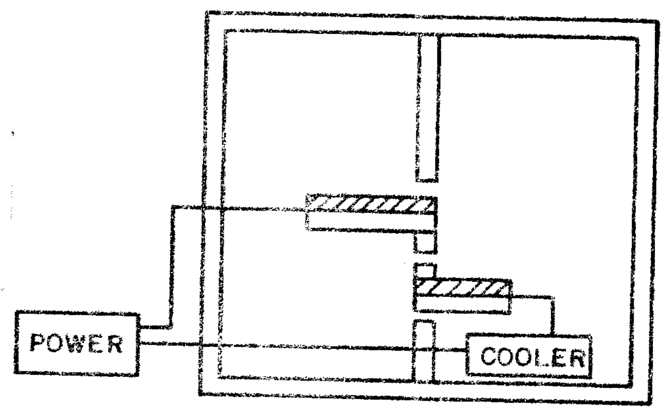

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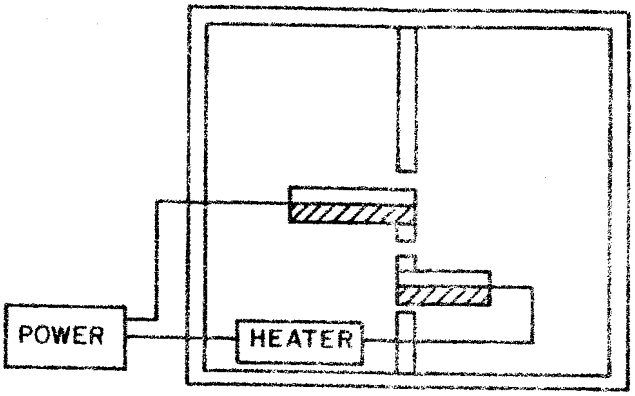

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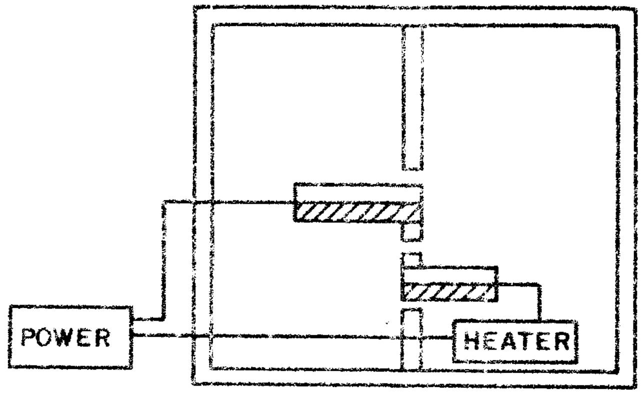
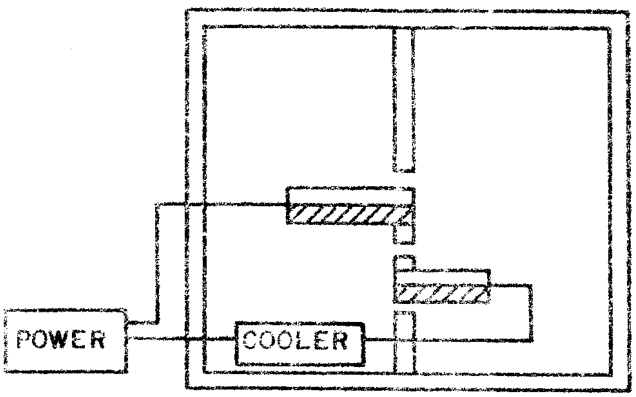
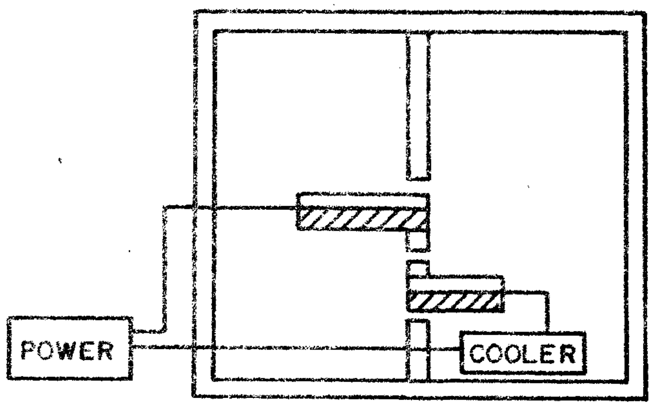


(F)



(G)



(H)

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