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Simple experiments on the use of solar energy

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In the light of the considerable publicity that has been given to the impending shortage of fossil fuels, students are strongly motivated towards an examination of the use of solar energy to meet our needs. Thus, at a recent summer school for science teachers at the University of New South Wales, we arranged a workshop consisting of a number of experiments in this field. It was our objective to demonstrate that solar-energy experiments can be carried out using inexpensive and easily-made equipment and that quantitative as well as qualitative work is possible.

The first essential in any such studies is a convenient thermometer. For most of the experiments a mercury-in-glass thermometer is unsuitable and we used instead a copper–constantan thermocouple made from 36-gauge wires connected directly to an electronic galvanometer of continuously adjustable sensitivity. Since precise measurements were not called for, we assumed the thermoelectric power to be independent of temperature and the reference junction to be at ambient temperature. The thermoelectric power of a chromel–alumel couple is less temperature dependent than that of a copper–constantan couple but the ease of soldering the junction of the latter made it preferable for our purposes.

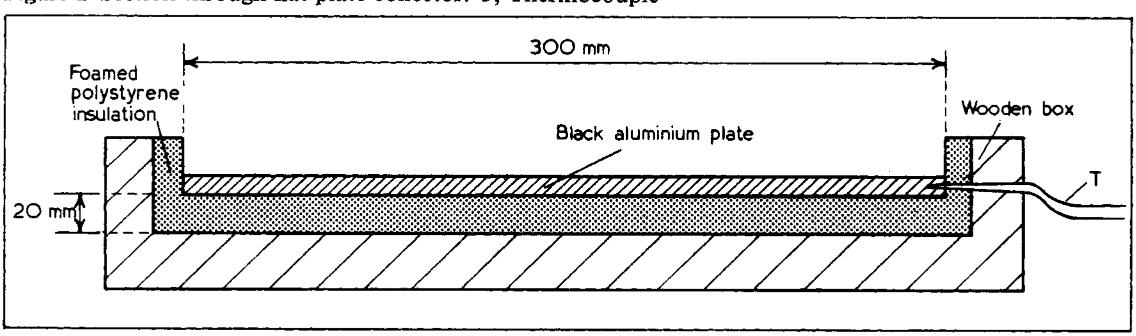
The thermometer was calibrated by dipping the junction alternately in melting ice and boiling water, the sensitivity of the galvanometer being adjusted until the change of deflection between the two temperatures was a convenient number (25) of scale divisions. The maximum sensitivity (10 μV/division) of our type 2707 galvanometer (made by Yokogawa Electric Works Ltd) was much more than adequate for our purpose. Any simple galvanometer with a sensitivity of about 100 μV/division or better would do just as well if it were fitted with a variable shunt.

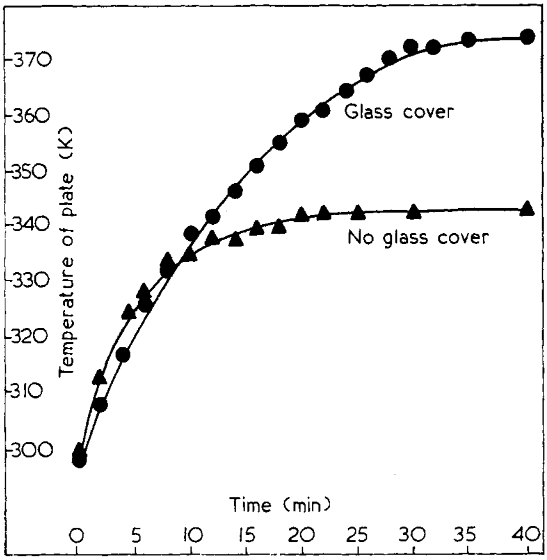
Experiment 1: Flat-plate collector

Surprisingly high temperatures can be reached by the flat-plate solar collector shown in figure 1. The apparatus consists of a sheet of aluminium, about 2·3 mm thick and 300 mm × 300 mm in area, that is coated with matt black paint (Nextel Velvet Coating, 101–C10 Black, 3M Company). This plate is laid on foamed polystyrene (waste packing material) and its temperature is found by a thermocouple glued into a hole drilled in it. When the plate is exposed to sunlight, its temperature is observed as a function of time. Typical results are shown in figure 2 for a nearly cloudless January day in Sydney. A temperature of about 340 K was reached for the uncovered plate and about 370 K was attained when a sheet of glass was placed on top.

