

We're In Hot Water Now

Student Objective

The student:

- will be able to explain how a solar thermal water heating system works
- will be able to explain conduction, convection and radiation in a solar thermal system
- will construct a simple solar thermal water heating system and analyze its performance

Key Words:

conduction
convection
heat transfer
insulation
radiation
solar collector
thermosiphon

Time: (1) class for construction
(1) class for testing and discussion

Materials:

- 2 liter plastic bottle (1 per group)
- cardboard box slightly larger than the bottle (1 per group)
- 3/8" plastic tubing or garden hose (6 feet per group)
- high temperature hot glue
- insulation material, both sheet and fluff types (styrofoam, cardboard, newspaper, batting, cotton, etc)
- long immersion thermometer (1 per group)
- modeling clay
- 3/8" soft copper tubing *
- shallow box (1 per group) *
- clear plastic sheet to fit box (1 per group)
- disposable type aluminum lasagne pan or cookie sheet * (1 per group)
- flat black high-heat spray paint
- aluminum foil or mylar
- copper tube bending tool
- tubing cutter
- box cutters
- black duct tape
- Science Journal

* See note in Procedure section for sizing of these materials.

Background Information

Solar thermal systems for household hot water consist of two main parts—the thermal collector and a storage tank. The storage tank which looks similar to a traditional hot water heater, is well insulated to keep the water hot until it is used. The thermal collector, which usually sits on the roof, can be of various shapes, sizes and materials; however, collectors for

domestic hot water all make use of conductive material (copper), clear covering (tempered glass called *glazing*) and dark colors. Shortwave, higher-frequency radiation from the sun travels through the glazing of the collector and is absorbed by the interior surfaces of the collector. The absorbed portion re-radiates lower frequency, long wave thermal radiation which becomes trapped by the glazing and insulation, thus increasing the interior temperatures within the collector, similar to the greenhouse effect. The heat travels through the copper pipes by **conduction** to the water flowing within them. On sunny days, the water that travels through the pipes reaches boiling temperature before leaving the collector. When the hot water circulates to the storage tank it increases the temperature of the water remaining in the tank by **convection**. Solar thermal systems are sized according to the household's water use and are designed in Florida to retain enough hot water for three days without sun.

The first commercial solar water heater was patented in 1891. These first solar thermal heaters were simple thermosiphon devices that could freeze in the winter. Because of this, they only sold well in Florida, California and the Caribbean where the weather is temperate; they did not sell well further north. During World War II, the government put a freeze on nonmilitary use of copper, so for a time, no solar collectors could be made. After the war, solar thermal water heaters became popular in Florida again; half of the homes in Miami and 80% of the new construction had solar water heaters installed. In the early 1950s electricity became cheap and the electric companies offered free electric water heaters to those willing to switch over. This crushed the business, leaving only two full-time solar water heating companies in the U.S.—both in Miami, Florida.

It wasn't until the OPEC oil embargo and the increase in fossil fuel prices that solar thermal became viable again. Federal and state tax credits for renewable energy gave the industry a boost and almost overnight solar thermal companies sprung up—some not so reputable. To help protect the citizens of Florida, the Florida Legislature created the Florida Solar Energy Center (FSEC). It became the mandate of FSEC to test and certify solar thermal systems and publish the results for the citizens of Florida.

According to EnergyStar, a family of three can expect to save between 50% and 80% on their water heating bill if they switch to a solar hot water system.

The solar thermal collectors that will be assembled in this lesson work by the process of **thermosiphon**. As the sun shines on the collector, the water inside is heated. It expands slightly and becomes lighter than the cold water in the tank. Gravity then pulls the heavier, cold water down from the tank and into the collector inlet. The cold water pushes the heated water through the collector outlet and into the top of the tank. This continuous heating and flowing action provides a tank full of hot water.

Procedure (prior to class)

Material Sizing:

- all collector boxes for this lesson should be shallow (approx. 4" deep) or cut to that depth (Note: If you are cutting the boxes, make sure that your cut is straight and level so the plastic sheet can be fitted and taped to make the box air tight)
- the width of the box should be 11 or 12" (you can fill in an extra inch or two with additional insulation if needed so that the sides are 1½" from the copper pipe)
- for a box with a 10" length, the length of pipe needed will be 26".

