DOE/CS/34039--T6

Renewable Energy Activities for Chemistry and Physics

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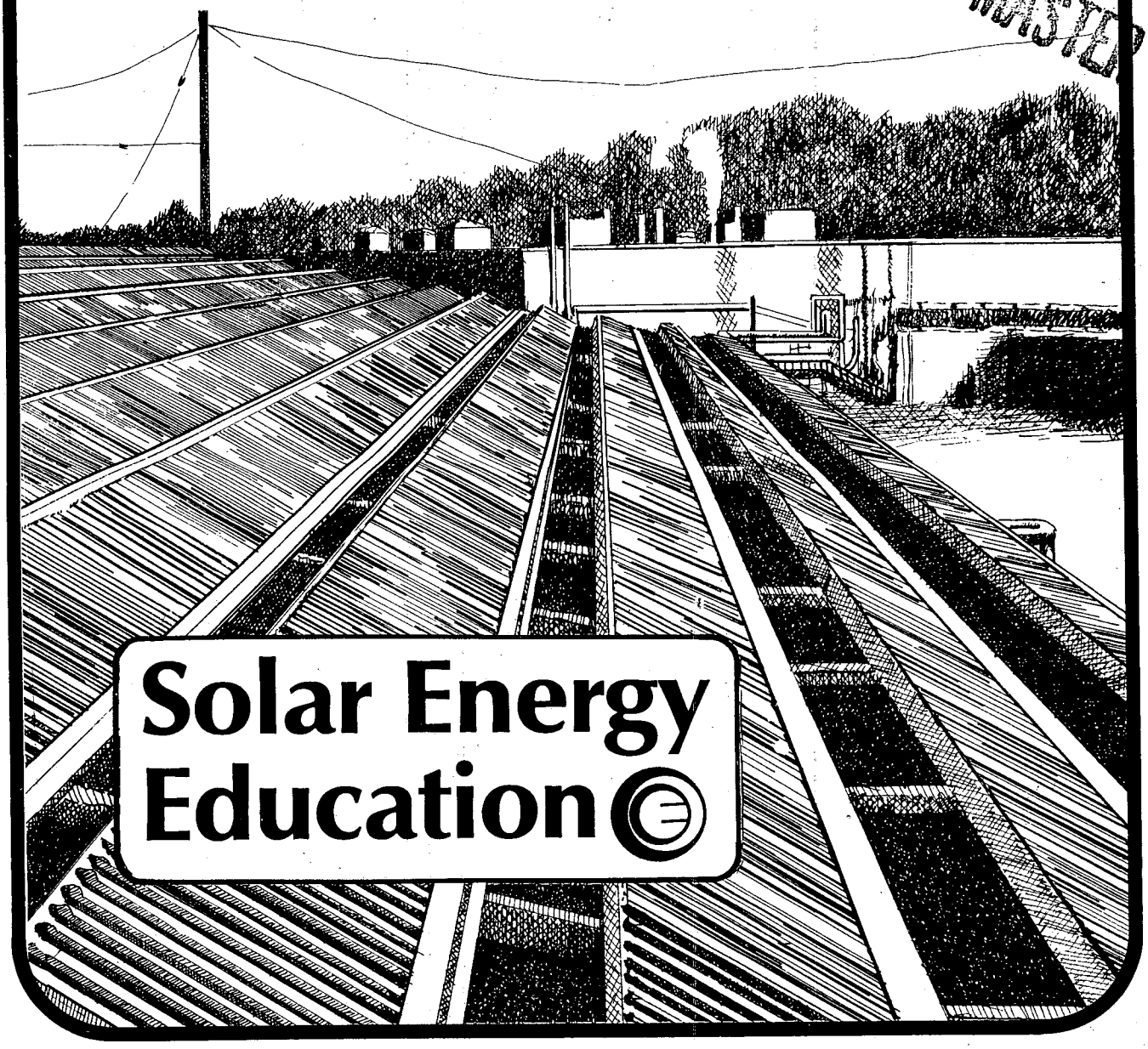

Solar Energy Education

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Authorizing Official
Date: 11/14/2006

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Introduction

For the teacher with a full workload and dozens of important topics to cover and skills to teach, the question that may occur in picking up this booklet is

Why Teach About Energy?

If you are asking that question, try to think of an area of human existence that is not affected by energy resources. Energy permeates our lives; it shapes our careers, our leisure, and our aspirations as well as providing food, clothing, and shelter.

Students are aware of this reality. They see that, as available energy resources change, their lives will also change, in ways as yet unknown. They recognize energy as a factor that will have an impact on them personally, for the rest of their lives, and they want to understand their energy options.

Subject Skills/Energy Content

You can capitalize on your students' strong interest in the topic of energy. With renewable energy as the content matter, the following activities are designed to give students practice in the subject skills that are high on your teaching agenda. Whether it's observing, estimating and predicting, measuring, computing, graphing, or constructing apparatus, you'll find here a renewable energy activity, ready to use.

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The Activities

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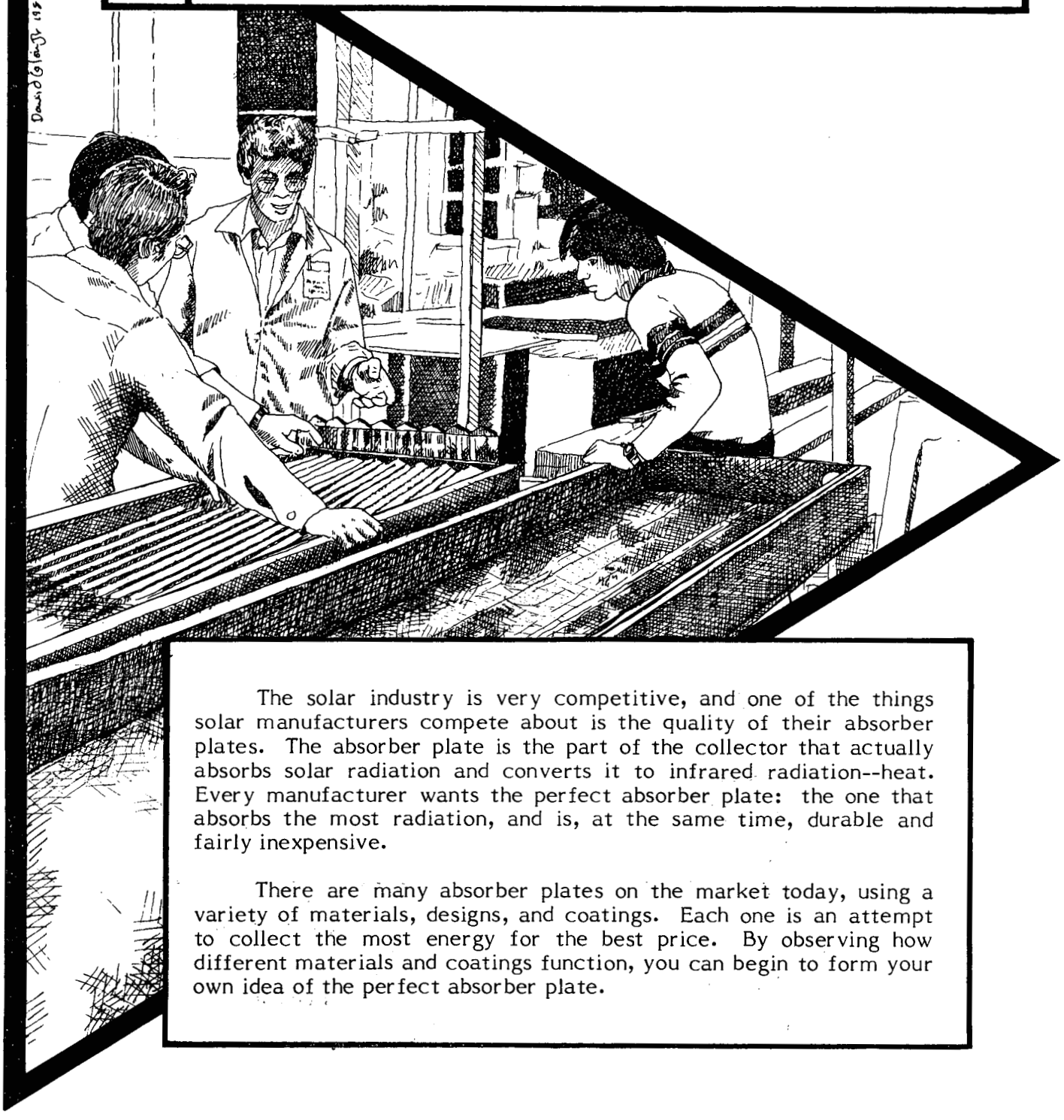
1 Comparing Absorber Plate Coatings



The solar industry is very competitive, and one of the things solar manufacturers compete about is the quality of their absorber plates. The absorber plate is the part of the collector that actually absorbs solar radiation and converts it to infrared radiation--heat. Every manufacturer wants the perfect absorber plate: the one that absorbs the most radiation, and is, at the same time, durable and fairly inexpensive.

There are many absorber plates on the market today, using a variety of materials, designs, and coatings. Each one is an attempt to collect the most energy for the best price. By observing how different materials and coatings function, you can begin to form your own idea of the perfect absorber plate.

objectives

At the completion of this activity, you should be able to

- o explain the function of the absorber plate in a solar collector,
- o calculate the rate of temperature change in absorber plates,
- o calculate the rate of heat absorption by absorber plates,
- o list absorber plates and coatings in order of decreasing effectiveness, and
- o explain how to determine the effectiveness of an absorber plate or coating.

skills and knowledge you need

Ability to graph data

Ability to use a metric balance

Knowledge of specific heat

materials

three 10 cm x 30 cm pieces of aluminum

several coatings, such as black, brown, green, or silver paints

several different 10 cm x 30 cm samples of commercially available absorber plates (optional)

three Celsius thermometers (-10 to 110°C)

three 10 cm x 30 cm pieces of styrofoam insulation (scored down the center)

tape

a metric balance

a table of specific heats

a watch or timer to measure minutes

a light source (if the sun is not shining)

procedure

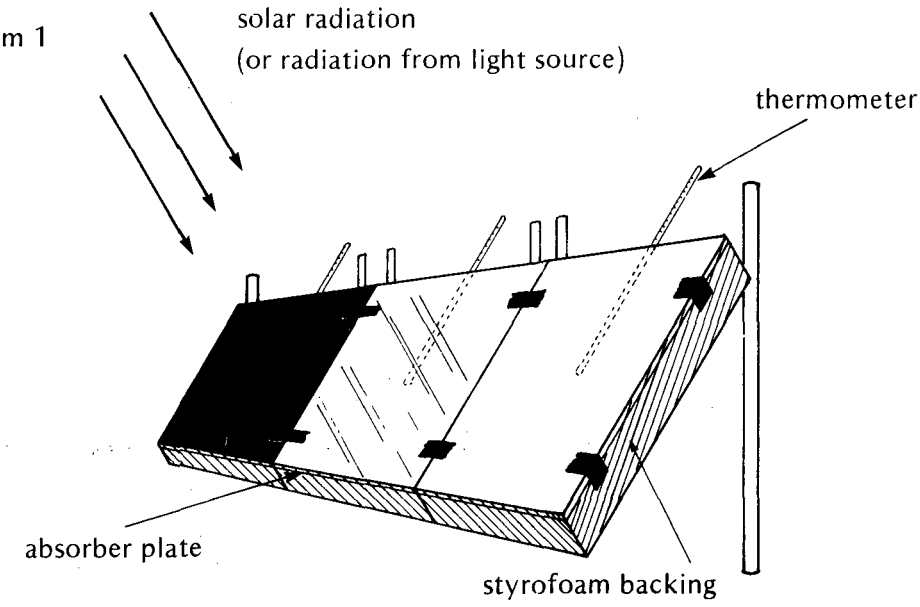
1. Decide which coatings or commercial absorber plate samples you will test.

2. If you chose paints to test as coatings, paint two of the pieces of aluminum with different coatings and allow them to dry. Leave the third piece uncoated.

Caution: Apply paints in a well-ventilated area only.

3. Set up the absorber plate apparatus as shown in Diagram 1, using either the two pieces of painted aluminum or two commercial absorber plate samples, with the uncoated aluminum as the third plate. Adjust the thermometers so that they can be read from the front. Tape the absorber plates to the styrofoam pieces.

Diagram 1



4. Set the plates perpendicular to the rays of the sun (or your light source). You may have to prop the plates with books or blocks of wood. Make sure all the plates are angled the same way so that each receives the same amount of energy.

Caution: Never look directly at the sun. Permanent eye damage can result.

5. Read and record in Data Table 1 the temperature of each plate at 1 minute intervals for a total of 20 minutes.

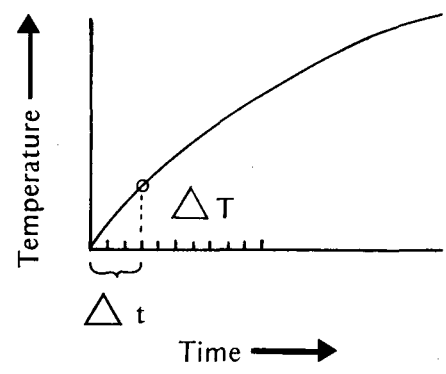
6. Use the graph provided to plot temperature vs. time for each metal plate. Be sure to label or key each line as to its absorber coating.

7. Calculate the heating rate for each absorber plate, using the rate at which the temperature changes during the first 3 minutes of the data collection. Refer to the explanatory graph in Diagram 2 and use the following equation.

$$\text{Heating rate } (^{\circ}\text{C/min.}) = \frac{\Delta T}{\Delta t} = \frac{\Delta T}{3 \text{ min.}}$$

Record in the appropriate space in Data Table 2 the heating rate for each absorber plate.

Diagram 2



8. Disassemble the apparatus and use the metric balance to mass each absorber plate. Record the mass in Data Table 2.

9. Use a table of specific heats to look up the specific heats of the aluminum and any other absorber plate materials you tested. Record the specific heats in Data Table 2.

10. Calculate the rate at which heat energy is absorbed by each plate, using the following equation.

Rate of Heat Energy Absorption (cal/min.)	= Mass (g) x	Specific heat (cal/g°C) x	Heating rate (°C/min.)

$$\frac{Q}{\Delta T} = m \cdot Cp \cdot \left(\frac{\Delta T}{\Delta t}\right)$$

Record each value in the appropriate space in Data Table 2.

questions

1. According to your graph, which absorber plate reached the highest temperature?

2. Does the fact that this absorber plate reached the highest temperature make it the most effective in absorbing heat energy? Why or why not?

3. According to Data Table 2, which absorber plate had the highest rate of heat absorption?

4. Is this absorber plate the most effective in absorbing heat energy? Why or why not?

5. Why was one piece of aluminum left uncoated?

6. Why was it important to place all three absorber plates at the same angle?

7. How did you determine the effectiveness of the absorber plates? Why is this method a good way to determine the effectiveness of an absorber plate?

8. List all absorber plates and coatings tested by the class in order of decreasing effectiveness.

9. Which type of absorber plate or coating seems to be most effective? Why?

10. Which type of absorber plate or coating seems to be least effective? Why?

11. What is the function of an absorber plate in a solar collector?

looking back

Did your observations help you to draw some conclusions about the best materials and coatings for absorber plates? You probably found that flat dark colors, especially black, absorb best. Manufac-

turers often apply a special black coating that absorbs sunlight even better than black paint, and that also emits less heat. These coatings, called "selective surfaces," make the collector even more efficient.

There are many other factors that affect the performance and efficiency of a solar collector. The glazing or transparent cover and the insulation have an effect on the collector's performance, and so does the way the collector is oriented. It is the combination of these and many other factors that makes for the best collector.

going further

Devise and carry out an experiment to determine if a curved absorber plate made from a sheet of the same dimensions as a flat absorber plate is more effective in absorbing solar energy. Explain any results you obtain.

Test the effect of the angle at which insolation strikes an absorber plate upon the rate at which the plate absorbs heat energy.

Determine the effect of insulation upon the rate at which an absorber plate absorbs heat energy. Repeat the activity without the insulation backing. How are the heat absorption rate and temperature affected?

Devise and carry out an experiment that determines how the size of the absorber plate affects both the highest temperature it attains and its heat absorption rate. Explain any results you obtain.

Find out the manufacturer's specifications for the absorptance and emittance of different absorber plates. Explain what absorptance and emittance are, then compare the values you obtained and determine which absorber plate is most effective. Compare its cost to the cost of other plates. Which plate seems to be the most cost-effective (delivers the highest absorption rate at the lowest cost)?

Investigate other factors which should be considered in selection of an absorber plate.

Determine the rate of heat loss from each absorber plate. Allow the plates to heat in the sun for 20 minutes, then record their temperatures every minute for 20 minutes after they are removed from the sun. Calculate the rate of heat loss in the same manner as you calculated heat absorption. How could heat loss from absorber plates be reduced?

How might the rate of heat absorption by an absorber plate be increased and the rate of heat loss be decreased? What effect would this have on solar collector efficiency?

Devise and carry out an experiment to determine how the tilt of an absorber plate affects the rate of heat loss from the plate through convection cooling. Explain any results you obtain. Why is reducing heat loss from convection cooling an important consideration in solar collector design?

To find out how selective coatings are applied to absorber plates, try the next activity, "Anodizing and Coating Absorber Plates."

Select the most effective absorber surface and use the same kind of surface in the construction of the flat plate collector in Activity 3 in this book, "Collecting and Storing Solar Energy."

