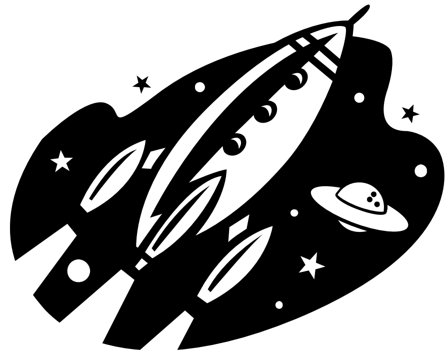
Energy and Efficiency



Measuring energy output, efficiency for the human body

Opening Remarks

It frequently happens that in the ordinary affairs and occupations of life, opportunities present themselves of contemplating some of the most curious operations of Nature; and very interesting philosophical experiments might often be made, almost without trouble or expense, by means of machinery contrived for the mere mechanical purpose of arts and manufactures...

Benjamin Thompson (Count Rumford), speech to Royal Society of London, 1798

The good Count goes on to describe how he observed people boring a cannon. He was "struck by the considerable degree of heat which a brass gun acquires, in a short time, while being bored..." and went on to do some experiments. Ultimately, he concluded that the heat of the cannon (and the brass chips that were machined off it) came from friction, and thus, ultimately, from the mechanical energy being put into the bit doing the boring.

Rumford is credited with establishing the principle of the conservation of energy: that energy can be converted into different forms, but, ultimately cannot be created or destroyed. This is a very powerful principle; it underlies quite a bit of modern physics. If you could take only one thing away from this course, an understanding of conservation of energy might not be a bad choice.

In this lab, you will do some experiments in which you convert energy from one form to another. Since energy, in the sense of what we get by burning fossil fuels, is a big topic in society, and energy, in the sense of food energy (calories) that many people keep careful track of, are so important in our everyday lives, you will get a chance to make some comparisons of different kinds of energies, and put some numbers on things.

Necessary Theory

Types of Energy

Energy is conserved; there is a certain amount of it, and there will never be any more. Or any less; when folks talk about the world "running out of energy," what they really mean is running out of useful forms of energy. Most of the work of the modern world is done by converting chemical energy in fossil fuels into kinetic energy (of vehicles), other forms of chemical energy (of fertilizers), thermal energy (of buildings and dwellings), and radiant (light) energy.

Here is a partial list of the different kinds of energy, with an example of each:

- Kinetic (a moving car has this)
- Potential:
  - -Gravitational (think of water piled up behind a dam)
  - -Elastic (a stretched spring has this)

- Chemical (gasoline has a lot of this for its mass, and so does food)
- Thermal energy (related to, but not the same as, temperature!)
- Radiant (light and radiant heat; think of the sun on your skin)
- Nuclear (typically from the fusion of nuclei of atoms; think atomic power)
- Electrical energy (what is running my computer as I type this)
- Sound energy (pretty obvious; screaming children give off a lot of it)

Formulas

It is possible to put numbers on each of these kinds of energy, so that we can compare them with each other. Here is how we calculate some of the basic forms of energy:

Kinetic energy: an object of mass m moving at speed v has a kinetic energy given by:

$$K = \tfrac{1}{2} m v^2$$

Gravitational potential energy: a mass *m* raised a distance *y* has gravitational potential energy:

$$U_g = mgy$$

Chemical energy is stored in the bonds within molecules. The chemical energy in food is released through oxidization, as noted in your textbook. Your body "burns" carbohydrates, fats and proteins. The reaction for a molecule of glucose, whether metabolized in the body or burned in air is:

$$\mathrm{C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + energy}$$

Each unit of energy your body uses requires you to breathe in oxygen and breathe out carbon dioxide. By measuring the carbon dioxide you exhale we can measure the metabolic power used by your body.

There will be two components to this measurement:

- A measurement of the fraction of your exhaled breath that is carbon dioxide. This reading is in ppm (parts per million). You'll need to convert this measurement to a fraction:

$$\text{Fraction of exhaled breath that is carbon dioxide} = \frac{\text{ppm of CO}_2}{1{,}000{,}000}$$

- A measurement of the volume of air exhaled during one minute.