The rate of rise of temperature depends on the thermal capacity of the plate as well as on the incident solar power and the heat losses. The thermal capacity is calculated from the mass of the plate (0·75 kg) and the specific heat capacity of aluminium (0·91 kJ kg^{-1} K^{-1}). The heating power that would be available from the collector at each temperature is the product of the rate of change of temperature and the thermal capacity and is shown in figure 3. When there is no glass cover, the available power is approximately equal to the incoming solar

Figure 1 Section through flat-plate collector. T, Thermocouple





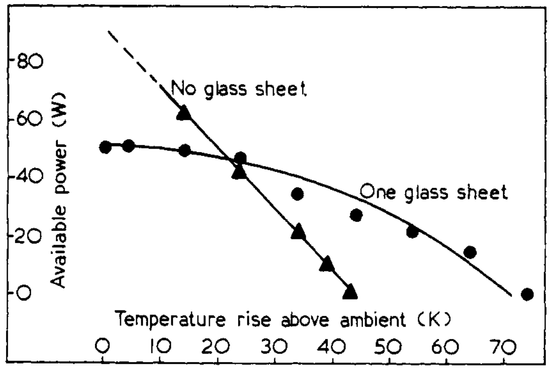


Figure 3 Available power from flat-plate collector plotted against temperature rise above ambient

Figure 2 (left) Temperature of flat-plate collector plotted against time of exposure to sunlight

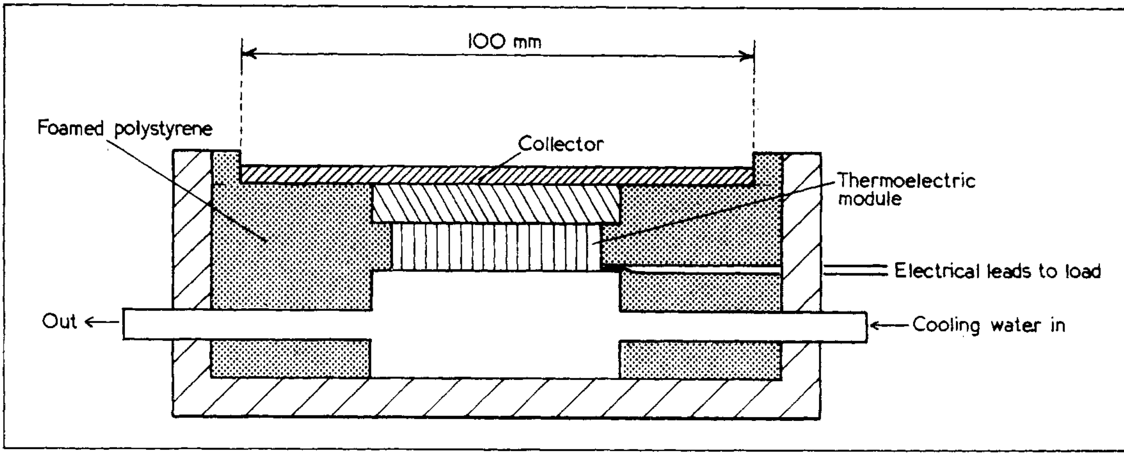


Figure 4 Section through solar–thermoelectric generator

radiation if the collector is at the same temperature as its surroundings; it may be assumed that the loss by reflection from the plate is small.

It would, of course, be possible to reduce the time for completion of the experiment by diminishing the thickness of the aluminium sheet and hence its thermal capacity.

Experiment 2: Solar thermoelectric generator

The full significance of experiment 1 becomes clear when one attempts to use solar heating to provide electrical or mechanical power. One type of heat engine, that will work satisfactorily from the rather small temperature differentials that are available from the flat-plate collector, is the thermoelectric generator. We used a bismuth telluride thermoelectric module consisting of six couples, having an electrical resistance of 30 mΩ, that had been manufactured by De La Rue Frigistor Ltd. It would be preferable to replace this by one of newer modules made by MCP Electronics Ltd (Alperton, Wembley) since, for a given power rating, the number of thermocouples—and hence the output voltage—is greater. A type TL0606 module with 18 couples would give an open circuit e.m.f. of about 0·2 V for a 25 K temperature difference.