- if you have one given (either a specific box or pre-cut pipe that you want to use), use this formula to figure the other measurement:

$$3y - 4 = x$$

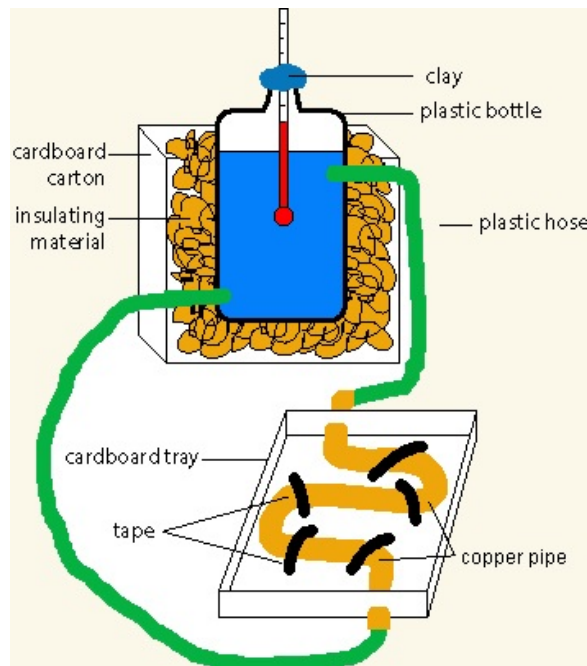
where y is the length of the box, or x is the length of the pre-cut pipe

Cut and bend the copper tubing (1 per lab group).

It is advisable to construct a model of the solar collector for the class to look at during their construction process. Check out the drawing below as you construct your collector.

For the storage tank:

- Punch two 3/8" holes in the bottle; one should be approximately 2" below the neck of the bottle and the other approximately 1" from the bottom.
- Place the bottle in the middle of the smaller cardboard box. Cut holes in the cardboard box to match the position of the holes in the bottle.
- Remove bottle. Cut the rubber tubing in half; push each piece into one of the holes. Seal around the tubing on the outside with hot glue.
- Fill the bottle to check for leaks. If leaks are found, repair them (or redo the connections) before continuing.
- Place the bottle back into the box and thread the tubing through the holes in the box. Stuff the area between the bottle and box with insulating material.



For the thermal collector:

- Trim the collector box if needed so that it is approximately 4" tall. Line the bottom of the box with insulation.
- Using a tube bending tool, carefully bend the copper tubing in an S shape where the three long runs are approximately 10 - 11".
- Lay the copper tubing on the metal sheet and tape them together snugly in several places with black duct tape. The tubing and the metal sheet must be in contact with each other

- as completely as possible.
- Place the plate inside the box, cutting holes in the box so that the copper pipe ends can stick out.
 - Spray the plate and tubing with the high temperature black paint.
 - Line the inside of the sides of the box with insulation and cover with aluminum foil or mylar.
 - Place the plastic sheet on top of the box and seal airtight with duct tape. Also with the duct tape, seal any gaps in the box or gaps around the tubing so that the box is as air-tight as possible.
 - Attach the plastic tubing to the copper ends, slipping the plastic over the copper.

For testing

- Push all the air out of the tubing and collector pipes by raising the tank above the collector so that the water is pushed through the system. Add more water to the bottle if needed.
- Suspend an immersion thermometer down into the bottle using modeling clay around the mouth of the bottle to hold the thermometer and seal the top.
- Place the collector in the sun.

Procedure - Construction (during class time)

1. Ask the students from their observations in the *Hot or Not?* activity, what factors seemed to be the most important in capturing solar radiation. (*facing towards the sun, black, clear layer for the sunlight to enter*)
2. Ask the students what they would do to retain the heat they have collected in the water. (*insulation*).
3. Tell the students they will be building a small scale solar thermal water heater. Lead a discussion on what it might look like, what materials they would like to use, and how it should be constructed. Make sure to reinforce the concepts of conduction, convection and insulation.
4. Show the class the collector you assembled (or alternately project the collector drawing). Point out the parts and have the students tell you what each part does and why it works (metal is a good conductor, black absorbs heat, etc). Briefly describe the building process and any problems they may encounter. Tell the students where the painting station is.
5. Help with the assembly process as needed.