Data Table 1

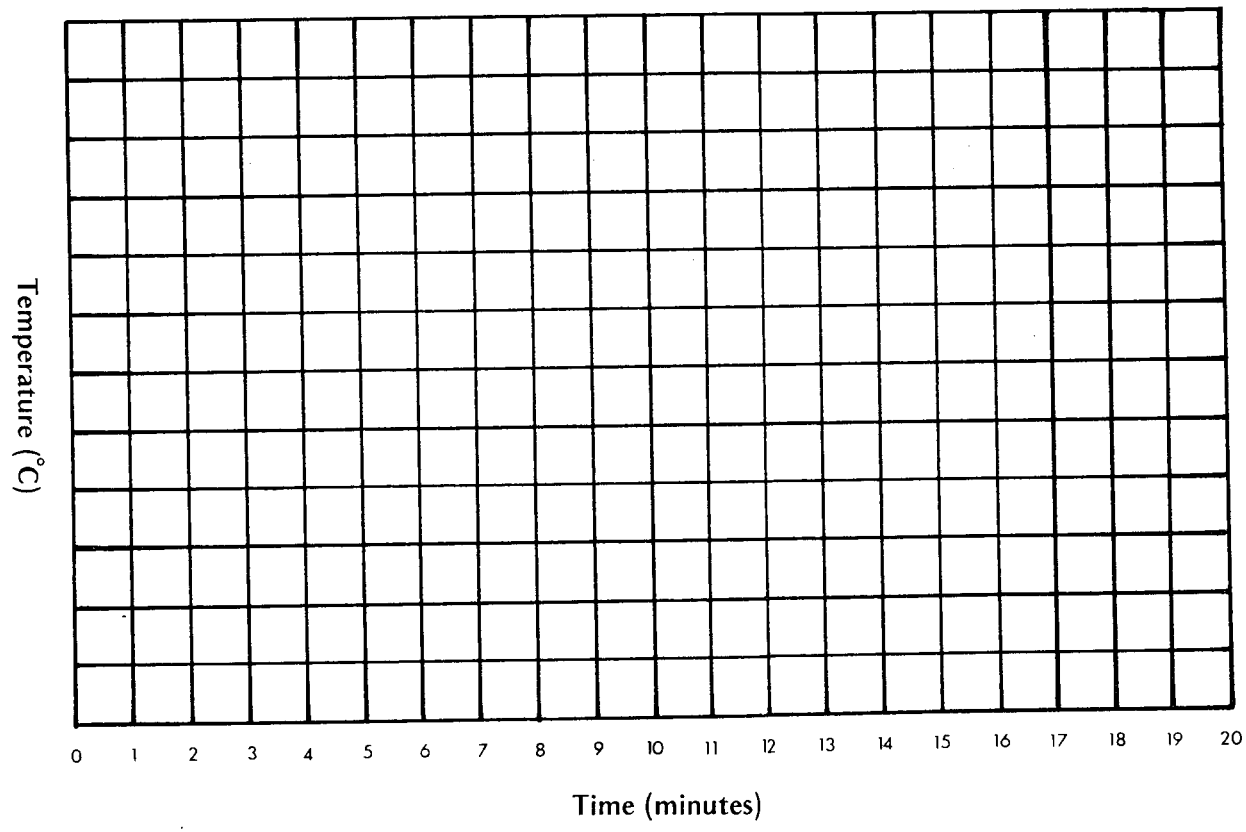
Time (minutes)	Temperature (°C)		
	Plate 1: _____ (coating and material)	Plate 2: _____ (coating and material)	Plate 3: Uncoated Aluminum
0			
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			

Data Table 2

Absorber Plate	Heating Rate (°C/min.)	Mass (g)	Specific Heat (Cp) (cal/g°C)	Rate of Heat Absorption (cal/min.)
Plate 1: _____				
Plate 2: _____				
Plate 3: Uncoated aluminum				

Graph

Absorber Plate Temperatures



Teacher Information

Comparing Absorber Plate Coatings

Suggested Grade Level and Discipline

Science, grades 10-12
Physics
Physical Science
Advanced Physical Science
Consumer Physics
Industrial Arts

Skill Objectives

Collecting, recording, and graphing temperature data

Determining rates of temperature change

Calculating rates of heat absorption

Interpreting and comparing experimental values

Major Understandings

The absorber plate in a solar collector converts solar radiation into heat energy.

The effectiveness of an absorber plate is determined by the amount of heat absorbed by the plate. Factors contributing to this effectiveness are plate material, shape, color, and coating.

An effective absorber plate is a selective surface: it increases absorption of short-wave radiation and decreases radiation of long-wave radiation.

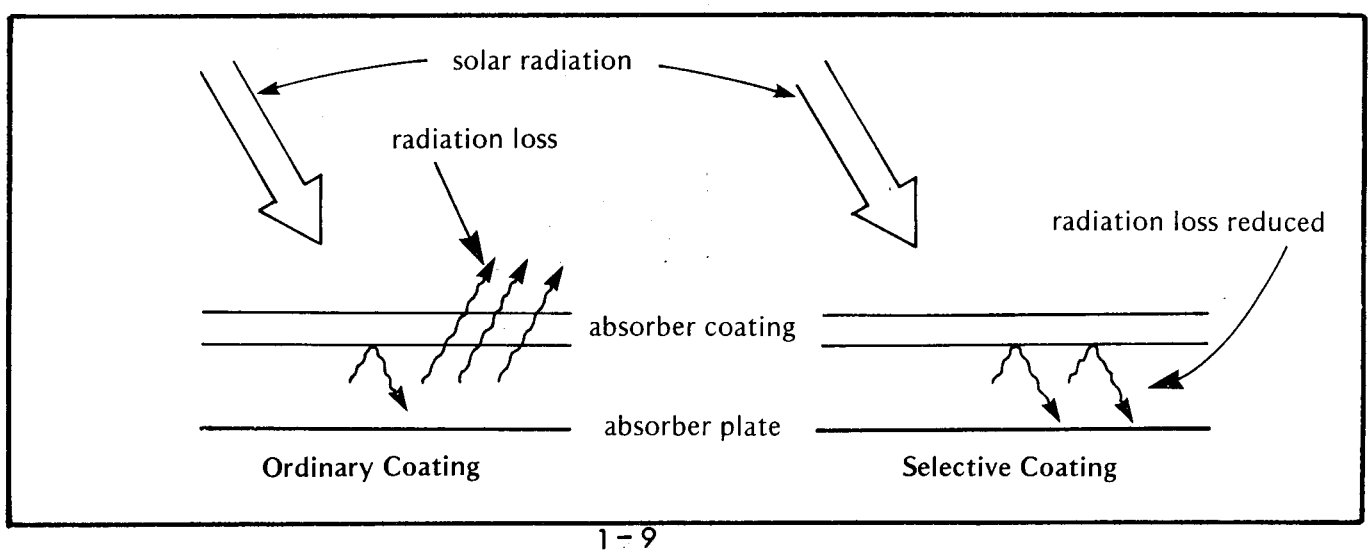
Rate of heat absorption by an absorber plate may be calculated by:

$$Q/\Delta t = m \cdot Cp \cdot (\Delta T/\Delta t).$$

Background

An effective absorber plate is solar selective; that is, it absorbs the maximum amount of incident radiant energy and emits a minimum of infrared radiation. A selective absorber plate, therefore, absorbs short-wave radiation maximally and emits long-wave radiation minimally. This selectiveness is important because an absorber plate converts short-wave visible radiation to long-wave infrared radiation.

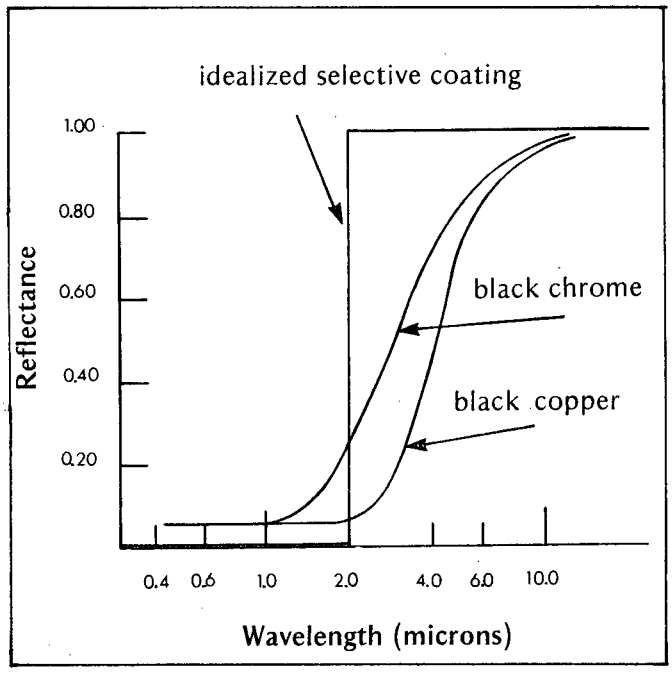
Solar absorptance (α) is the ratio of radiant energy absorbed by a plane surface to the radiant energy incident upon the surface. Generally, absorptance values vary from 80% on a matte black surface up to 98% on special surfaces. Solar emittance (ϵ) is the ratio of radiant energy emitted at a given temperature to the radiant energy that would be emitted by a black body at the same temperature. A desirable selective absorber



has a low emittance value. Absorptance and emittance values for some commonly available commercial surfaces are listed below. Usually the highest ratio of absorptance to emittance is desirable.

Surface	Absorptance(α)	Emittance (ϵ)	α/ϵ
Copper Oxide	.91	.16	5.69
Anodized Aluminum	.96	.98	.98
Chromium Oxide	.95	.10	9.50
Alcoa 655 Surface	.98	.44	2.23
Flat Black Paint	.96	.53	1.81

Reflectance is the ratio of radiant energy reflected from a plane surface to the radiant energy incident upon the surface. Reflectance data form the basis for calculations of absorptance and emittance. A selective surface will have low reflectance (high absorptance) in the incident radiation range and high reflectance (low absorptance and low emittance) in the infrared range. A graph of the reflectance of an idealized selective surface is given below.



The efficiency of an absorber plate depends upon both the metal it is made of and the coating placed on the metal. Currently, absorber plates are manufactured from copper, aluminum, and galvanized steel. Of these, copper is the best conductor and the most corrosion resistant, although it is also the most expensive. Research is being conducted on other possible materials for absorber coatings in addition to those materials listed in the table above, including black chrome, black zinc, and black copper. These three materials are high-performance and moderate-cost coatings, and are widely available through the coating industry.

Advance Planning

Prepare the styrofoam insulating pieces by scoring them down the center. The thermometer should fit snugly into the groove when the plate is attached. Don't score so far down the styrofoam that the thermometer, when inserted to the bottom of the groove, can't be read.

Obtain the plates or coatings to be tested. Aluminum plates are used in printing and discarded plates may be available from a printer or newspaper print shop. You may be able to obtain samples of actual plates from solar collector dealers. Copper oxide, anodized aluminum, chromium oxide, Alcoa 655 Surface, and several high-carbon flat black paints (especially barbeque grill paints and Nextel Black Velvet) are the most frequently used surfaces. Obtain different paints to use as coatings. Invite students to bring from home particular paints they wish to test. Spray paint or latex paint is preferable because it dries quickly and cleans easily.

Prepare the aluminum plates by cutting them to size. Prepare other plates as needed. Tape any sharp or rough metal edges.

Obtain tables of specific heats.

If you will be using artificial light, decide on the type of lamp to use. A sun lamp is preferable to a heat lamp because the wavelength distribution of the light is more similar to that of sunlight. However, a sun lamp should be used only with extreme care on the part of students. A heat lamp is preferable to an incandescent bulb. Determine the best distance at which to position the chosen light source from the plates. Plates should be illuminated equally as they are tested. You

may, therefore, have to use more than one lamp per set-up, or you may have to test just one plate at a time, keeping the plate to lamp distance the same for each trial.

If appropriate, duplicate the teacher background information for student use.

Suggested Time Allotment

One or two class periods to set up the apparatus and perform the activity (after the plates have been painted)

One class period to complete calculations, answer questions, discuss results, and draw conclusions

Suggested Approach

Introduce the activity by discussing the parts of a solar collector and their functions. Elicit from students the qualities and properties of an effective absorber plate. Ask them how an absorber plate should function in a collector to produce the highest temperatures. Discuss the concept of collector efficiency.

Divide students into groups of two or three to work on the activity. Each group should have a "standard" plate (the uncoated aluminum) as a control, but otherwise the plates and/or coatings may vary.

If necessary, help students with calculations. When the calculations are finished, allow time for groups to share data.

Explain absorptance and emittance when discussing results. Stress the special properties of selective surfaces.

Precautions

Apply paint outdoors or in a well-ventilated room only, especially if spray paints are used.

Remind students that they should never look directly at the sun.

If sun or heat lamps are used, instruct students to exercise extreme caution. Both lamps will become very hot and the sun lamp emits dangerous ultraviolet radiation. Students should never look directly at the sun lamp, nor expose their skin to its radiation.

Tape any rough or sharp metal edges on the absorber plates.

Points for Discussion

How well was the experiment controlled? How many different types of experimental error can you cite?

Why did the temperatures level off near the end of the experiment?

How should the effectiveness of an absorber plate be judged? What criteria should be considered?

Which type of absorber plate or coating would you choose for use in a solar collector? Why?

Typical Results

Results will vary significantly, depending on the coatings, plates, and light source used. In general, light colors of regular paint will produce the smallest amount of heat absorption, while dark colors will show a greater amount, and black will show the greatest amount. Dull paints will produce higher heat absorptions than shiny paints. Flat black, high carbon, and barbeque grill paints will produce similar results in the range of high heat absorption. Commercially-available paints made especially for collectors and actual samples of absorber plates and selective surfaces will produce the highest values for heat absorption. As measurable in this activity, there may not be significant differences among these latter products.

Evaluation

Examine students' data tables and graphs for neatness and accuracy.

Collect and review students' calculations and answers to questions for accuracy and degree of understanding.

Have students explain the function of an absorber plate.

Ask students to list absorber plates and coatings in order of decreasing effectiveness.

Present students with sample data and ask them to calculate rates of temperature change and heat absorption.

Ask students to explain how the effectiveness of an absorber plate or coating is determined.

Modifications

Copper, tin, and galvanized steel may be used in addition to (or substituted for) the aluminum absorber plates.

Replace the thermometers with thermocouples. The increased accuracy of the results obtained may be more useful, especially to physics students.

References

Build Your Own Solar Water Heater, Stu Campbell and Doug Taff.
(Garden Way Publishing Co., Charlotte, VT 05445, 1978, $7.95/paper.)

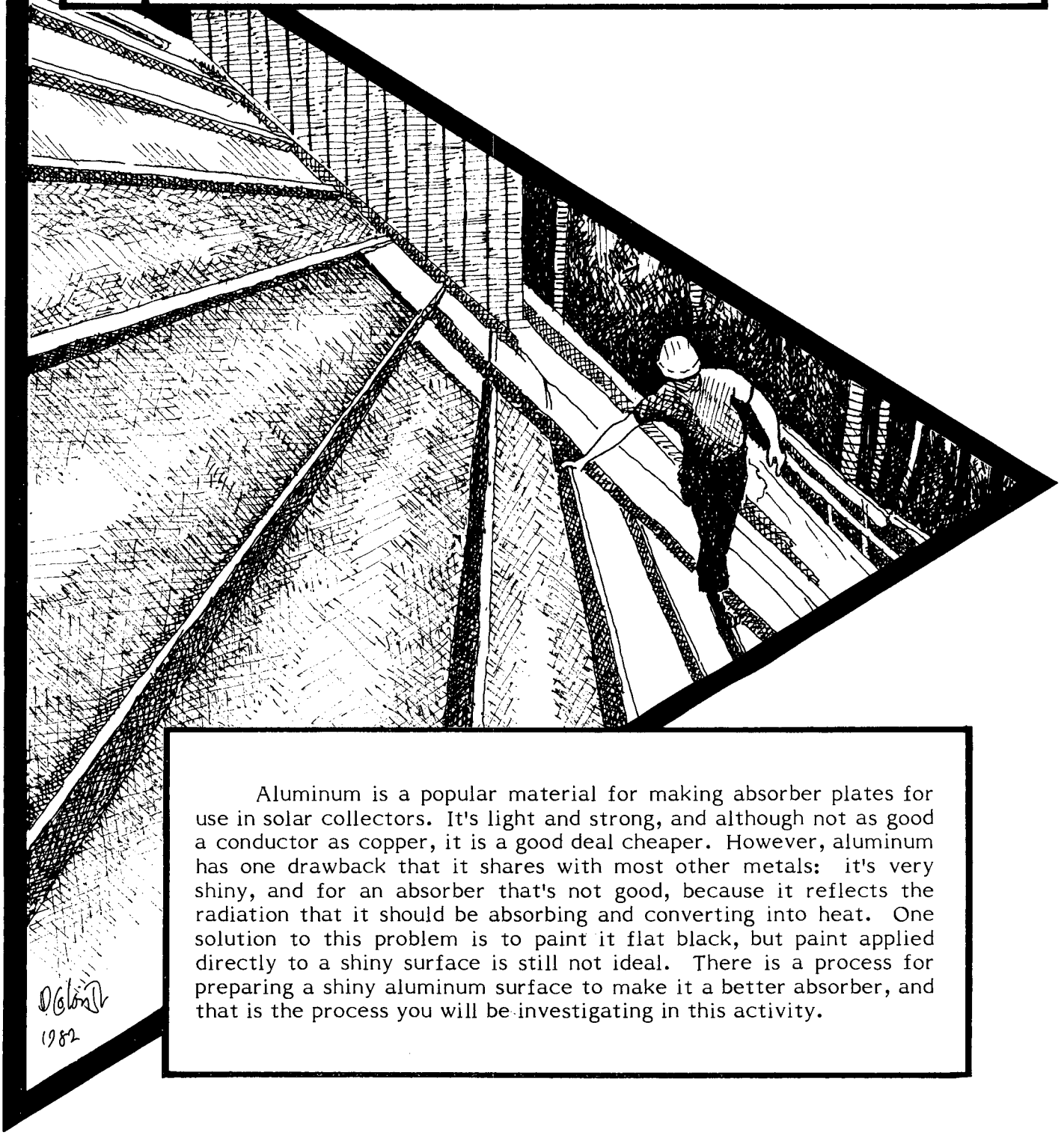
Engineer's Guide to Solar Energy, Yvonne Howell and Justin Bereny.
(Solar Energy Information Services, P.O. Box 204, San Mateo, CA 94401, 1979, $29.50/paper.)

Home Guide to Solar Heating and Cooling, Jackson Hand.
(Harper & Row Publishers, Inc., Keystone Industrial Park, Scranton, PA 18512, 1978, $3.95/paper.)

"Coatings Seek Their Place in the Sun: Parts I and II."
(Products Finishing, Gardner Publications, Inc., 600 Main St., Cincinnati, OH 45202, January and February 1977.)

"Solar Savvy: Who Needs It?"
(Plating and Surface Finishing, American Electroplaters Society, Inc., 1201 Louisiana Ave., Winter Park, FL 32789, October 1976.)

2 Anodizing and Coating Absorber Plates



Aluminum is a popular material for making absorber plates for use in solar collectors. It's light and strong, and although not as good a conductor as copper, it is a good deal cheaper. However, aluminum has one drawback that it shares with most other metals: it's very shiny, and for an absorber that's not good, because it reflects the radiation that it should be absorbing and converting into heat. One solution to this problem is to paint it flat black, but paint applied directly to a shiny surface is still not ideal. There is a process for preparing a shiny aluminum surface to make it a better absorber, and that is the process you will be investigating in this activity.

objectives

At the completion of this activity, you should be able to

- o construct and use a direct current circuit containing an electrolytic cell,
- o identify the steps required in anodizing and coating aluminum and state the purpose of each step,
- o describe the reaction that occurs at the anode of the electrolytic cell, and
- o explain why aluminum is anodized and coated before being used as an absorber plate in a solar collector.

skills and knowledge you need

Maintaining the temperature of a water bath

Setting up an electrical circuit

Following safe laboratory procedures

materials

one 1.5 volt dry cell or low voltage D.C. power supply

two 2.5 x 15.5 cm aluminum strips

a D.C. voltmeter

test leads with alligator clips

four 500 ml glass beakers containing, as labelled: a caustic etch rinse, a nitric acid rinse, a sealing solution, and a coating solution (optional)

a plastic tank for the electrolytic cell, containing the electrolyte solution

a water bath

an alkaline metal cleaning fluid (such as Janitor-in-a-Drum)

a sponge or rag

flat black spray paint

a Celsius thermometer

a forceps or tongs

a 425-450°C drying oven (optional)

procedure

Caution: Wear safety goggles and a lab apron when handling the chemicals in this activity. Take care not to splatter or spill the chemicals.