You know the fraction of the exhaled breath that is carbon dioxide. You also know how much air is exhaled in one minute. You can then determine how much energy the body used during that minute, because each liter of carbon dioxide (at a typical atmospheric pressure in Fort Collins) corresponds to the release of a certain amount of energy. If we assume that all of the "fuel" burned by your body is carbohydrate (an approximation, but for our level of accuracy, a reasonable one):

$$1.0 \text{ liter of CO}_2 \text{ (at our altitude)} \rightarrow 17\ \text{kJ}$$

There's one more formula we'll need for this lab—the definition of efficiency:

$$\text{Efficiency} = e = \frac{\text{what you get}}{\text{what you had to pay}}$$

When you pedal a generator—as you will—the energy output is what you get. Your body uses carbohydrates to perform this task, this is "what you had to pay."

We've seen that, for most tasks, you can assume an efficiency of 25% for the body.

Units and Conversions

There are (as we have seen) different units of energy, and therefore different units of power. Common units for energy are joules (the preferred one for us), calories, Calories (really kilocalories), or kilowatt-hours (what the power company measures electric energy in terms of; the energy used if you run a one kilowatt device for for one hour) Common units for power are watts (the preferred one for us) or horsepower. It is important to know how to convert among different units; here is a brief table:

1 Calorie (a food calorie) = 1 kcal = 1000 calories

1 calorie = 4.184 joules

1 joule = 0.239 calories

1 horsepower = 745.7 watts

1 watt = 0.001341 horsepower

1 kilowatt-hour = 3,600,000 joules

You can use these conversions to switch back and forth between the different units.

Experiments and Calculations

There will be two parts to this experiment. In the first, you will make some simple calculations of the energy output of your body. In the second, you will directly measure energy output of the body and the energy use by the body to determine the efficiency.

Energy Output of the Body

In this part of the lab, you will do a simple experiment to determine your output power when you are sprinting and when you are running up stairs.

Equipment Needed

Stopwatch
Meter stick
FlipCam
Bathroom scale

Measurements, Calculations, Questions, Conclusions

Part I: Running up Stairs

Question

When you run up a set of stairs at a constant rate what energy transformations are taking place?

Measurement

Pick a member from your group to run up the stairs. Measure the height from the bottom of the stairs to the top of the stairs. Determine the person's mass in kg.

Measurement

Have your runner sprint from the basement to the top floor, as fast as possible, timing how long it takes him or her to do this. He or she really needs to work at this, to run as fast as possible.

Calculation

How much did the runner's gravitational potential energy change as he or she ran up the stairs? What was the average power output in W and in horsepower?

Calculation

How much metabolic energy did the person use to climb the stairs? How much metabolic power?

Calculation

What is the power divided by the body mass in W/kg? How does this compare with numbers you've seen in class?

Calculation

Electricity in Fort Collins costs about $0.08 per kilowatt-hour. If you used an electric motor to raise the person up the stairs, assuming a motor efficiency comparable to that of the body, what would be the cost?

Speculation

How many horsepower do you suppose a horse puts out? This is a serious question. We don't expect you to know the answer, but we do expect you to be able to make an estimate or a deduction. Think about how you might have defined a horsepower. Do you want to think about how much power the horse can develop for a few minutes, or how much the horse can keep putting out all day long? Think about how much power a horse is likely to be able to produce, given how much power you found for your group member. Does this make sense?

Part II: Sprinting

Question

When you sprint from a standstill, what energy transformations are taking place?

Measurement

Pick a member from your group to sprint from a standstill. Do this outside, recording the motion using a FlipCam. Have him or her accelerate at the greatest possible rate for a few seconds. While filming, be sure to stand far enough back that you capture the entire motion and **do not move the camera!** Return to the lab, and analyze the video in the usual manner.

Calculation

What was the runner's kinetic energy after 2.0 s?

Question

How much metabolic energy did his or her body use to get up to speed? What was the metabolic power?

Calculation

What is the power divided by the runner's mass in W/kg? How does this compare with numbers you've seen in class?