Procedure - Testing & Discussion

1. Students should purge their systems of air, top up the water as needed and suspend the thermometer; assist them as needed.
2. Students should place their systems in the sun and follow the directions in their Science Journal.
3. After the groups have finished their calculations, have one group share their results with the class. Ask the rest of the class if their results were identical or similar. Have several groups share the graphs of the temperature increase in their system. Lead a discussion on

the **difference** in specific points between the group's graphs, but the **similarity** in the **trend** of the graphs. Have the students speculate on the design and construction aspects that caused the differences.

4. Lead a discussion on the advantages and disadvantages of solar thermal water heaters for domestic use. (*Advantages: monthly utility cost saving, uses renewable energy, no emissions. Disadvantages: upfront cost of system, can run out of 'really hot' water during extended times of rainy weather and times when the hot water usage in the house increases dramatically*)

Key Words & Definitions

- **conduction** - the transmission of heat across matter
- **convection** - heat transfer in a gas or liquid by the circulation of currents from one region to another
- **heat transfer** - the flow of heat from one substance to another. Heat always transfers from a higher temperature to a lower temperature.
- **insulation** - the process of keeping heat or cold in one place and preventing it from escaping with little or no air movement.
- **radiation** - the way we receive heat from the sun each day. The energy is emitted in the form of waves/particles, and can move from one object to another without heating the area in-between
- **solar collector** - a device used to collect the radiant energy from the sun and trap it as heat
- **thermosiphon** - heat exchange using natural convection (warm rises, cold sinks) to circulate a substance without a pump

Related Research

1. Does it make a difference if the collector is flat or angled to the sun? Test different angles to see.
2. Research which countries use solar thermal collectors for household hot water.
3. Research how solar thermal collectors work in climates that experience freezing weather during part of the year. What parts are different? What parts are the same? Are they able to heat water during the winter months?
4. Using the Department of Energy Fact Sheet (listed in the Internet Sites below) have the students calculate their family's hot water usage for a day and a week.

Related Reading

- ***Solar Energy Projects for the Evil Genius*** by Gavin Harper (McGraw-Hill, 2007)
This book includes more than 50 solar energy projects with plans, diagrams and schematics.

Internet Sites

<https://www.youtube.com/watch?v=uOWzNBXk3ss>

Short video, *From Solar Energy to Heat*, explains how photons from the sun turn into heat

<http://www.neok12.com/video/Solar-Energy/zX4501794c04647766705041.htm>

Video on Solar Thermal usage in Europe

http://apps1.eere.energy.gov/buildings/publications/pdfs/building_america/26465.pdf

Department of Energy Fact Sheet on domestic hot water usage. Includes breakdown of usage by activity and appliance so students can calculate their family's hot water usage.

www.energy.gov/energysaver/articles/estimating-cost-and-energy-efficiency-solar-water-heater

Department of Energy site to estimate the cost and energy savings of installing a solar thermal water heating system.

We're In Hot Water Now

			.1	.2	.3	.4	.5	.6	.7	.8	.9	.10	.11	.12
Grade 6														
Practice of Science	# 1	SC.6.N.1	X		X	X								
Role of Theories	# 3	SC.6.N.3				X								
Earth Systems & Patterns	# 7	SC.6.E.7	X											
Forces & Changes in Motion	# 13	SC.6.P.13	X											
Grade 7														
Practice of Science	# 1	SC.7.N.1	X		X									
Role of Theories, Laws, Hypotheses, and Models	# 3	SC.7.N.3		X										
Forms of Energy	# 10	SC.7.P.10	X	X										
Energy Transfer & Transformations	# 11	SC.7.P.11	X	X		X								
Grade 8														
Practice of Science	# 1	SC.8.N.1	X											
Role of Theories, Laws, Hypotheses, and Models	# 3	SC.8.N.3	X											

Sixth Grade Benchmarks

Science—Big Idea 1: The Practice of Science

- SC.6.N.1.1 - Define a problem from the sixth grade curriculum, use appropriate reference materials to support scientific understanding, plan and carry out scientific investigation of various types, such as systematic observations or experiments, identify variables, collect and organize data, interpret data in charts, tables, and graphics, analyze information, make predictions, and defend conclusions.
- SC.6.N.1.3 - Explain the difference between an experiment and other types of scientific investigation, and explain the relative benefits and limitations of each.
- SC.6.N.1.4 - Discuss, compare, and negotiate methods used, results obtained, and

explanations among groups of students conduct the same investigation.