1. Prepare a water bath for the caustic etch solution. The solution should be maintained at a temperature of 55°C.

2. If you are using a dry cell as the power source, test it with the voltmeter to make sure it is delivering 1.5 volts. Prepare an electrolytic cell as shown in Diagrams 1 and 2. Use one aluminum strip as the cathode (connected to the negative terminal of the power source). Leave the power source disconnected from the electrolytic cell.

Caution: If you are using a low voltage D.C. power supply or other step-down, plug-in power source, always follow the "one hand in the pocket" rule to prevent a possible bridging of power from one hand to the other.

Diagram 1

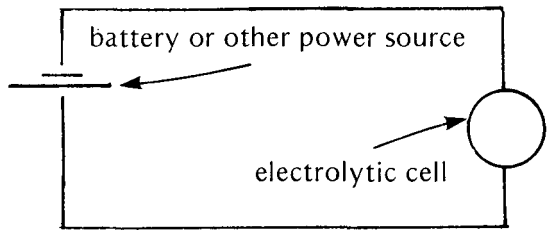
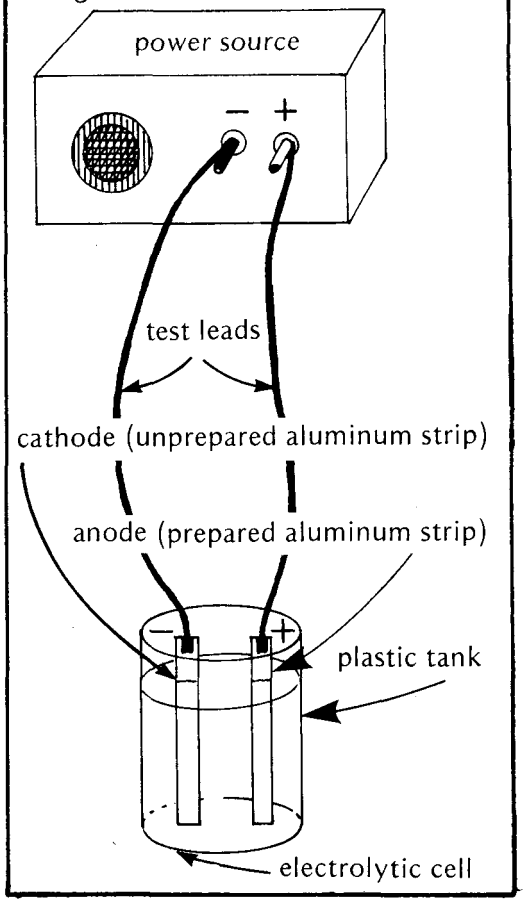


Diagram 2



3. Prepare the second aluminum strip for anodizing by scrubbing it with the alkaline metal cleaner. Rinse thoroughly in water. Observe the appearance of the aluminum strip and record your observations in the appropriate space on the data table provided.

4. Soak the strip for five minutes in the 55°C caustic etch solution. Rinse the strip thoroughly in water. Record in the data table your observations of the rinsed strip.

5. Start increasing the temperature of the water bath to boiling and replace the caustic etch solution with the sealing solution. The sealing solution should be boiling by the time you reach Step 10.

6. Rinse the strip in the nitric acid solution by moving the strip up and down with forceps or tongs for about one minute. This procedure will remove the "smut" (film) produced during the etching process. Rinse thoroughly in water, then record in the data table your observations of the strip.

Caution: Be sure you rinsed the strip in water first.

7. Use the prepared aluminum strip as the anode of the electrolytic cell and connect it to the positive terminal of the power source.

8. Connect the power source to the electrolytic cell. Supply current for a total of 2-3 minutes.

Caution: Follow the "one hand in the pocket" rule.

9. When the anodizing is completed, disconnect the power source. Use forceps to remove the aluminum strip from the anode of the electrolytic cell and to place the strip in successive water rinses. Record your observations of the strip in the data table.

10. Place the strip in the boiling sealing solution for 15 minutes. Rinse thoroughly in water. Record your observations of the strip in the data table.

11. Reduce the temperature of the water bath to within a range of 27-32°C and replace the sealing solution with the coating solution. (This is an optional step.)

12. Now, either spray the strip with flat black paint and let dry

or

immerse the strip in the coating solution for 10 minutes, maintaining a temperature between 27°C and 32°C. Then dry the immersed strip for several hours in a drying oven set at its highest temperature, until the surface has become almost black.

Record your observations of the aluminum strip.

Caution: Use spray paint in a well-ventilated area only.

questions

1. What properties of aluminum make it valuable as the material for an absorber plate in a solar collector?

2. What property of aluminum must be altered in order for it to perform effectively as an absorber of solar energy?

3. What was the appearance of the aluminum strip after cleaning? Why did you clean the strip with an alkaline metal cleaner?

4. How did the aluminum strip look after being soaked in the caustic etch solution? Why did you soak the strip in the etch?

5. Did the appearance of the aluminum strip change after being rinsed in the nitric acid? Why did you rinse the strip this way?

6. What was the appearance of the aluminum strip after anodizing it?

7. What reaction occurred at the anode? Why is this reaction important to the use of aluminum in a solar collector?

8. Did the appearance of the aluminum strip change after sealing? What was the purpose of sealing the strip?

9. How did the appearance of the strip change after it was painted or coated? What was the purpose of the painting or coating?

10. Why is aluminum anodized and coated before being used as an absorber plate?

looking back

You have just carried out a process very similar to the one that industry uses to prepare and coat aluminum for solar absorber plates. Each of the solutions served a definite purpose, along with the electrolytic cell, in producing on the aluminum a surface that would not only accept a coating but also keep it over time. The anodized, coated surface will be a better absorber, resistant to scratching and peeling from abrasion and temperature change.

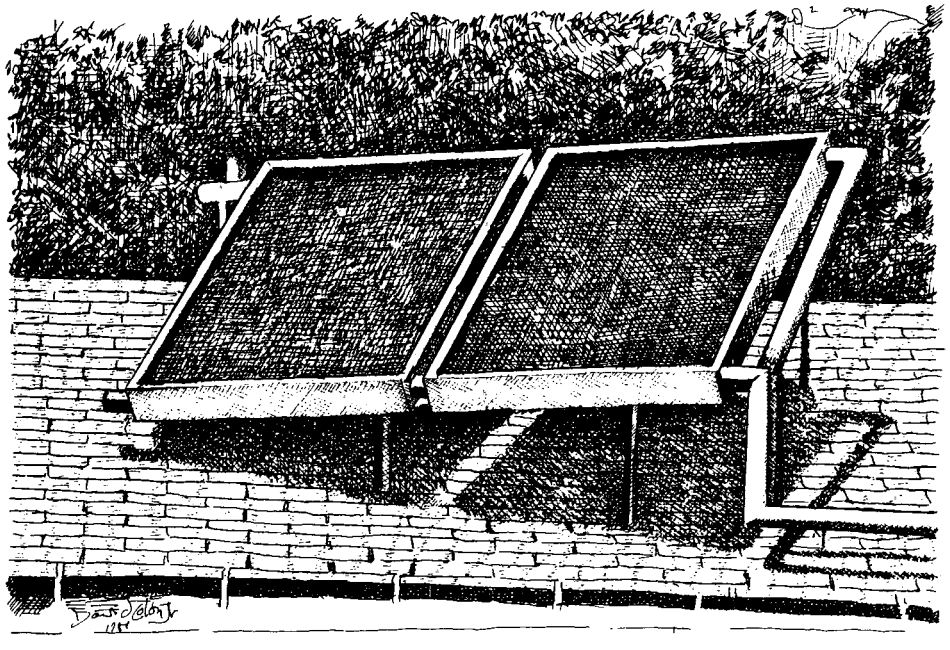
going further

Paint a strip of aluminum which has not been anodized. Use a solar meter or photometer to compare the reflectivity of this strip with the one you prepared in the activity. Is there a measurable difference?

Anodize and coat a 15 x 30 cm piece of aluminum. Include it as one of the absorber plates to be tested for heat absorption capacity in the activity "Comparing Absorber Plate Coatings."

Compare the heat absorption properties of an anodized and painted strip with an anodized and chemically coated strip. Is there a significant difference in heat absorption between the two strips?

Devise an experiment to test how well the finish coat (the paint or chemical) has bonded to the anodized surface. Use an unanodized painted or chemically coated strip as the control. Try such methods as alternately placing the strips in cold (ice) water and hot ($40^{\circ}C$) water, flexing the strips, and attempting to scratch the surfaces of the strips with various objects. Follow an exact procedure for each method, record your observations, and present tabulated results.



Data Table

	Observations
Of cleaned aluminum strip	
After soaking in caustic etch solution	
After rinsing in nitric acid solution	
After anodizing	
After sealing	
After painting or coating	

Teacher Information

Anodizing and Coating Absorber Plates

Suggested Grade Level and Discipline

Science, grades 10-12
Chemistry
Physics
Industrial Arts, grades 10-12

Skill Objectives

Maintaining a water bath

Using chemicals safely and following safe laboratory procedures

Setting up and using a circuit containing an electrolytic cell

Making, recording, and interpreting observations

Stating the purpose of each step in an anodizing and coating process

Major Understandings

Aluminum is often used as the material for absorber plates because it is lightweight, relatively abundant, inexpensive, and a good conductor of heat.

Aluminum is a highly reflective material. To use aluminum effectively as an absorber plate, its surface must be altered to become light absorptive. This is usually accomplished by applying a dark, light-absorptive paint or chemical coating.

Anodizing alters an aluminum surface by oxidizing it. Pits are created in the surface so that it becomes more porous.

Particles of paint pigments and chemical coats will form a tighter bond with the porous surface of anodized aluminum. This tighter bond renders the surface more resistant to temperature changes and mechanical abrasion.

Background

Nearly all pure metals are shiny, tending to reflect any light which falls on them. However, metals conduct heat efficiently from point to point and to the surrounding environment. If metal surfaces could be altered so that incident radiation was absorbed rather than reflected, then metals would be highly efficient materials to use as absorber plates. The process of anodizing and coating metals alters their surfaces in this manner.

In this activity, an industrial process commonly used in anodizing and coating aluminum is adapted for the laboratory. Aluminum is frequently used as an absorber plate because it is lightweight, strong, and abundant. Although aluminum is not quite as good a conductor nor quite as corrosion resistant as copper, it is much less expensive. In fact, aluminum is next only to gold, silver, and copper in heat conductance.

The steps in the anodizing and coating process sequentially prepare the aluminum for its light-absorptive surface. Cleaning with an alkaline metal cleaner removes dirt particles, oils, grease, and oxides. The caustic etching solution removes any remaining oxides in preparation for anodizing. The nitric acid is a rinse which neutralizes the caustic etch (a base) and "passivates" the aluminum surface to prevent unwanted reactions. The electrolyte solution oxidizes the aluminum as current passes through the circuit, creating a pitted surface. The anodizing is conducted for only 2-3 minutes so that a properly pitted surface results. The sealing solution contains a highly oxidizing chemical that causes chromate to be deposited on the aluminum surface, thereby developing a surface of proper porosity and, by passivating the aluminum, preventing other oxidation reactions. The coating solution also contains oxidizing chemicals, as well as an acid to

provide the correct pH for the reaction. The manganese dioxide deposited on the aluminum surface in the coating process will darken upon high-temperature drying to provide a highly absorptive surface. Both paint and the chemical coating will tightly bond to the sealed surface as their particles are trapped in its pores. Anodized and coated surfaces are more resistant to temperature changes and mechanical abrasions than are unanodized, painted surfaces.

Advance Planning

Order well in advance of the activity any chemicals needed from the list below. Most of these chemicals should be available from the chemistry stock room.

Decide on the number of set-ups to be used in the activity (see the suggested approach). Prepare solutions according to the directions below. Volumes given provide enough solution for only one set-up.

Caustic etch solution

Dissolve 25 g of caustic soda (approximately 5% weight/volume) in 500 ml H_2O. (Granular Drano can be substituted for the caustic soda.)

Nitric acid rinse

Add 75 ml concentrated HNO_3 (15% volume/volume) to 500 ml H_2O.

Electrolyte solution

Add 60 ml concentrated H_2SO_4 to 500 ml H_2O.

Sealing solution

Dissolve 25 g of K_2CrO_4 or Na_2CrO_4 in 500 ml H_2O.

Coating solution

Dissolve 5 g of $KMnO_4$, 12.5 g of $CuNO_3$, and 2 ml of concentrated HNO_3 in 500 ml H_2O.

Decide what will be used as the power sources. Low voltage D.C. power supplies (transformer/rectifiers) or 1.5 volt dry cells should be available from the physics lab. Test leads and voltmeters can also be obtained from the physics lab.

Glass beakers, plastic tanks, water baths, and forceps or tongs are standard chemistry labware.

Cut aluminum strips. Used aluminum plates are readily obtainable from printers. The strips should have a surface of at least 38-40 cm^2.

If desired, set up equipment at stations in the lab (see the suggested approach).

Suggested Time Allotment

One class period to introduce the activity and set up necessary equipment (especially water baths and electrolytic cells)

One class period to perform the activity (If necessary, the procedure can be halted after a particular step and resumed the next day.)

One class period to complete the activity (if necessary) and to answer questions and summarize results

Suggested Approach

Introduce the activity by asking the class what properties of aluminum make it an outstanding construction material and desirable for use as a solar collector absorber plate. Then emphasize the need for a dull, dark coating if the aluminum is to be effective as a solar absorber.

If necessary, explain the operation of the electrolytic cell and of the direct current circuit, and demonstrate how to maintain a water bath, set up the circuit, and read voltmeters.

Emphasize the need for extra caution in working with the chemicals and power sources.

You may wish to follow one of two recommended approaches, each requiring one complete set-up for 6 to 10 students.

1. Each group works through the entire procedure by moving from station to station within the set-up.
2. Each group has one or two individuals responsible for one part of the procedure, thus forming an "assembly line."

Stations or individual responsibilities can be allocated in the following manner.

1. Cleaning, etching, and rinsing the strips
2. Setting up the electrolytic circuit and anodizing the strips
3. Sealing the strips
4. Applying finish coats

Stations 1, 3, and 4 can handle several groups of students at once, and you may want only one or two classroom stations for each of these. Any number of aluminum strips can be placed in the beakers for etching, rinsing, sealing, and finishing. The bottleneck will be Station 2, where only one strip can be anodized at a time. You may wish to set up extra stations for this part of the procedure.

If you choose the assembly line approach, allow students time to observe other stations.

The procedure may be halted after the nitric acid rinse (leave strips in rinse water) or after sealing, and then completed the next class period.

As students answer the questions, discuss with them the chemical reaction at the anode of the electrolytic cell, the purpose of anodizing (providing a surface for more perfect adhesion of coatings), and the practical applications of the procedure in the solar energy industry.

This activity may be substituted for more standard laboratory investigations that demonstrate the use of electrolytic cells and direct current circuits.

For physical science classes, a demonstration may be more appropriate than a lab activity.

Precautions

In preparing solutions, always add acid to water.

Remind students that they must wear safety goggles and lab aprons throughout the procedure and should be especially careful in using the solutions.

Emphasize the "one hand in the pocket" rule if students are using a plug-in power source.

Allow spray painting in well-ventilated areas only. Outdoors is preferable.

Points for Discussion

Why are commercial absorber plates often anodized and/or coated?

Describe how this activity was an "electrochemical" process.

What are some of the important aspects and implications of an industrial process such as the one you followed in this activity?

Why is observing the safety precautions so important in this activity?

Typical Results

The anodized and painted or coated aluminum strips will be a dull, black color and highly absorptive. Abrasion and temperature resistance tests should show a tighter bond of the coating to the aluminum than for unanodized strips. Progressive steps in the procedure will cause the aluminum strips to become duller, more abraded, and pitted (this last will not be visible to the eye).

Evaluation

Assess students' ability to follow directions and to organize their time and the steps in the procedure.

Check students' laboratory skills in observing safety precautions, maintaining water baths, setting up electrolytic cell circuits, and recording observations.

Ask students to list the steps required in anodizing aluminum and to state the purpose of each step.

Have students describe the purpose of the chemical reaction at the anode of the electrolytic cell.

Ask students why aluminum is anodized and coated before use as an absorber plate.

Modifications

For chemistry classes, you may wish to have students prepare solutions themselves as a means of practicing this laboratory technique.

For physics classes, you may wish to have students tabulate and graph amperage and voltage as a function of time if the dry cells are used, and to calculate the resistance of the circuit. This approach will emphasize the relationship E = IR.

Glass baking dishes may be substituted for the glass beakers containing the etch and rinse solutions.

If a drying oven is not available, a regular oven in the home economics room can be substituted.

References

Advanced Inorganic Chemistry, Albert Cotton and Geoffrey Wilkinson.
(John Wiley & Sons, Inc., 605 Third Ave., New York, NY 10016, 1980, $27.50.)

Build Your Own Solar Water Heater, Stu Campbell and Doug Taff.
(Garden Way Publishing Co., Charlotte, VT 05445, 1978, $7.95/paper.)