Efficiency of the Body

In this part of the lab, your lab group and another will join forces to make a direct measurement of the body's efficiency.

Equipment Needed

LabQuest with CO_2 sensor

Generator and power meter

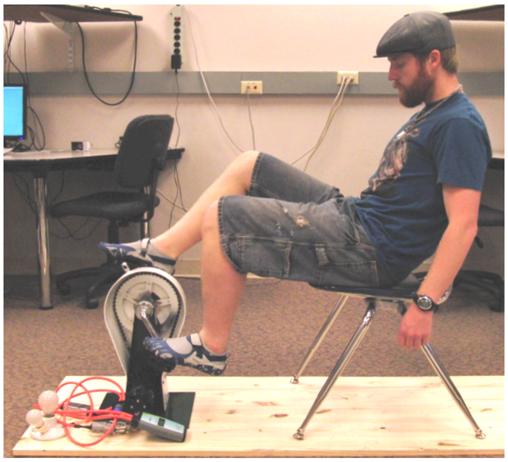
Spirometer

From your combined group, pick one person who will operate the human powered generator—someone who does not mind breathing into a spirometer.

First Steps

First, we need to get an initial reading of the CO_2 in the room. Run the LabQuest for a minute, or until the readings no longer change. Note the CO_2 concentration in parts per million (ppm).

Measurement: What You Get



Now, have your group member sit at the human powered generator. You might need to move the chair forwards or backwards for comfortable cycling; your volunteer will be sitting there for several minutes.

Once he or she is settled, he or she should begin cycling. It's necessary to work fairly hard to light the 25 W lightbulb; make sure that your volunteer provides at least 20 W of power as measured in the attached power meter.

This number—the output power—is the one that you are after. He or she should try to keep the power output as constant as possible over several minutes of cycling.

For additional resistance, you can plug in the smaller 15 W bulb into the side of the socket, which should then require more then enough power output from the volunteer.

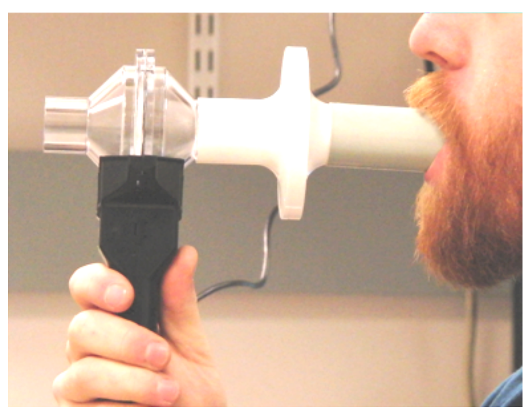
You are measuring the output power of the generator. But the actual power output of the body is larger than this; the generator is only 10% efficient.

Calculation

What was the actual power output of the volunteer's body during the cycling?

Measurement: What You Had to Pay

You know how much power your volunteer can provide. Now, you'll measure how much power his or her body is using when providing this output power.



After three minutes of cycling, have the volunteer breathe in and out of the computer-controlled spirometer (while still cycling) for one minute to obtain the average volume of air exhaled in one minute. Record the data in the supplied LoggerPro file on the computer.

Next, have the volunteer exhale a few times into the ziplock bag, and seal it around the CO_2 meter. Once you have a few good breaths in the bag, your volunteer can stop cycling.

Watch the meter. Wait for the readings to come to equilibrium, (it should take roughly a minute) and note the concentration of CO_2 in the subject's breath.

Question

Is the initial concentration of CO_2 in the room negligible? If not, make sure to account for it.

Calculation

What volume of CO_2 did your volunteer exhale during one minute?

Calculation

How much metabolic energy did he or she use during one minute?

Calculation

What was his or her average metabolic power?

Calculation: Efficiency

What is the volunteer's metabolic efficiency for this activity? How does this compare with the usual 25% figure we've been using in class?

Summing Up

Modern America is really experiencing a metabolic energy crisis: as we, as a nation, have gotten more sedentary, we are taking in a lot more energy than we use. If you gain weight, you can blame it on conservation of energy—yet another use for this far-reaching principle.

Go in peace.