Science–Big Idea 3: The Role of Theories, Laws, Hypotheses, and Models

- SC.6.N.3.4 - Identify the role of models in the context of the sixth grade science benchmarks.

Science–Big Idea 7: Earth Systems and Patterns

- SC.6.E.7.1 - Differentiate among radiation, conduction, and convection, the three mechanisms by which heat is transferred through Earth's system.

Science–Big Idea 13: Forces and Changes in Motion

- SC.6.P.13.1 - Investigate and describe types of forces including contact forces and forces acting at a distance, such as electrical, magnetic, and gravitational.

Seventh Grade Benchmarks

Science–Big Idea 1: The Practice of Science

- SC.7.N.1.1 - Define a problem from the seventh grade curriculum, use appropriate reference materials to support scientific understanding, plan and carry out scientific investigation of various types, such as systematic observations or experiments, identify variables, collect and organize data, interpret data in charts, tables, and graphics, analyze information, make predictions, and defend conclusions.
- SC.7.N.1.3 - Distinguish between an experiment (which must involve the identification and control of variables) and other forms of scientific investigation and explain that not all scientific knowledge is derived from experimentation.

Science–Big Idea 3: The Role of Theories, Laws, Hypotheses, and Models

- SC.7.N.3.2 - Identify the benefits and limitations of the use of scientific models.

Science–Big Idea 10: Forms of Energy

- SC.7.P.10.1 - Illustrate that the sun's energy arrives as radiation with a wide range of wavelengths, including infrared, visible, and ultraviolet, and that white light is made up of a spectrum of many different colors.
- SC.7.P.10.2 - Observe and explain that light can be reflected, refracted, and/or absorbed.

Science–Big Idea 11: Energy Transfer and Transformations

- SC.7.P.11.1 - Recognize that adding heat to or removing heat from a system may result in a temperature change and possibly a change in state.
- SC.7.P.11.2 - Investigate and describe the transformation of energy from one form to another.
- SC.7.P.11.4 - Observe and describe that heat flows in predictable ways, moving from warmer objects to cooler ones until they reach the same temperature.

Eighth Grade Benchmarks

Science–Big Idea 1: The Practice of Science

- SC.8.N.1.1 - Define a problem from the eighth grade curriculum, use appropriate reference materials to support scientific understanding, plan and carry out scientific investigation of various types, such as systematic observations or experiments, identify variables, collect and organize data, interpret data in charts, tables, and graphics, analyze information, make predictions, and defend conclusions.

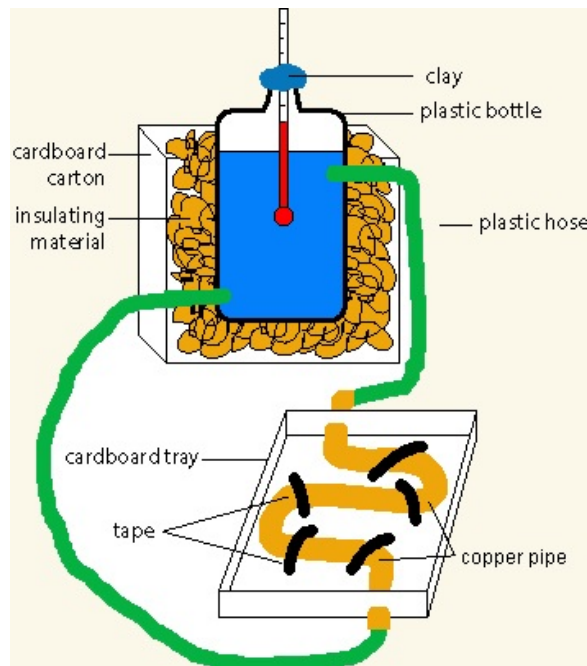
Science–Big Idea 3: The Role of Theories, Laws, Hypotheses, and Models

- SC.8.N.3.1 - Select models useful in relating the results of their own investigations.