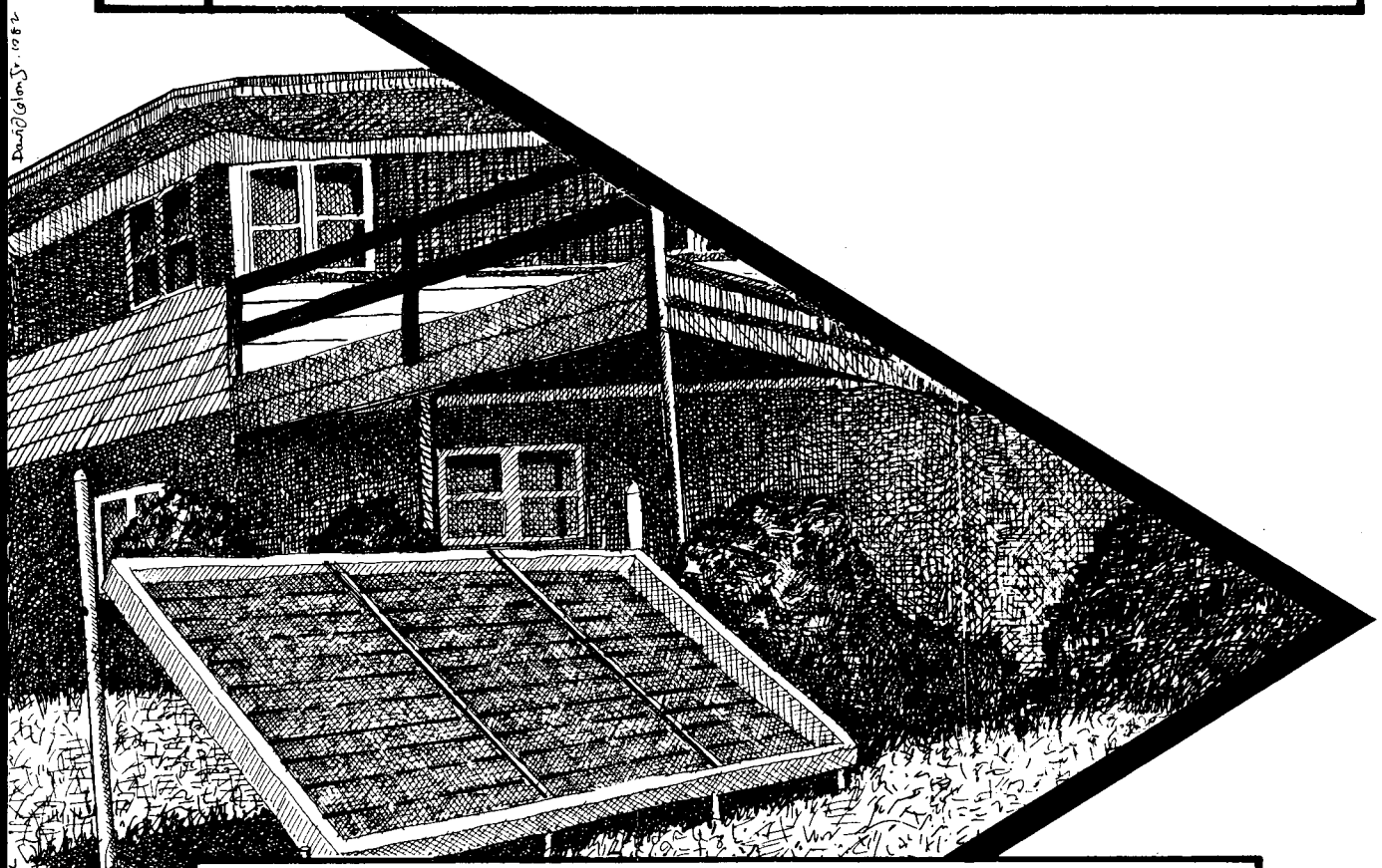
Fundamentals of Physics, David Halliday and Robert Resnick.
(John Wiley & Sons, Inc., 605 Third Ave., New York, NY 10016, 1981, contact the publisher for price.)

Home Guide to Solar Heating and Cooling, Jackson Hand.
(Harper & Row Publishers, Inc., Keystone Industrial Park, Scranton, PA 18512, 1978, $3.95/paper.)

Modern Physics, John E. Williams et al.
(Holt, Rinehart & Winston, 383 Madison Ave., New York, NY 10017, 1976, $15.72.)

"Anodizing Titanium in School Shops," Christopher Gabel.
(School Shop, P.O. Box 8623, Ann Arbor, MI 48107, February 1979.)

3 Collecting and Storing Solar Energy



If you had seen a solar collector ten years ago, you might not even have known what it was. Today solar collectors are a familiar sight, and almost everyone recognizes them. But there's more to a solar collector than meets the eye, and collectors are not all the same. For example, there are efficient collectors that work very well, and there are inefficient ones that don't function nearly as well as they might if they were properly designed and installed.

Then, too, the collector itself is only the "tip of the iceberg" -- the part that shows. There is also a circulation system of pipes and ducts, often leading to a storage tank or bin, where heat can be stored overnight.

As with any other investment, the wise consumer will collect information before making a choice. In this activity you will add to your store of information about solar collectors, their parts, and their operation.

objectives

At the completion of this activity, you should be able to

- o assemble a model flat plate air-flow solar collector and a heat storage system,
- o identify and explain the purpose of the components of each system,
- o test different absorber plates, glazings, and insulations to determine the most effective combination for a solar collector, and
- o explain how the effectiveness of the collector was determined.

skills and knowledge you need

The ability to record and graph data

A knowledge of heat and solar energy

materials

For the Collector:

a preconstructed collector box (15 x 60 x 120 cm)

two Celsius thermometers

samples of insulation to fit the box
- fiberglass
- rigid polyurethane
- packing material
- cellulose

sample absorber plates, painted various colors, to fit the box
- aluminum
- copper
- tin
- cardboard
- sheet steel

framed glazing covers to fit the box
- plexiglass
- vinyl plastic
- lightweight and heavyweight polyethylene sheeting
- tempered glass
- translucent plastic
- clear plastic
- reinforced polyester sheeting

a watch or timer to measure minutes

tape

For the Storage Unit:

a 5-gallon plastic pail, with a lid

gravel or stone, 1-2 cm in diameter

a colander or wire mesh to support the gravel

a blower fan (such as a hair dryer)

two pieces of plastic tubing, approximately 50 cm long and 4 cm in diameter

a Celsius thermometer

an extension cord

a watch or timer to measure minutes

procedure

Part 1: Heat Collection

1. Obtain the solar collector box and other materials needed for Part 1.

2. Cover the bottom of the box with one kind of insulation, as shown in Diagram 1. Choose an absorber plate to test, and place it over the insulation. Both the insulation and the absorber plate should fit snugly in the bottom of the box.

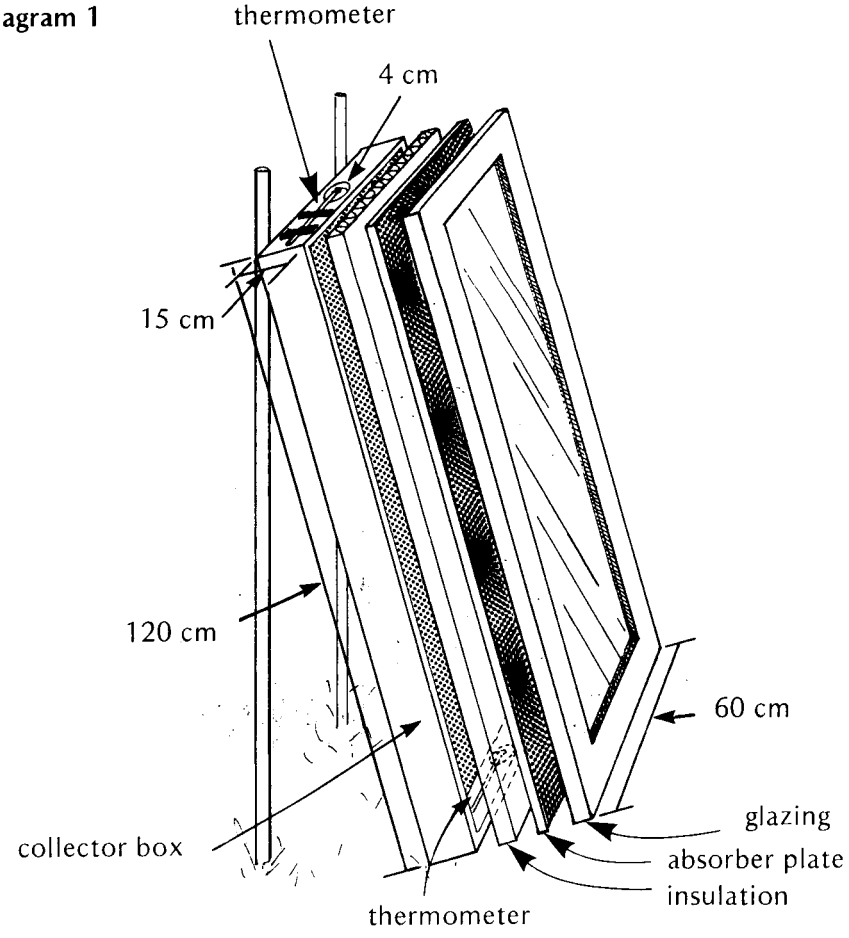
Caution: Wear gloves and safety goggles when handling fiberglass insulation.

3. Choose a glazing cover and place it securely over the top of the box.

Caution: Handle glass glazing covers with care.

4. Locate the intake and output holes in the box. Tape one thermometer to the box so that the bulb is located over the intake hole. (See Diagram 1.) Tape the other thermometer over the output hole.

Diagram 1



Caution: Never look directly at the sun. Permanent eye damage can result.

5. Take your solar collector outside and place it in direct sunlight. Orient the collector so that the sides with the holes form the top and bottom of the collector. The hole on the bottom is the intake; the hole on the top is the output. Set the collector's surface perpendicular to the rays of the sun. (You may wish to use a protractor, astrolabe, or transit to determine the angle at which to place the collector.) If necessary, raise the collector on blocks and use poles or boards as props.

6. Record in Data Table 1 the intake and output temperatures every 2 minutes for a total of 30 minutes. Also record the variables being tested.

7. In the last column of Data Table 1, record the difference in temperature ($\triangle T$) between intake and output for each reading.

8. Repeat the procedure using different combinations of insulation, absorber plate, and glazing. (Other students may have been collecting these data for you. If so, you should share data now.)

9. On Graph 1, plot $\triangle T$ as a function of time for each combination of variables tested. Key or label each line appropriately.

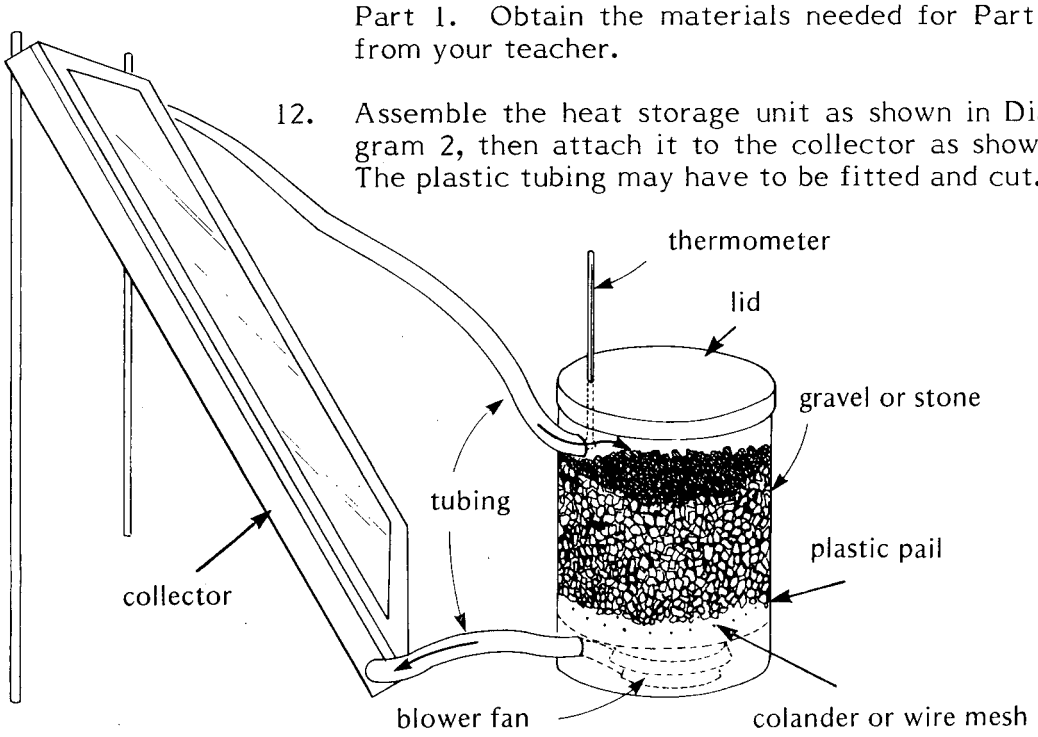
10. From Graph 1, select the combination of collector variables which performed most effectively.

Part 2: Heat Storage

Diagram 2

11. Assemble a collector using the combination of variables which performed most effectively in Part 1. Obtain the materials needed for Part 2 from your teacher.

12. Assemble the heat storage unit as shown in Diagram 2, then attach it to the collector as shown. The plastic tubing may have to be fitted and cut.

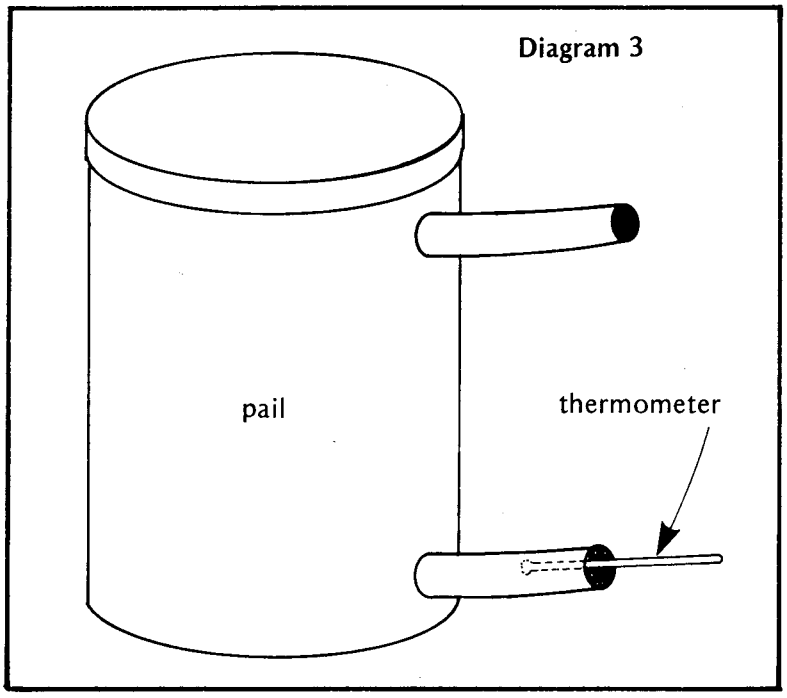


13. Aim the collector at the sun as in Part 1. Turn on the blower fan so that air is circulating through the entire system. (A hair dryer fan should be set on "cool.")

14. Record in Data Table 2 the temperature of the air in the storage unit at 2 minute intervals for a total of 30 minutes.

15. Turn off the blower fan and disconnect the collector from the storage unit. Move the storage unit out of direct sunlight.

16. Place a thermometer into the opening of the lower hose, as shown in Diagram 3. Turn the blower fan on.



17. Record in Data Table 2 the temperature of the exiting air at 2 minute intervals for a total of 30 minutes. Turn the fan off.

18. On Graph 2, plot both sets of data (Steps 14 and 17) from the storage unit. Key or label each line appropriately.

questions

1. What were the variables tested in Part 1 of this activity?

2. You used Graph 1 as a measure of the effectiveness of collector design. From the graph axes, identify the independent variable and the dependent variable. Which variable was used as an indicator of collector effectiveness?

3. Based on Graph 1, which combination of variables produced the most effective collector design?

4. Why did this particular combination of variables produce the most effective design?

5. Study your graph and attempt to separate out the effects of different variables. Which absorber plate seemed to be most effective? Why?

6. Which glazing seemed to be most effective? Why?

7. What was the effect of the type of insulation on the collector's performance?

8. Draw simple input-output sketches to show the two operating modes of the collector/heat storage system in Part 2 of the activity:

   a. collecting and storing heat energy, and
   b. extracting heat from storage and supplying it to the area to be heated.

   Use arrows to show the direction of air and heat flow. Label the parts of each operating mode and appropriately indicate intake and output air as hot or cool.

9. What does Graph 2 tell you about the ability of gravel to store heat energy and release it for later use?

10. In general, how effective does gravel seem to be in storing heat energy?

11. Why is it important to store the energy absorbed by solar collectors?

12. What are the components of a solar collector and of a heat storage system? Explain the function of each component.

looking back

On the surface, a solar collector seems to be a rather simple device. However, the decisions you make about glazing, insulation, absorber plate, storage material, and so on are not so simple. Bad choices and decisions about these components will result in problems and frustrations for the owner. On the other hand, a good combination of collector components will give you a strong, efficient collector, yielding energy savings over a long period.

going further

Test additional combinations of insulation, absorber plate, and glazing.

Redesign the activity as a controlled experiment and retest each of the variables. Graph your results and compare them to the results of the original activity. Are there significant differences in your conclusions?

Select the most effective combination of collector variables and reassemble the collector. Use this collector to test other variables that affect collector performance, such as

air flow patterns over the collector plate (perforated plates, baffled plates),
number of glazings (single, double, or even triple glazings),
rate of air flow (variable sizes of intake and output holes),

angle of insolation,
ambient air temperature,
other weather conditions,
distance of absorber from glazing, and
methods of reflecting light into the collector.

Test other possible heat storage materials, such as different size gravel and stone, crushed concrete, cement block, brick, sand, dirt, water, and eutectic salts. Are there significant differences in the heating or cooling curves? Which storage mediums are most effective?

Investigate the properties of materials which make them desirable for heat storage. How is the most effective and efficient material determined?

Find out how much heat was added to and extracted from the storage material. Mass the gravel used in the activity, then use the following formula.

$$\underset{\text{(calories)}}{\text{Heat}} = \underset{\text{(g)}}{\text{Mass}} \times \underset{\text{(cal/g}^{\circ}\text{C)}}{\text{Specific Heat}} \times \underset{(^{\circ}\text{C})}{\Delta T} \text{ (ending - initial gravel temperature)}$$

Determine the rate of heat gain/minute and the rate of heat loss/minute for the heat storage system, then compare the two values.

Calculate the efficiency of different collector designs. Research the parameters of collector performance and the derivation of the following equation. Then use your research to help you apply the formula to collector designs in this activity.

$$\eta = \frac{\text{Usable output energy}}{\text{Solar energy input}}$$

$$\eta = \frac{F \times c \times (T_o - T_i)}{A \times H}$$

Where η = efficiency
F = fluid flow rate
c = heat capacity of fluid
T_o = temperature at output
T_i = temperature at intake
A = collector area
H = insolation upon collector

Plot efficiency curves for the collector designs, where η is the vertical axis and $\frac{(T_i - T_a)}{H}$ the horizontal axis. (T_a = ambient air temperature.)

For more information on absorber plates, try Activities 1 and 2 in this book. To construct a thermosiphoning collector which can be mounted on the south-facing wall of a classroom or house, do Activity 6 in the Industrial Arts Activities book.