We're In Hot Water Now

You will be building a solar thermal hot water heater and testing its efficiency. Although your water heater is a model, it has the same main parts that a larger home water heater has, and it will heat water using the same physical properties that the large scale systems use.

Below is a diagram to help you with the construction process.



For the storage tank:

- Punch two $\frac{3}{8}$ " holes in a 2-liter bottle; one should be approximately 2" below the neck of the bottle and the other one approximately 1" from the bottom. The top hole will be attached to the 'return' hose and the bottom hole will be attached to the 'supply' hose.
- Place the bottle in the middle of a cardboard box that is slightly larger than the bottle. Cut holes in the cardboard box to match the position of the holes in the bottle. The tubing will run through these holes to reach the bottle.
- Remove the bottle. Cut the rubber tubing in half; push each piece into one of the holes. Seal around the tubing on the outside with hot glue.
- Fill the bottle to check for leaks. If leaks are found, repair them (or redo the connections) before continuing.
- Place the bottle back into the box and thread the tubing through the holes in the box. Stuff the area between the bottle and box with insulating material to keep the water hot once it is collected.

For the thermal collector:

- Trim the collector box if needed so that it is approximately 4" tall. Line the bottom of the

- box with insulation to keep the heat in.
- Take your piece of copper tubing that has been bent in an “S” shape and lay in on the metal sheet. The two ends of the “S” should be sticking out past the metal sheet and the “S” should be centered on the sheet. Tape the tubing down onto the metal sheet in two or three places with black duct tape. (Remember: copper is a good conductor of heat!) The tubing and the metal sheet must be in contact with each other.
- Place the plate inside the box, cutting holes in the box so that the copper pipe ends can stick out. Use duct tape to seal around the holes with the pipes sticking out so that air (and heat!) will not escape around them.
- Spray the plate and tubing with the high temperature black paint. (Remember: black helps to absorb heat!)
- Line the inside of the sides of the box with insulation and then cover them with aluminum foil or mylar to reflect the sunlight from the sides of the box to the center towards the copper pipe and the water.
- Place the plastic sheet on top of the box and seal it with duct tape to make it airtight. Also use the duct tape to seal any gaps in the box to make it as air-tight as possible.
- Attach the plastic tubing to the copper ends, slipping the plastic over the copper.

Testing and Observations

Fill your solar thermal water heater system with water. Since you will be calculating the thermal heat energy in the system, you will need to know the exact weight of the water that you add to the system.

- Measure 2 liters of water (2000mL) and pour it carefully into the bottle that is serving as your storage tank. As you pour into the bottle, raise the bottle above the collector so that the water fills up the rubber and copper tubing.
 - Measure another liter of water (1000mL) in a graduated cylinder. Pour the water into the bottle slowly. Stop when the water level is just above the inlet (the upper tube connection). Make note of how much water has been added to the system from this cylinder.
1. How much water (in mL) has been put into your system? _____ mL
 2. Put your solar thermal water heater in the sun. Place a couple books or other object under the storage tank to raise it a couple of inches. Hang a thermometer into the water tank, securing it around the neck of the bottle with modeling clay. Check the water temperature in the tank and fill in the table below (continued on the next page).

Elapsed Time	Temperature
0 (Start)	°C
5 minutes	°C

10 minutes	°C
15 minutes	°C
20 minutes	°C
25 minutes	°C
30 minutes	°C

3. The increase in temperature of the water in your system in 30 minutes is _____.

4. Graph the temperature below. (Time should be on the x-axis)

5. Since we are measuring the heating potential of a solar thermal system, we will be using BTUs (like in the *Hot or Not?* lesson). Convert the volume of water in your system to weight using the formulas:

$$1 \text{ mL water} = 1 \text{ gm water}$$

$$100 \text{ gm} = .220462 \text{ lb}$$

6. Calculate the heat gain in BTUs.

Remember: 1 BTU = amount of energy needed to raise 1 pound of water 1°F (1.8°C)

7. In what direction does the water flow in the system? Draw a diagram below of the system with arrows showing the flow direction through the system.

8. Would the solar water heater work if the storage container was placed lower than the collector? Why or why not?

9. If you had an unlimited budget and access to any material, how would you improve your solar water heater?

10. What are the advantages of a solar thermal system for hot water production over using natural gas or electricity?