Data Table 1

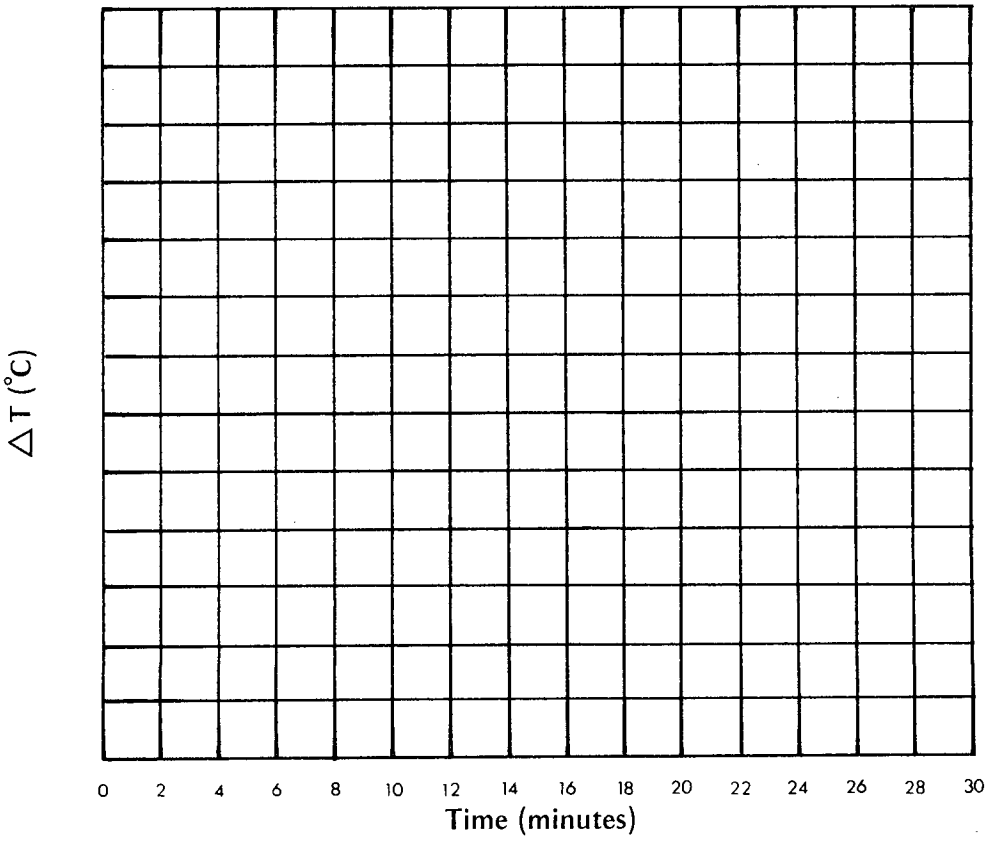
Insulation Material: _____
Absorber Plate: _____
Glazing: _____

Time (minutes)	Intake Temperature (°C)	Output Temperature (°C)	ΔT (°C)
2			
4			
6			
8			
10			
12			
14			
16			
18			
20			
22			
24			
26			
28			
30			

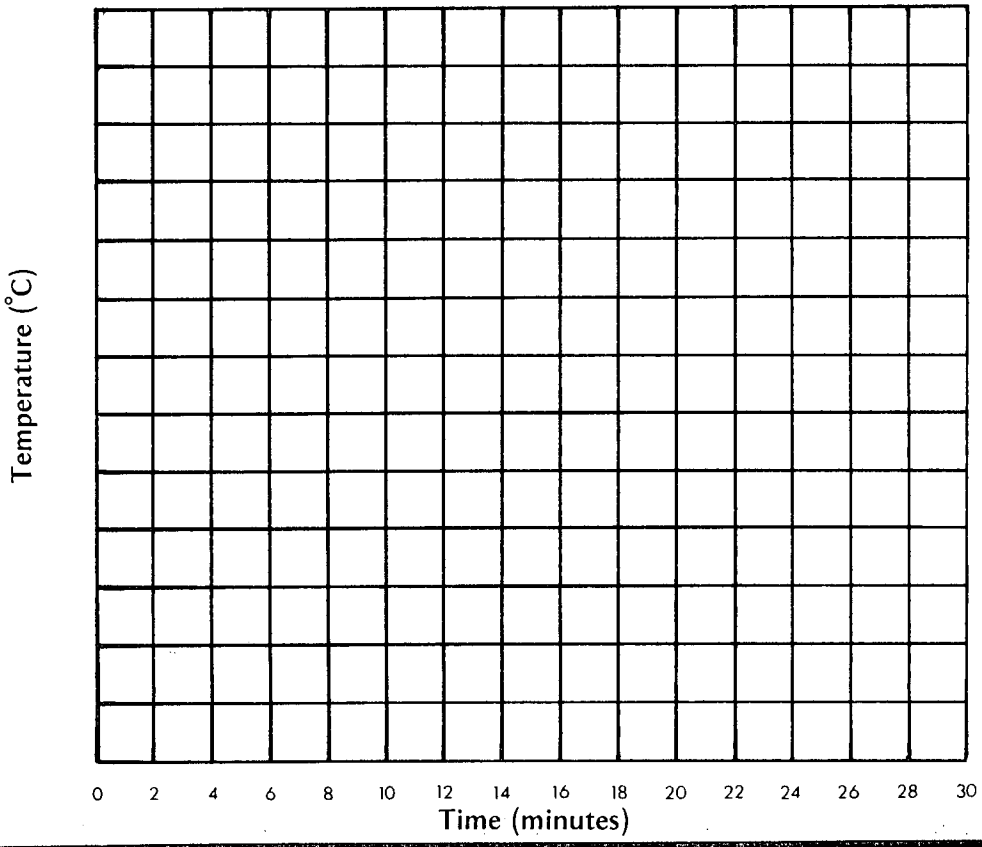
Data Table 2

Time (minutes)	Temperature (°C)	
	Heating Phase	Cooling Phase
2		
4		
6		
8		
10		
12		
14		
16		
18		
20		
22		
24		
26		
28		
30		

Graph 1



Graph 2



Teacher Information

Collecting and Storing Solar Energy

Suggested Grade Level and Discipline

Science, grades 9-12
Physics
Advanced Physical Science
Earth Science
Industrial Arts

Skill Objectives

Assembling a model flat plate air-flow solar collector and a heat storage system

Testing different combinations of collector design variables

Determining the effectiveness of various combinations of collector variables

Sketching systems in terms of inputs and outputs

Recording, graphing, interpreting, and comparing data.

Major Understandings

A solar collector consists basically of a box to house the collector apparatus, insulation to decrease heat loss, a glazing to transmit incident solar radiation and trap long-wave reradiation, an absorber plate to convert incident solar radiation into heat energy, and a fluid to transport the heat energy collected.

A heat storage system consists basically of a container to hold the heat storage material, transport piping to move the transfer fluid into the storage area, a material to absorb and store the heat energy transferred, and a natural or forced convection loop to circulate the fluid to the space to be heated.

The components of a solar collector can be varied and then tested to determine the most effective combination of insulation, glazing, and absorber plate.

One simple measure of collector effectiveness is the difference in temperature ($\triangle T$) between the fluid at the intake (in this case the ambient air temperature) and the fluid at the output.

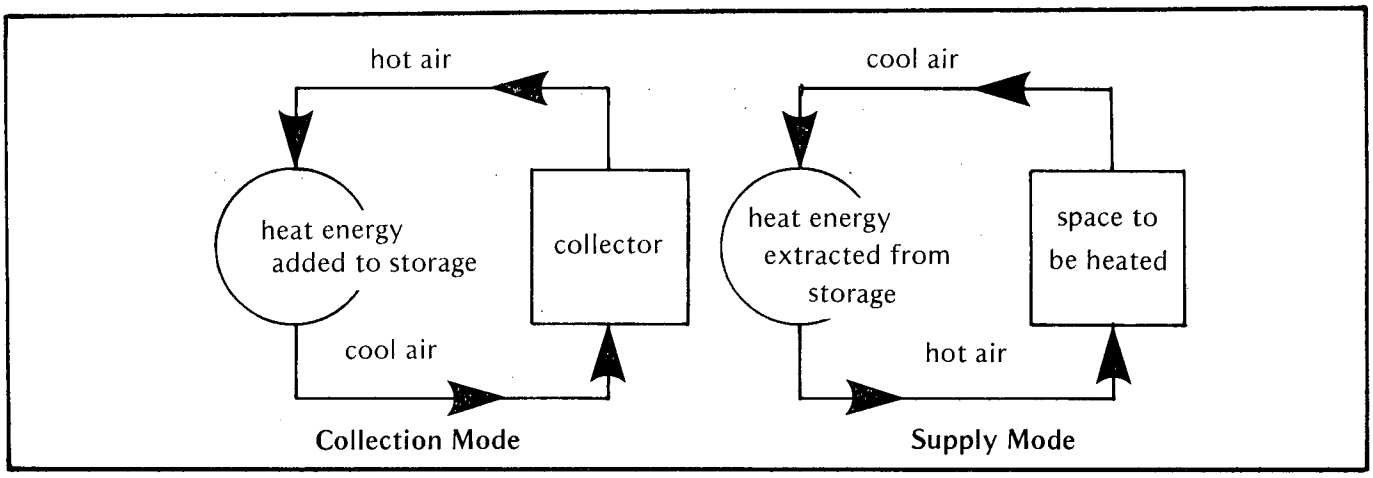
Gravel is fairly effective for storing heat energy, as shown by its heating and cooling curves.

Background

Solar collection can be passive or active, with natural or forced convection. The collector assembled in this activity is a flat plate air-flow collector, which, depending on how it's used, can be either a passive or an active collector.

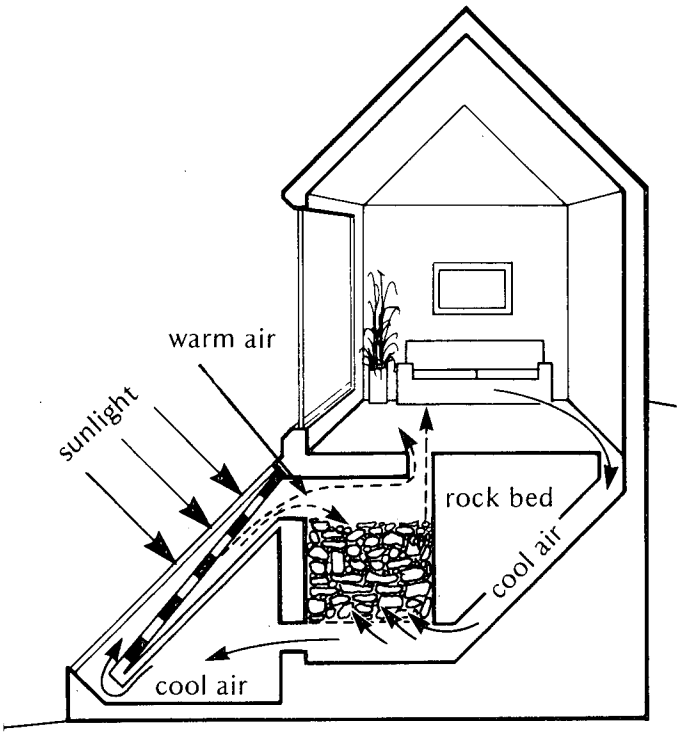
In Part 1 of the activity, the collector operates as a simple thermosiphon to test the effectiveness of collector components. A thermosiphoning collector works on the principle of convection: as air passes over the absorber plate, it is warmed, expands and becomes less dense, and rises toward the output hole. As this warmed air rises and exits, cooler air is drawn in through the lower intake hole, and a continuous flow of air begins to move through the collector, always convecting upward.

In Part 2 of the activity, the collector functions as part of an active collection and storage system. Here, air is forced through the collector and into storage by a mechanical device that requires an outside source of energy, in this case electricity. The solar collection/heat storage system operates in two modes, which can be diagrammed as follows.



In the collection mode cool air is blown into the collector, where it is heated as it passes over the absorber plate. The heated air then moves into the storage mass, where it cools as it gives up its heat energy to the storage material. The cooled air recirculates into the collector, completing the closed loop.

In the supply mode cool air from the space to be heated is blown through the storage mass. As this cool air circulates through the warm storage material, heat energy is transferred to it and it becomes warm. The warmed air then is moved into the space to be heated, forming a second closed loop. In actual operation, the two modes can function together or independently, as indicated in the diagram.



(For more information on heat storage in a solar collection system, see Activity 10, "Storing Heat Energy," in the Junior High/ Middle Grades Activities book.)

Advance Planning

Decide on the materials to be used in constructing the collector boxes. These can vary from corrugated cardboard to plywood and pine boards, depending upon the permanence of equipment desired. You might enlist the help of students or an industrial arts teacher in constructing the boxes, or possibly they might be built as an industrial arts project. At the same time, construct the frames for the glazings.

Collect insulations, absorber plate materials, paints, and glazings. Don't overlook donations of discarded, damaged, or even new materials from solar collector dealers and insulation contractors. Students may bring in scrap materials from home.

Cut insulations, absorber plates, and glazings to size. Students may be willing to help with these tasks outside of class time. Paint absorber plates. Place glazings in frames.

Obtain plastic pails from your custodial and cafeteria staffs. Cut holes in the pails as indicated in the student diagrams. Holes should be sized to accept plastic tubing.

Colanders are inexpensive and readily available from discount and kitchen supply stores, which may be willing to donate them. Wire mesh is also readily obtainable from hardware stores.

Gravel can be obtained from lumber yards, hardware stores, pet supply stores, or sand

and gravel companies. A gravel company is likely to give you the small amount you need.

A good source for a blower fan is a discarded bonnet-type hair dryer, which students may have at home or which is often sold at yard sales. These hair dryers also include the plastic hose. Just make sure that any student donors understand that the hose will be cut. Other types of blower fans may be available from physics or industrial arts teachers, or perhaps from custodial staff.

Suggested Time Allotment

Highly variable, depending on the time available for the activity and the degree of testing and sophistication desired

Two to three class periods to test combinations of components

Two to three class periods to collect data on heat storage

One to three class periods to summarize results, discuss conclusions, and answer questions

Suggested Approach

The first three activities in this book are closely related, and if all three are to be performed, they may be used in an order which best fits your teaching needs. This activity may serve as either an introduction or conclusion to the other two.

Introduce the activity by asking how solar energy can be collected and what is needed to increase the efficiency of its collection. Elicit from students suggestions for materials to test in a solar collector. Have students hypothesize about which materials and combinations of materials will be most effective.

Demonstrate for students how to angle the collector into the sun. Stress the safety precautions.

Students can work in groups of two to four. If applicable, allow time for student groups to share data. If necessary, help students to plot graphs.

You may wish to set Part 1 of this activity up as a contest. The winner is that group of students which assembles the best combination of collector components, as shown by the effectiveness graph.

If desired, Part 2 may be done as a teacher or student demonstration. If double lab periods are not available, the time can be shortened to a 15 minute period of heating and a 15 minute period of cooling.

During the discussion of results, explain heat capacity and the importance of heat storage to the success of solar heating.

For advanced students, selection of a "Going Further" suggestion will provide for more in-depth study of solar collection concepts.

Precautions

Remind students never to look directly at the sun.

Make sure students observe the standard safety precautions for working with electrical appliances.

Do not use styrofoam insulation in the collector as contact with the hot absorber plate may cause it to melt.

Points for Discussion

Did this activity provide for a controlled experiment? Why or why not?

What are some other measures of the effectiveness of a collector?

How could you measure the effectiveness of a heat storage system?

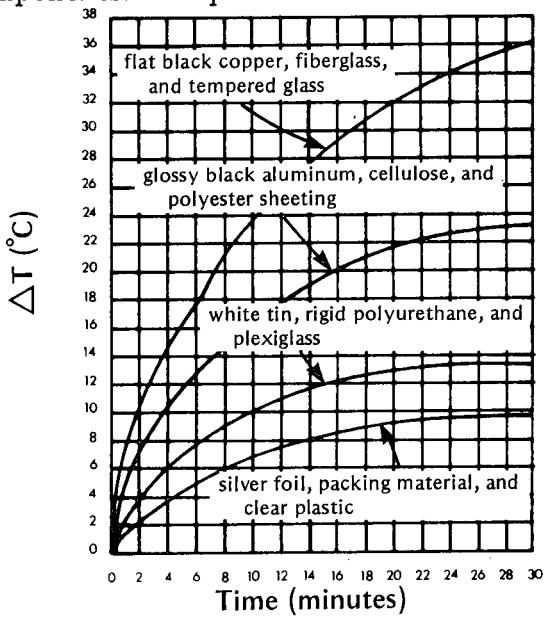
How could your own family use a solar collector?

For what purposes might you want to use an air collector?

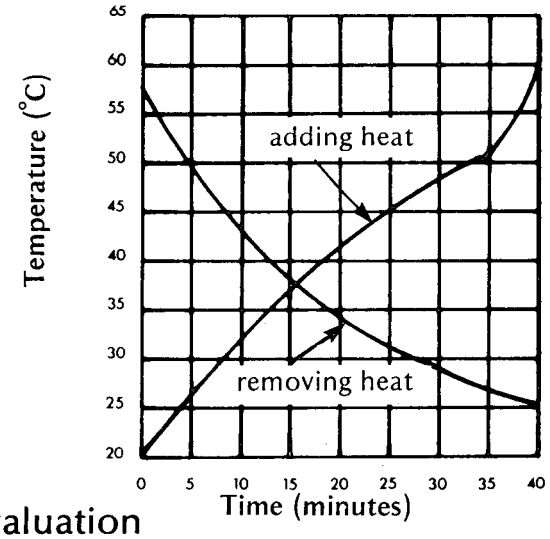
Typical Results

$\triangle T$ should increase over time until a levelling-off point is reached. $\triangle T$ will be different for different combinations of collector

components. Sample curves are shown below.



Sample heating and cooling curves for approximately 5 kilograms of stone storage are displayed below.



Evaluation

Check students' data tables and graphs for accuracy and neatness.

Ask students to identify the components of both a solar collector and a heat storage system, and to explain their functions.

Have students explain how they determined the effectiveness of their collector.

Analyze students' answers to the questions to determine degree of understanding of concepts.

Modifications

This activity may be made as simple or as sophisticated as desired for a particular group of students. Boxes of smaller size will work just as well. Ready-made collector boxes include cardboard boxes such as case-lot soup or soda boxes, styrofoam packing containers, and lab storage drawers. Newspaper, cardboard, and packing materials can serve as insulations. Sandwich wrap and window plastic make effective glazings.

A more sophisticated apparatus might consist of a permanent self-contained collector box which stores all needed materials, including absorber plates, insulations, glazings, a built-in protractor, a level, an aiming device (such as a shadow pole), adjustable support rods, a hinged glazing frame with single and double glazing tracks, thermometer holders for safe transport, and a carrying handle. Such a collector apparatus makes an excellent lecture-display apparatus.

References

Build Your Own Solar Water Heater, Stu Campbell and Doug Taff.
(Garden Way Publishing Co., Charlotte, VT 05445, 1978, $7.95/paper.)

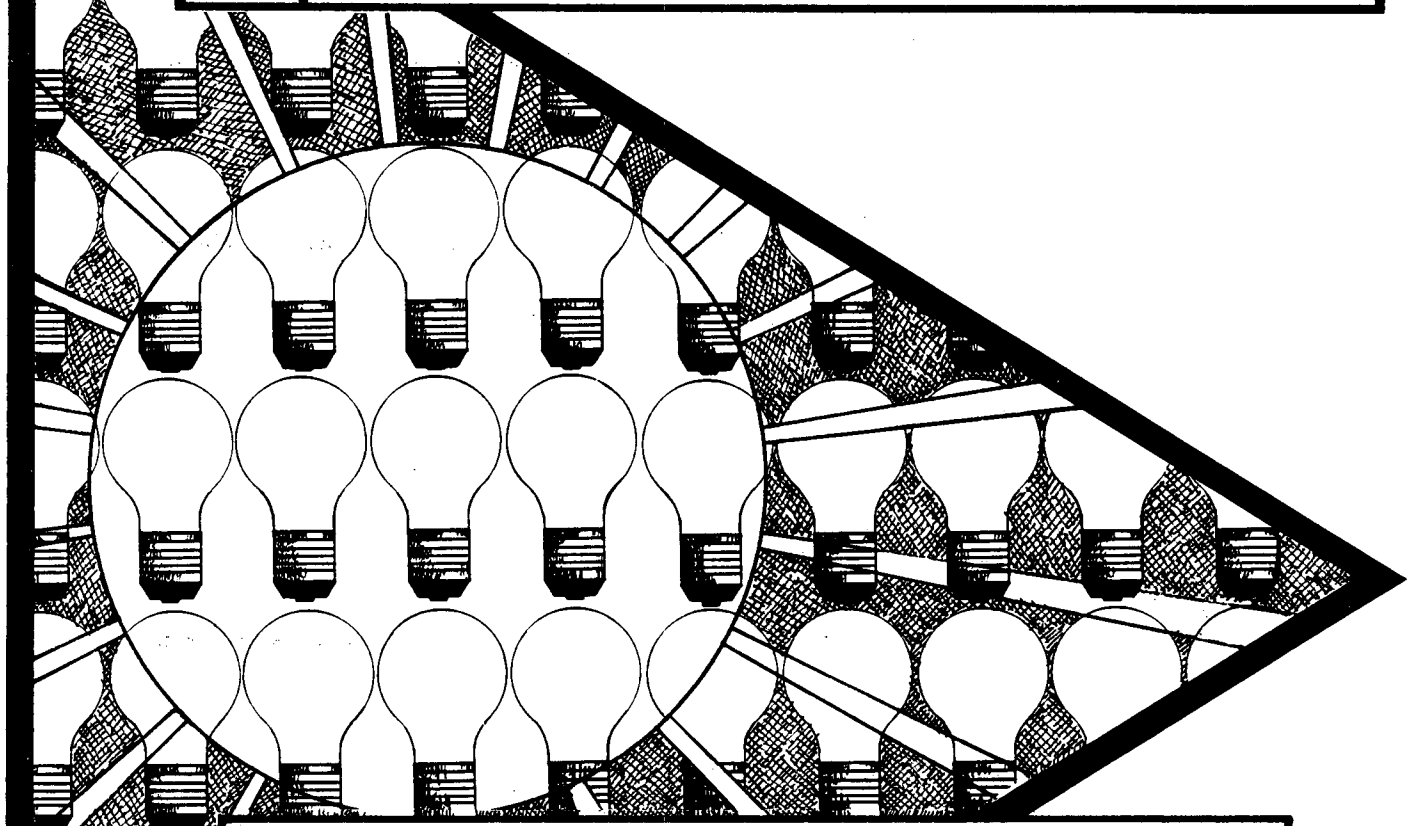
Direct Use of the Sun's Energy, Farrington Daniels.
(Ballantine Books, Inc., 400 Hahn Rd., Westminster, MD 21157, 1974, $1.95/paper.)

Engineer's Guide to Solar Energy, Yvonne Howell and Justin Bereny.
(Solar Energy Information Services, P.O. Box 204, San Mateo, CA 94401, 1979, $29.50/paper.)

Home Guide to Solar Heating and Cooling, Jackson Hand.
(Harper and Row Publishers, Inc., Keystone Industrial Park, Scranton, PA 18512, 1978, $3.95/paper.)

Solar Age (April 1978)
(SolarVision, Inc., Church Hill, Harrisville, NH 03450.)

4 How Many Light Bulbs Equal the Sun?



Most days and seasons, the sun provides us with a tolerable amount of light and heat: not too much but not too little. Yet we know that this pleasant, rather small disc in our sky is in reality a gigantic sphere of fusing gases, emitting a tremendous amount of energy. How are we able, from our position on earth, to determine how much energy the sun is giving off? There is a way. In this activity you will find out how it is done.

The "inverse square law" can be used to calculate the power output of a distant object like the sun. Using this law and a simple apparatus you will measure the power output of a nearby light bulb and use that measurement to calculate the power output of the sun.

objectives

At the completion of this activity, you should be able to

- o construct and use a simple device to indirectly measure the sun's power output,
- o state and explain the inverse square law,
- o use the inverse square law to calculate the power output of the sun in watts,
- o compare the power output of the sun with that of a 100-watt light bulb, and
- o calculate the percent of error for the experimental value of the sun's wattage and cite and explain the possible sources of error in this procedure.

skills and knowledge you need

The ability to solve equations and to average numbers

The ability to use scientific notation

A basic understanding of percent of error and sources of experimental error

A knowledge of the inverse square law

materials

a thin metal strip (2 x 6 cm)

flat black paint

a meter stick

a pair of optical bench stands

a glass jar with a hole in the lid

a one-holed rubber stopper (to fit hole in jar lid)

a Celsius thermometer (-10 to 110°C)

glycerin

a 100-watt incandescent bulb in a receptacle box

a calculator (optional)

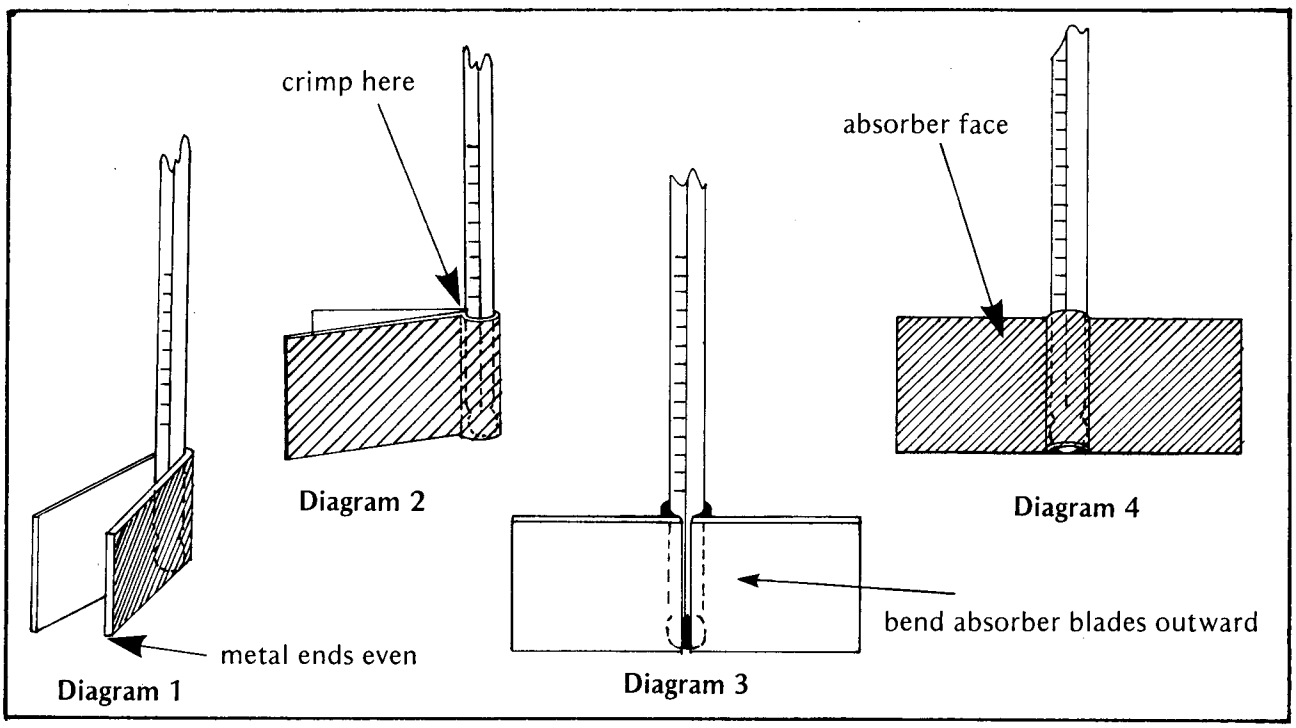
procedure

Caution: Spray paint should be used in a well-ventilated room only.

1. Thinly (but completely) coat one side of the metal strip with flat black paint.

Caution: A thick coat of paint will prevent the apparatus from working properly.

2. With the blackened side facing out, fold the middle of the metal strip around the thermometer bulb, as shown in Diagram 1. The ends of the metal should line up evenly.



3. Crimp the metal so that it completely surrounds the bulb (Diagram 2). Use a straight edge to bend each end of the metal outward 90° so that the absorber blades form a flat, even surface (Diagram 3). The blackened front of the absorber is shown in Diagram 4.

Caution: To avoid breaking the thermometer, crimp the metal gently.

4. Use glycerin to insert the thermometer into the one-holed stopper. Remove the lid from the jar and place the stopper in the lid. Adjust the thermometer so that, when inserted into the jar, the absorber plate will be located in the middle. Place the lid on the jar and make any final adjustments needed.

Caution: To avoid breaking the thermometer, insert it into the stopper very gently.

5. Take your apparatus outdoors and set it so that the absorber face is perpendicular to the rays of the sun. (You may want to use a protractor, astrolabe, or transit to accomplish this.)

Caution: Indoor and outdoor temperatures should be as similar as possible. Weather conditions should be sunny with minimal haze.

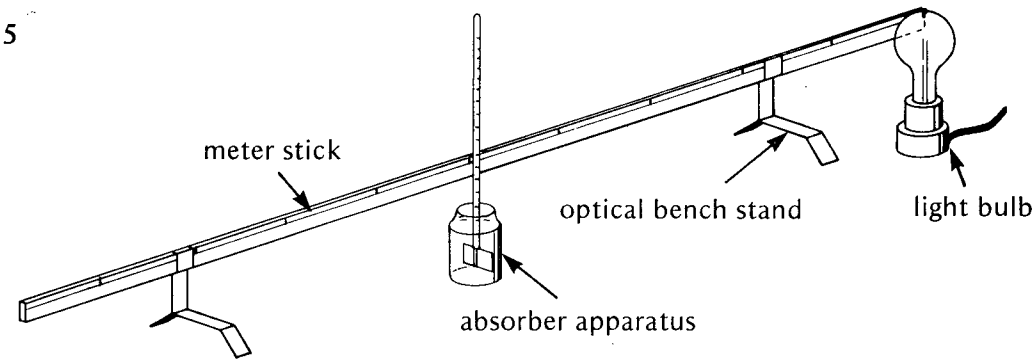
6. Leave the apparatus in this position until the maximum temperature is reached. Record this temperature in the appropriate space on the data table.

Caution: Never look directly at the sun. Permanent eye damage can result.

7. Return to the classroom and allow the thermometer to cool to room temperature. (You may speed this process by partially immersing the jar into a cold water bath. Be sure to wipe the outside dry.)

8. Place the light bulb so that its filament is located at the 0 mark of the optical bench, as shown in Diagram 5. Position the jar apparatus at the 50 cm mark so that the absorber plate is perpendicular to the light rays from the bulb. (You may need to shim the apparatus.) Allow the temperature of the jar to stabilize.

Diagram 5



Caution: Do not look directly at the light bulb. Keep your back to the bulb as much as possible.

9. Turn the light bulb on. Slowly advance the apparatus, 5 cm at a time, toward the light bulb, allowing its temperature to stabilize each time. As the temperature of the apparatus approaches that obtained in Step 6, advance the apparatus only 1 cm at a time, then only 0.1 cm at a time. Stop moving the apparatus when the temperature obtained in Step 6 is reached and maintained for two minutes. Turn the light bulb off.

10. Measure as exactly as possible the distance between the absorber plate of the apparatus and the filament of the bulb. Record this value in the data table.

11. Enter in the data table the distances obtained by other members of the class or repeat Steps 8-10 to obtain additional trial distances.

12. For each distance obtained, use the inverse square law to calculate the wattage of the sun.

$$\frac{\text{Wattage (sun)}}{d^2\text{ (sun)}} = \frac{\text{Wattage (bulb)}}{d^2\text{ (bulb)}}$$

where d = distance in meters
d (sun) = 1.50×10^{11} m

13. Calculate the average wattage of the sun over all trials.

14. Use this averaged experimental value to calculate the number of 100-watt light bulbs that would equal the sun's power.

15. Determine the percent of error for the experimental value of the sun's wattage by substituting in the equation below. The accepted value for the sun's wattage is 3.83×10^{26} W.

$$\% \text{ Error} = \frac{\text{Experimental value (class average)} - \text{Accepted value}}{\text{Accepted value}} \times 100$$

16. Before you accept the experimental value for the sun's wattage, account for your percent of error by considering some of the inherent sources of error in your experimental procedure. The following questions should guide you.

a) How would differing indoor and outdoor temperatures affect the experimental results?

b) How would the atmosphere and atmospheric weather conditions affect the experimental results?

c) Does a 100-watt bulb actually have an output of 100 watts?

d) How does the radiation spectrum emitted by the light bulb differ from that emitted by the sun?

e) Does the apparatus absorb these spectra differently?

f) How would a slight change in the angle of the absorber to the light source affect the experimental results?

g) How would a slight error in measurement affect the experimental results?

questions

1. How many light bulbs were equal to the averaged experimental value of the sun's wattage? To the accepted value?

2. Would it be possible to turn on this many light bulbs at once? Explain.

3. Why was an incandescent bulb used in this activity instead of a fluorescent bulb?

4. What was the percent of error for the averaged experimental results?

5. List as many factors as you can that might account for experimental error.

6. Explain how each factor in Question 5 would affect the experimental results.

7. Would your latitude and the time of year affect your experimental results? Explain.

8. If the experimental value of the sun's wattage differed from the accepted value by one order of magnitude (10^1), how large would the percent of error be?

9. State the inverse square law and explain what it means.

10. Explain why the inverse square law can be applied to this experiment and how this application was accomplished.

looking back

Using an inexpensive apparatus and a simple equation, you have determined an approximate value for the radiation emitted by the sun. You probably also became aware, in the course of this experiment, of the many factors that might interfere with the accuracy of your results. Carrying out a precisely controlled experiment under real conditions is a challenge for any scientist; the rewards are reliable results and new knowledge.

going further

If the sun's power output were to increase or decrease by one order of magnitude (10^1), how might climatic conditions on earth be affected?

If the earth's distance from the sun were to increase or decrease by one order of magnitude (10^1), how might climatic conditions on earth be affected? Would there be a greater or lesser effect than a similar change in the sun's wattage? Explain.

If this experiment were conducted outside the earth's atmosphere (say 3×10^5 m above the surface of the earth), how might the data collected and the experimental results be affected?

How much of the sun's power output is intercepted by the earth? How does the sun's power output compare to that of a conventionally-sized power plant? What is the United States' total power generating capacity in watts? The world's? How do these values compare with the sun's total wattage and with that portion intercepted by the earth?

Data Table

Temperature of Absorber (Step 6): _____ °C

Wattage of Light Bulb: _____ W

Trial	d (bulb)	Calculation	W (sun)
1			
2			
3			
4			
5			
6			
7			
8			

Average Wattage of Sun _____

Percent of Error _____

Equivalent Number of 100-watt Light Bulbs _____

Teacher Information

How Many Light Bulbs Equal the Sun?

Suggested Grade Level and Discipline

Physics
Advanced Physical Science
Earth Science

Skill Objectives

Constructing a device to absorb heat energy

Using the inverse square law

Performing arithmetic operations on exponential numbers

Working in scientific notation

Following a precise procedure and measuring precisely

Calculating percent of error

Determining possible sources of error in experimental procedures

Major Understandings

A simple apparatus can be used to derive experimental values that allow calculation of the sun's power output.

The inverse square law applies to illumination by a point source of light. By experimentally using a light bulb to produce a light intensity on a receiving surface equal to that of the sun's, one can calculate the sun's wattage according to

$$\frac{I_1}{(d_1)^2} = \frac{I_2}{(d_2)^2} .$$

The power output of the sun is enormous, a figure so large it is virtually incomprehensible.

Percent of error is an indication of the reliability of the experimental results and can be calculated by

$$\frac{\text{Experimental Value - Accepted value}}{\text{Accepted Value}} \times 100$$

Sources of error in an experiment are many. Besides errors in taking the measurement, error is caused by the conditions under which the measurements are made, the limitations of the measuring devices, and assumptions that are not completely correct.

Background

With a simple adaptation, a standard laboratory experiment can be used to measure the power output of the sun. Usually the intensity of an unknown light source is determined by using a photometer and employing the inverse square law. When a light source of known intensity produces an illumination equal to that of a light source of unknown intensity,

$$E_1 = E_2 .$$

If, according to the inverse square law,

$$E = \frac{I}{d^2},$$

then

$$\frac{I_1}{(d_1)^2} = \frac{I_2}{(d_2)^2} .$$

The inverse square law is true when considering light from a point source. The light bulb is assumed to be a point source for the purposes of this experiment. Light from a point source radiates in all directions, and spreads out with distance. Illumination, or the intensity of the light at the receiving surface, therefore decreases as the square of the surface's distance from the light source. In this experiment the temperature of the surface is used to indicate the intensity of light at the receiving surface, since the temperature of an object is proportional to the intensity of the light falling upon it.

Values reported for the power of the sun vary from 3.7 to 4×10^{26} watts. Therefore, approximately 4×10^{24} 100-watt light bulbs would be required to match the sun's

power. Such large numbers are virtually incomprehensible, although comparing them with somewhat more comprehensible values may help.

Wattage Values	
10^{26}	power output of sun
10^{17}	solar power incident on the earth
10^{15}	solar power striking the United States
10^{13}	total world energy consumption
10^{12}	total U.S. energy consumption
10^{9}	output of one large generating plant
10^{4}	solar power striking a house roof
10^{3}	output of electric stove or clothes dryer
10^{2}	output of one light bulb
10^{1}	daily food consumption by a human
10^{0}	output of electric clock or flashlight output of a sedentary human

Errors in measurement come from several sources: methodology, environmental fluctuation, instrument limitation, and personal error. Averaging a large number of observations will tend to reduce the random errors caused by inaccurate student measurement. However, several important sources of error remain in this experiment, including atmospheric aberrations causing absorption of light energy and fluctuation in the sun's observed power output, the efficiency of the light bulb (its actual power output as opposed to the 100-watt electrical input), the differences in spectral distribution between the sun and a light bulb, the tilt of the apparatus (which might cause differences in convection currents inside the glass jar), differences between indoor and outdoor temperatures, and the assumptions that the bulb is a point source and that the receiving surface (absorber) is exactly perpendicular to the light beam.

Less tangible learning outcomes may also result from performing this experiment: an appreciation that simple equipment and a simple procedure can often yield the answer to a seemingly difficult or sophisticated problem, a developing patience in performing tedious operations that leads to higher accuracy in results, and an understanding of the utility of scientific notation.

Advance Planning

Obtain glass jars with tight-fitting lids. Peanut butter jars, mustard jars, and other similar-sized jars are appropriate. Obtain rubber stoppers and drill a hole in each jar lid large enough to hold a stopper.

Thin metal sheeting should be available from the industrial or visual arts departments. The metal should be thin enough to be easily crimped by hand around the thermometer bulb. Copper, aluminum, tin, and similar conductive metals can be used. Cut the metal into 2 x 6 cm strips.

You may want to spray paint the metal strips ahead of time.

Use unfrosted or lightly frosted incandescent bulbs.

To avoid accidental breakage, you may want to insert the thermometers into the stoppers yourself.

You may want to set up the light bulbs and optical benches ahead of time.

Metal strips and glass jars may be saved and reused from year to year.

Duplicate needed quantities of the data table.

Suggested Time Allotment

One-half to one class period to introduce the experiment and prepare the apparatus

One to two class periods to collect data and calculate experimental values (if the class shares trial results)

One-half to one class period to answer questions and discuss results

Suggested Approach

Introduce the activity by asking students to guess at the power output of the sun. Establish that a watt is a common unit of power and define it in terms of common wattages, for example, of a light bulb or other common appliance.

Ask students if it is possible to measure the sun's wattage. Is there a common wattage they can compare it to? How? Introduce the inverse square law.

Stress the importance of the experimental conditions required for this activity (see the precautions). Also stress the importance of careful laboratory technique to the reduction of error.

To reduce the number of set-ups required, students can work in groups of two or three.

If necessary, help students with scientific notation and mathematical calculations.

Discuss the concept of experimental error. As students work through the procedure, make sure they are alert to sources of error. At the end of the activity, discuss possible sources of error in detail.

Students will have no concrete understanding of the size of the values obtained in this activity. If a computer is available, a print-out of one million (10^6) dots, perhaps 200 pages of 5000 dots each, can be easily obtained. Using the print-out as an example will help students understand the meaning of values as large as 10^{24} or 10^{26}.

This activity can be used when students are studying measurement, orders of magnitude, scientific notation, and experimental error or when they are studying illumination by a point source.

Precautions

There are two environmental conditions which must be met before this activity can be performed: indoor and outdoor temperatures should be equal, and the day should be clear, with minimal clouds and haze.

All laboratory directions should be followed as precisely as possible to reduce experimental error.

Use glycerin as a lubricant when inserting thermometers into stoppers.

Remind students not to look directly at the sun or the light source.

Remind students to take the same precautions with a light bulb as they do with any electrical appliance.

Use spray paint in a well-ventilated area only.

Points for Discussion

Why was it so important to use scientific notation in this activity?

How large is a number in the order of magnitude of 10^{26}?

Where does the sun rank as a source of power?

Why was such a simple experiment able to provide the answer to a seemingly difficult question?

Why was the inverse square law employed in this experiment?

Typical Results

Results from several trials are displayed below. In general, careful adherence to laboratory technique should provide values in the same order of magnitude as the accepted value of the sun's wattage. Averaging experimental values should reduce error to an acceptable amount.

d (bulb)	W (sun)
9.53 cm	2.477×10^{26} W
6.67 cm	5.06×10^{26} W
6.35 cm	5.58×10^{26} W
5.40 cm	7.716×10^{26} W
12 cm	1.563×10^{26} W
15 cm	1.0×10^{26} W

Average Wattage of Sun = 3.96×10^{26} watts

Percent Error = 1.8%

Evaluation

Review students' data tables for completeness and accuracy of calculations. Check students' answers to the questions for degree of understanding.

Rate students' ability to construct the apparatus and manipulate the laboratory equipment.

Ask students to state and explain the inverse square law.

Give students sample values for "d (bulb)" and ask them to calculate the sun's experimental wattage and the percent of error.

Ask students to list possible sources of error in the experiment and to explain why these variables might cause error.

Modifications

An electric calorimeter, with the resistance wire removed, may be substituted for the glass jar.

A photoelectric or photovoltaic cell connected to a milliammeter can be substituted for the absorber plate apparatus. Move the cell towards the light bulb until the current it produces equals that produced by the sun.

A 100-watt light bulb was used for convenience in performing calculations. A different wattage bulb or a point source of light of known wattage may be substituted.

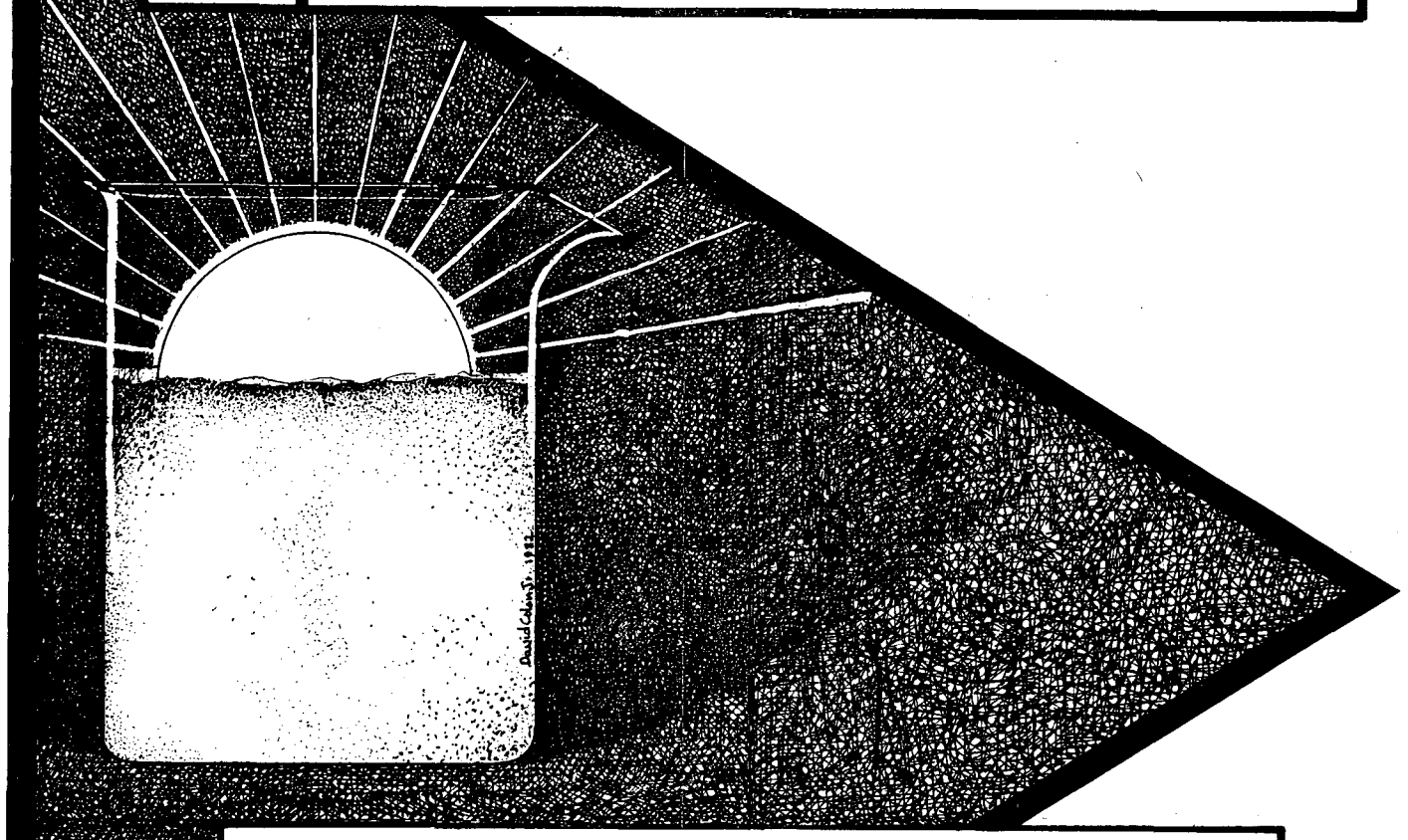
The procedure may be modified so that the apparatus is moved away from rather than towards the light source. After each adjustment, allow the temperature to stabilize before continuing. This procedure may require less time.

References

Energy: An Introduction to Physics, Robert H. Romer.
(W.H. Freeman and Co., 660 Market St., San Francisco, CA 94104, 1976, $19.95.)

Modern Physics, John E. Williams et al.
(Holt, Rinehart, and Winston, Inc., 383 Madison Ave., New York, NY 10017, 1976, $15.72.)

5 Storing Solar Energy in Salts and Paraffin



Oil can be stored in a barrel and coal can be stored in a bin, but how do you store the sun's energy? Efficient heat storage has been a continuing challenge to solar experts. Various solar energy systems use water, sand, or crushed rock to store their collected heat, but these storage materials are rather bulky because they only store a limited number of calories per volume in the normal temperature range that solar collection systems can achieve.

One good way to store large amounts of heat is through a phase change--from solid to liquid or liquid to gas. Imagine the perfect solar storage material: a material that melts as the temperature goes above the human comfort level, storing any extra heat, and that solidifies to give off that heat when the temperature drops below the human comfort level. The materials you will be working with in this activity fit that description, and may solve the problem of how to best store solar energy.

objectives

At the completion of this activity, you should be able to

- o explain the following terms: law of heat exchange, specific heat, and heat of fusion;
- o describe how certain materials can be used to store heat energy;
- o experimentally determine the amount of heat stored by certain materials as they change phase;
- o describe the properties which make these materials useful for storing heat energy; and
- o compare the heat storage capacity of these materials with that of water in the same temperature range.

skills and knowledge you need

Preparing water baths

Measuring metric mass and volume

Accurately reading a Celsius thermometer

Following a precise, sequential procedure without interruption

Recording data and graphing heating and cooling curves

Using mathematical equations to perform calculations

materials

a metric balance

a hot water bath assembly
- bunsen burner
- 400 ml beaker
- ringstand and clamp

a cold water bath assembly
- styrofoam cup
- cold, distilled water (at or below $10^{\circ}C$)
- ringstand and two clamps

two Celsius thermometers (-10 to $110^{\circ}C$)

a small rubber band

a clear plastic cooking or oven browning bag

Glauber's salt ($Na_2SO_4 \cdot 10H_2O$)

paraffin

a watch, clock, or timer to measure seconds

a calculator (optional)

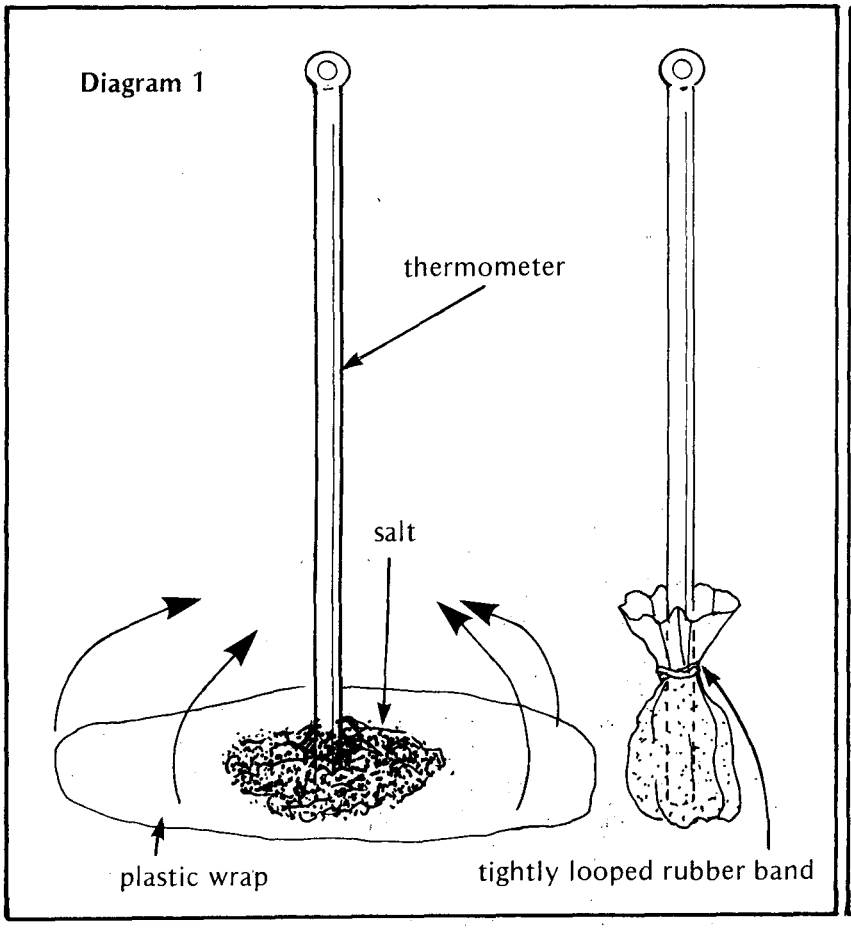
Part 1: Storing and Releasing Heat Energy

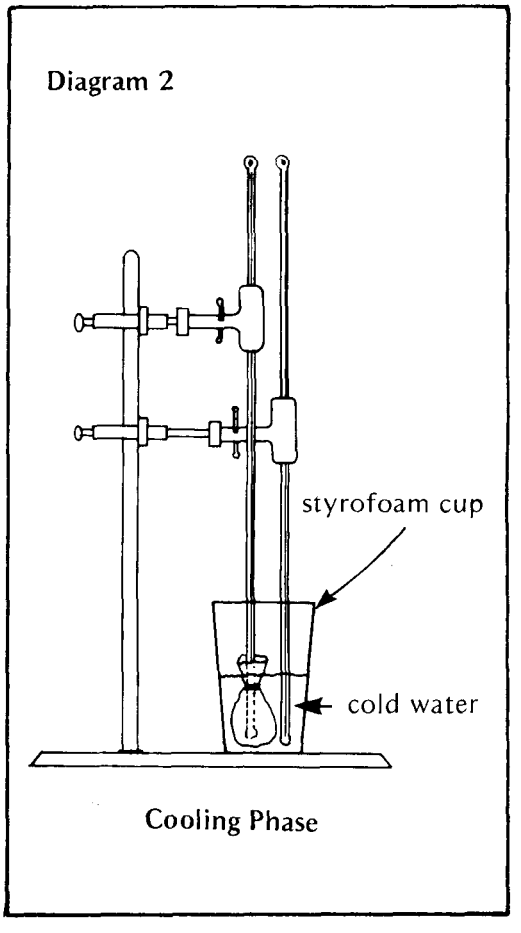
1. Select a partner to work with and obtain all needed equipment.

2. Measure out 5 grams of Glauber's salt (sodium sulfate decahydrate) and record its name, chemical formula, and mass in the appropriate spaces on Data Table 1.

3. Observe the physical properties of the salt and record your observations in Data Table 1 under "Heating Phase." (If room temperature is above 25°C, cool the salt to at least 25°C before observing it.)

4. Seal the salt and a thermometer in a 20 cm diameter circle of plastic wrap, as shown in Diagram 1.

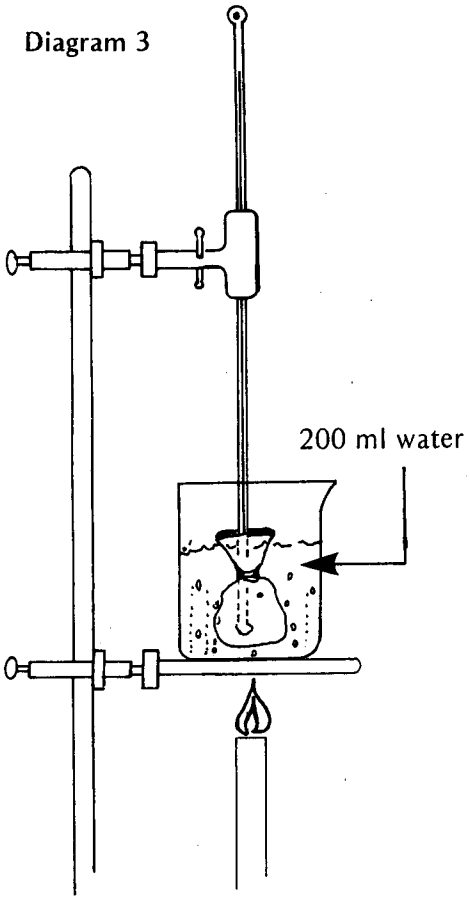




5. Accurately measure out 75 grams of cold, distilled water and place in the styrofoam cup. Record the mass of the water in the appropriate space on Data Table 1. Set up the cold water bath (minus the salt bag and thermometer) as shown in Diagram 2.

Caution: Wear safety goggles and an apron when heating chemicals with a bunsen burner.

Diagram 3



Heating Phase

Caution: Make sure the salt bag is completely immersed in the water.

6. Set up the hot water bath as shown in Diagram 3. Begin heating the water slowly.

7. Determine which of you will act as timer/recorder and which will handle the apparatus and read the thermometer(s).

8. READ OVER THE REST OF PART 1 AND LOOK OVER DATA TABLE 1 BEFORE YOU GO ON TO THE NEXT STEP. FROM HERE ON YOU WILL HAVE TO WORK THROUGH THE PROCEDURE WITHOUT A BREAK. MAKE SURE YOU UNDERSTAND THE SEQUENCE OF THE STEPS AND WHAT OBSERVATIONS YOU HAVE TO RECORD.

> *Caution: Data must be read quickly and accurately. Remember to keep your eyes level with the top of the liquid in the thermometer.*

9. On the signal of the recorder, place the salt bag in the hot water bath. Record in Data Table 1 the initial temperature in the salt bag. Continue to record the temperature every 15 seconds until the temperature reaches about 45°C.

10. Observe the physical properties of the salt and record your observations under the "Cooling Phase" column of the data table.

11. Record under the "Cooling Phase" column the temperature of the water in the styrofoam cup. This is the water's initial or beginning temperature (T_i).

12. Quickly transfer the salt bag to the cup and record its temperature just as you immerse it in the water. This is the salt's initial cooling temperature (T_i).

13. Gently swirl the cup under the salt bag to keep the water stirred. Continue to record the temperatures of both the water and the salt bag every 15 seconds until the temperature of the salt falls below 25°C.

14. At this time, carefully check and record the final temperature of both the water and the salt (T_f).

15. Use Graph 1 to plot your heating data. Label the solid and liquid phases of the curve. Use Graph 2 to plot the cooling data for both the salt and the

water. Label each line appropriately. Also label the solid and liquid phases of the salt curve.

16. Repeat Part 1 of the procedure making these changes:

    a. substitute paraffin for Glauber's salt, and
    b. allow the paraffin to reach at least 70°C before transferring it to the cold water.

Part 2: Calculating Stored Heat

17. Your styrofoam cup acts as a calorimeter, trapping in the water virtually all of the heat lost by the substance you're testing. Calculate the quantity of heat gained by the water by substituting in the following equation. Enter all the values in Data Table 2.

    $Q\ (cal) = m\ (g) \times c\ (cal/g^{o}C) \times \Delta T\ (^{o}C)$

    where Q = heat gained by the water

    m = mass of the water

    c = specific heat of water (1 cal/g°C)

    ΔT = change in temperature of the water ($T_f - T_i$)

18. According to the law of heat exchange, in this closed system the quantity of heat gained by the water equals the quantity of heat lost by the substance you're testing.

    $Q_{\text{gained by water}} = Q_{\text{lost by substance tested}}$

    Determine the amount of heat lost by the substance and record the value in Data Table 2.

19. To find out the quantity of heat stored <u>per gram</u> of substance, divide the quantity of heat lost by the substance by the number of grams of substance tested. Record in Data Table 2.

    $$Q\ (cal/g) = \frac{Q \text{ lost by substance}}{m\ (\text{substance})}$$

20. Calculate the mass of <u>one liter</u> of the substance, using the formula $D = \frac{m}{V}$

    where D = density of the substance in grams/cm^3
    ($D = 1.464$ for $Na_2SO_4 \cdot 10H_2O$)

    m = mass of substance (grams/liter)

    V = 1000 cm^3 (1 liter)

    Record in Data Table 2.

21. Calculate the amount of heat that can be stored per liter of substance, using the following equation.

Q (cal/liter) = Q (cal/g) x m (g/liter)

Record in Data Table 2.

22. Repeat Part 2 for paraffin. Ask your teacher for the density of the paraffin sample you're testing.

questions

1. What Celsius temperature range did your heating and cooling curves cover for each substance?

2. Are these useful ranges in which to store and release energy for home heating? Why or why not?

3. Glauber's salt and paraffin are known as heat storage materials. What is meant by the term heat storage?

4. At what temperature does each substance change phase?

5. During which phase change do the substances store heat? Release heat?

6. What property of these substances associated with phase change makes them useful for storing heat energy?

7. Why is the density of the substances important in considering them for storing heat?

8. What other properties determine the usefulness of these substances for heat storage?

9. How much heat did each substance store and then deliver to the water per unit of mass?

10. How much heat can each substance store per liter in its phase-change temperature range? How does this compare with the amount of heat the same volume of water can store in this temperature range?

11. Explain the following terms: law of heat exchange, specific heat, and heat of fusion.

12. Use these terms to explain how the substances you tested could be used to store solar energy.

looking back

The substances you worked with in this activity change their phase, from solid to liquid or liquid to solid, within a commonly-experienced temperature range, not much above the human comfort

level. For this reason, the solar energy industry calls substances like these "phase-change materials." Their phase-change characteristics give them great potential as heat storage materials in solar energy systems. Although research is continuing to improve the reliability and packaging of phase-change materials, they are already being marketed for solar homes.

going further

Repeat this activity using other heat storage materials suitable for storing solar energy, such as potassium aluminum sulfate dodecahydrate ($KAl(SO_4)_2 \cdot 12H_2O$) or sodium acetate trihydrate ($NaC_2H_3O_2 \cdot 3H_2O$).

Heat and cool the same sample of Glauber's salt several times. Does the salt continue to completely recrystallize each time? If it doesn't, why is this a problem in storing heat? Can you suggest a means to encourage recrystallization?

Check The CRC Handbook of Chemistry and Physics to locate other salts which might be used to collect solar energy. Justify your choices based on the information you find under "Physical Constants of Inorganic Salts."

Research the current status of heat storage materials in solar heating. Use the Reader's Guide to Periodical Literature to locate specific articles in such magazines as Popular Science, Popular Mechanics, and Solar Age.

Write to manufacturers of heat storage materials for promotional literature about their products.

To find out how well rock and air store solar energy, try Activity 3 in this book and Activity 10 in the Junior High/Middle Grades Activities book.

Data Table 1

Name of Substance Tested: _____

Chemical Formula: _____

Mass: _____ Mass of Water: _____

Heating Phase Description: _____		Cooling Phase Description: _____	
Time (minutes)	Temperature of Substance (°C)	Temperature of Water(°C)	Temperature of Substance (°C)
Initial		(T_i)	(T_i)
0:15			
0:30			
0:45			
1:00			
1:15			
1:30			
1:45			
2:00			
2:15			
2:30			
2:45			
3:00			
3:15			
3:30			
3:45			
4:00			
4:15			
4:30			
4:45			
5:00			
Final		(T_f)	(T_f)

Data Table 2

Substance	$Na_2SO_4 \cdot 10H_2O$	Paraffin
Mass (g)		
Specific Heat of Water (cal/g°C)		
Mass of Water (g)		
ΔT(°C)		
Q gained by water (cal)		
Q lost by substance (cal)		
Q substance (cal/g)		
Density (g/cm³)		
Mass (g/liter)		
Q substance (cal/liter)		

Summary of Calculations

$$Q_{g_w} = Q_{l_s}$$

$$Q_{g_w} = m_w \cdot c_w \cdot \Delta T_w$$

$$Q_s(\text{cal/g}) = \frac{Q_{l_s}}{m}$$

$$D = \frac{m}{V}$$

$$Q_s(\text{cal/liter}) = Q\ (\text{cal/g}) \cdot m\ (\text{g/liter})$$

where g = gained
l = lost
w = water
s = substance

Graph 1

Substance: _____

Temperature (°C)

Time (minutes)

Graph 2

Substance: _____

Temperature (°C)

Time (minutes)

Teacher Information

Storing Solar Energy in Salts and Paraffin

Suggested Grade Level and Discipline

Science, grades 11-12
Chemistry
Physics

Skill Objectives

Measuring metric mass and temperature

Observing and recording data

Graphing heating and cooling curves

Following an uninterruptable procedure

Using the law of heat exchange

Calculating heat gain, heat loss, and heat stored per unit mass and volume

Major Understandings

Energy is stored when a material changes phase from a solid to a liquid and released when it returns to a solid state. The heat of fusion is the amount of heat (cal/g) required to melt a substance.

This phase-change property of substances may be used to store heat energy and is especially applicable to solar heating, where solar energy is stored as heat during periods of insolation and then released during periods of darkness or cloud cover.

To be useful for storing solar energy, a substance must have a high heat of fusion, a melting point near the range of home heating temperatures, and a relatively high density.

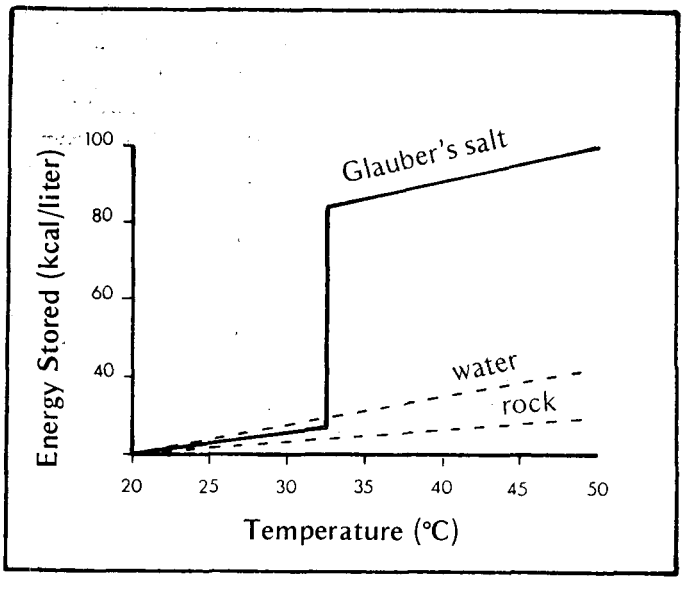
Within a closed system, heat transfer follows the law of heat exchange, where the heat lost from hot objects equals the heat gained by cold objects, or $Q_l = Q_g$.

The heat stored during a phase change can be determined by releasing this heat to water in a closed system. The formula is $Q = m \cdot c \cdot \Delta T$.

The heat stored per gram and per liter for heat storage substances can be calculated and compared to the heat stored by water in the same temperature range (1 cal/g^{o}C or 1 kcal/liter^{o}C).

Background

Collecting solar energy is the easy part; storing it for later use during cloudy periods or at night is the hard part. The usual mediums for storage are water, rock, or sand, but they require large volumes to store relatively small amounts of heat. Certain inorganic salts and even paraffin are, on the other hand, capable of storing large quantities of heat when they change phase from solid to liquid. Glauber's salt, for example, can store 84.5 kcal/liter in the temperature range normally achieved by solar gain, while water can store only 20 kcal/liter, and rock only 8 kcal/liter. A typical house, then, would require only 4 m^3 (125 ft.^{3}) of salt storage, while 30 m^3 (1000 ft.^{3}) of water and over 60^{3}m (2000 ft.^{3}) of rock would be required.



The key to using certain inorganic salts or organic compounds for heat storage is the temperature at which they melt, which must be within the temperature range associated with home heating (45-55°C) or cooling (5 - 15°C). Ideally, the more heat stored in the "fusion" process, the better the salt. Practically, the salt must otherwise qualify as a heat storage material: it must be reasonable in cost and readily available, have a high enough density for proper storage, and be non-toxic and non-corrosive.

Why, then, haven't salt storage materials become commonplace? There are several major problems with salts: after repeated phase changes they are affected by supercooling, a condition in which the temperature must fall below the normal freezing point before recrystallization occurs, thus delaying heat release; the salts encapsulate, or do not completely resolidify, thus reducing the amount of heat released; and they undergo phase separation, in which the solid phase encrusts on the walls of the container and acts as an insulator, reducing heat absorption. Research is slowly solving these problems. The addition of nucleators to the salt now prevents failure to recrystallize and initiates the freezing process, and agitation of the salt can prevent encapsulation and encrustation. Several heat storage salts are now being marketed (see reference Solar Age, February 1982).

In this activity, the heat lost by the substance being tested is determined by calculating the heat gained by the water. The heat gained by the plastic wrap has not been accounted for since the amount is so small as to be negligible. Plastic wrap is used because several of the salts (including Glauber's salt) are efflorescent and because plastic wrap contains the salt in a sealed container, much as in an actual heating application. The transparency of the plastic allows, of course, for the observation of the material undergoing phase change.

Advance Planning

Order Glauber's salt and paraffin if not in stock.

Assemble all needed equipment.

Duplicate needed quantities of the data tables and graphs. Each group will need one copy of Data Table 1 and of the graphs for each trial.

Run through the activity to work out any "bugs."

You may want to pre-cut the plastic circles.

Determine the density of the paraffin being tested.

Suggested Time Allotment

One class period to set up equipment and run the first trial

One class period to run the second trial, graph results, and start answering questions

Additional class periods to retest substances (optional)

One class period to answer questions and compare and discuss results

Suggested Approach

This activity can be used to introduce or reinforce the concepts of energy, entropy, phase change, and heat exchange. It may also be used when studying the properties of crystals.

Students should work in groups of two or three, dividing the tasks into recorder/timer and thermometer reader or into recorder, timer, and reader. Be sure students exchange tasks when the procedure is repeated. If desired, some groups may work only with Glauber's salt while others work only with paraffin. If the class is large, you may want to add other salts or substances for testing. In any case, allow for several trials of the same substance so results can be compared. Allow students time to exchange data.

Go over the procedure carefully with the students before they begin so they understand the continuous nature of the experiment and are aware of all observations to be taken.

Make sure the heating and cooling of the substances proceed slowly enough for students to see the plateaus on their curves. Continue the cooling process until the phase-change plateau is passed and the temperature

again drops steadily. If possible, continue the cooling process until the substance and water temperatures are equalized.

Students will probably need to interpolate points on their curves. Spreading out the axes on larger pieces of graph paper than those provided may allow students to see the curves better.

Help students with calculations as necessary. Help students to understand the purpose of each calculation in Part 2.

During discussion of results, relate the experimental findings to the practical application of heat storage materials in solar heating. Explain any variations in the salt's cooling curves and relate them to the problems inherent in using salts to store heat.

Precautions

Check to make sure that students are wearing safety goggles and aprons.

Remind students that data must be collected systematically, quickly, and accurately.

Due to aging, salts may not show clear plateaus upon cooling.

Points for Discussion

Why can you assume your cooling apparatus is a closed system?

Why do plateaus occur on your heating and cooling curves? What is happening during this time?

What would be some of the advantages of using the materials you tested to store solar energy? The disadvantages?

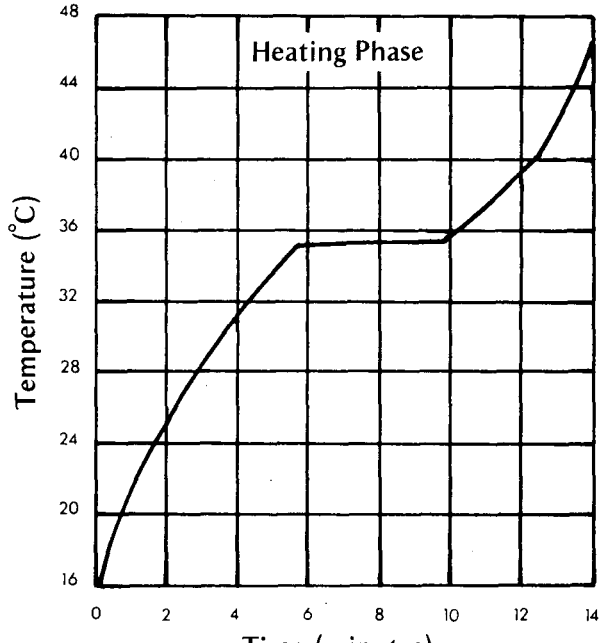
What are some of the problems associated with using these materials to store solar energy?

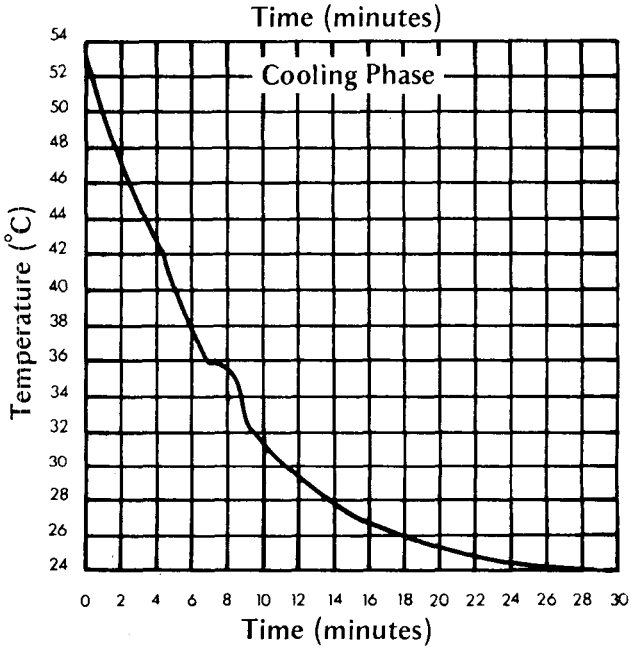
How valid or reliable were your results? Why?

What was the purpose of each separate calculation in Part 2?

Typical Results

Sample heating and cooling curves for Glauber's salt are shown below.





Because of failure to recrystallize, the cooling curve plateau for Glauber's salt will not be as distinct as that of its heating curve and will occur at a lower temperature.

The heat of fusion for Glauber's salt varies from 33 to 58 cal/g, depending on the source cited (probably a result of aging differences). Student results may be closer to the lower value because the system is not completely closed.

No typical results are given for paraffin, since paraffin samples vary substantially.

Evaluation

Check students' data tables and graphs for completeness and accuracy.

Check students' calculations for accuracy and correct use of equations.

Review students' answers to questions for degree of understanding.

Rate students' laboratory technique as they work through the activity.

Ask students to explain the law of heat exchange, specific heat, and heat of fusion.

Ask students to explain how heat storage materials can be used to store solar energy.

Have students describe the properties which make these materials useful for storing heat energy.

Ask students why the substances tested are better for storing heat energy than water.

References

Direct Use of the Sun's Energy, Farrington Daniels.
(Ballantine Books, Inc., 400 Hahn Rd., Westminster, MD 21157, 1974, $1.95/paper.)

Engineer's Guide to Solar Energy, Yvonne Howell and Justin Bereny.
(Solar Energy Information Services, P.O. Box 204, San Mateo, CA 94401, 1979, $29.50/paper.)

"Solar Salts: New Chemical Systems Store the Sun's Heat," Richard Stepler.
(Popular Science, Boulder, CO 80302, March 1980.)

"A Study of Selected Thermal Energy Storage Materials," Allen and Malawer.
(Paper presented to American Section International Solar Energy Society, Proceedings ASISES, Denver, CO, 1978.)

"Super Storage for Solar Heat," Charles A. Miller.
(Mechanix Illustrated, P.O. Box 8162, Greenwich, CT 06836, October 1978.)

"Weighing the Contenders in Solar Heat Storage," David Godolphin.
(Solar Age, SolarVision, Inc., Church Hill, Harrisville, NH 03450, February 1982.)

Metric Conversion Table

Unit of Measure	English Unit	Multiply By ► ◄ Divide By	Metric Unit	Symbol
Length	inches	2.54	centimeters	cm
	feet	30.0	centimeters	cm
	feet	0.3	meters	m
	yards	0.91	meters	m
	miles	1.61	kilometers	km
Area	square inches	6.5	square centimeters	cm^2
	square feet	0.09	square meters	m^2
	square yards	0.8	square meters	m^2
Mass (Weight)	ounces	28	grams	g
	pounds	0.45	kilograms	kg
Volume	gallons	3.8	liters	l
	cubic feet	0.03	cubic meters	m^3
Temperature	degrees Fahrenheit	5/9 (after subtracting 32) 5/9 plus 32	degrees Celsius	^oC
Heat	Btu	252	calories	c
Speed	miles per hour	1.61	kilometers/hour	km/hr

Energy Units

barrel: a liquid volume equal to 42 gallons or 159 liters. One barrel of crude oil has about the same heat energy as 350 pounds of bituminous coal, 5.8×10^9 joules or 5.5×10^6 Btu or 1.39×10^6 kcal.

Btu: British thermal unit, a unit for measuring heat; a Btu is the quantity of heat necessary to raise the temperature of one pound of water one degree Fahrenheit, about one-fourth of a kilocalorie (252 calories).

calorie (also: gram calorie): a metric unit of heat energy; the amount of heat needed to raise the temperature of one gram of water one degree Celsius. It equals 0.0039 Btu. One thousand calories make one kilocalorie (kcal), sometimes called a Calorie or food Calorie.

kilowatt: a measure of power, usually electrical power or heat flow; equal to 1,000 watts or 3,413 Btu per hour.

kilowatt-hour: the amount of energy equivalent to one kilowatt of power being used for one hour; equals 3,413 Btu, or about 860 kcal.

watt: a unit of measure for electrical power equal to the transfer of one joule of energy per second. The watt is the unit of power most often associated with electricity and is determined by multiplying required volts by required amperes. One horsepower = 746 watts.