The experimental arrangement is shown in figure 4. The output from the generator is connected to a load that is comparable to the module in resistance (a short length of nichrome wire was used). The power output is determined from the voltage observed across the load. The incident solar power is known from the area of the collector (0·01 m^2) using the data from experiment 1. We observed 25 mV across a 45 mΩ load on a rather cloudy day for which the incident power was estimated at 0·5 kW m^{-2}. The overall efficiency was about 0·3% on this occasion.

It is worthwhile examining the effect on the efficiency of blocking part of the incident radiation (using an insulating mask to prevent heat loss from the unilluminated part of the collector). If the temperature of the collector is determined one can find how this affects the efficiency. The collector efficiency is low for large temperature differentials while the generator efficiency is low for small temperature differentials. The overall efficiency is the product of the efficiencies of the collector and the thermoelectric generator.

Experiment 3: Simple concentrators

Experiment 2 highlights the fact that only small efficiencies can be obtained from electrical generators that incorporate flat-plate collectors. This is the motivation for investigating the concentration of solar energy as a means of reaching higher temperatures. Quite effective concentrators can be achieved using nonfocusing devices, which have the advantage over lenses and focusing mirrors that they do not have to be accurately aligned with the sun. For example, the School of Electrical Engineering at this university has been considering conical concentrators for increasing the power output from solar cells. Figure 5 shows how rays parallel to the axis of a 15° cone travel after reflection; for a given diameter of the receiving surface, there is a limit to the useful cone length.

Our experiment makes use of a blackened copper disc of 25 mm diameter as the receiver; its temperature is found using an imbedded thermocouple. Cones of various length up to 150 mm have been made from cardboard lined with aluminium cooking foil. The temperature of the disc was found to rise to as high as 450 K. Conical (and other) concentrators are easily made by students and their design gives ample scope for ingenuity.

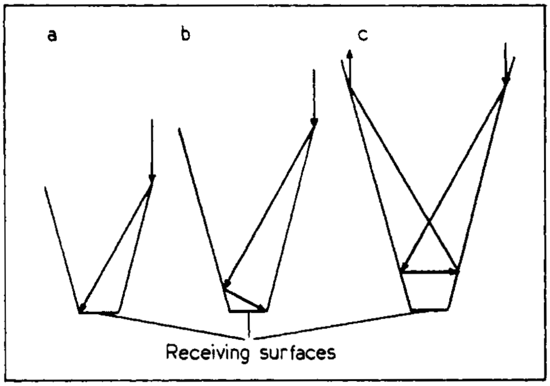


Figure 5 Reflections of rays parallel to the axis of cones of 15° half-angle. Receiving surface intercepts all rays (a) after one or zero reflections, (b) after two, one or zero reflections; (c) receiving surface fails to intercept outer rays and is theoretically no improvement on (b)

Experiment 4: Solar cell

Experiments relevant to solar energy do not have to be performed out of doors. Thus, we may study the performance of a silicon solar cell indoors using an incandescent lamp as the source of light. By varying the current through the lamp, we may simulate different conditions of brightness of solar illumination.

Our apparatus consists of a silicon solar cell (type 2A Centralab) of about 28 mm diameter mounted 320 mm below a 24 V 150 W quartz–iodine incandescent lamp. The solar cell is connected to a resistance box and, for a given lamp brightness, the voltage across various resistive loads is found. The arrangement is shown in figure 6 and some experimental current–voltage plots are shown in figure 7. Although the maximum efficiency of a solar cell does not depend very much on the illumination, it is important that the load should be adjusted according to the brightness if a good performance is to be achieved; that is apparent from figure 8. It is interesting to observe whether changes in the light intensity have a greater effect on the open-circuit voltage or on the short-circuit current.

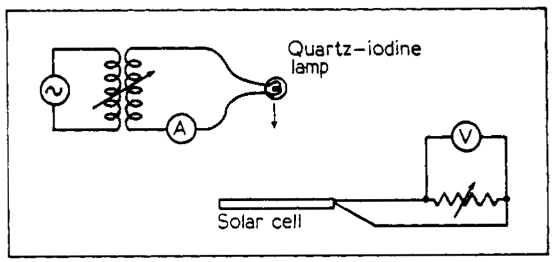


Figure 6 Arrangement for experiment on a solar cell

Experiment 5: Natural storage of solar energy

The physicist should not be deceived into thinking that he will necessarily provide the answer to the problem of economic solar-energy utilization. It is quite possible that the best way of producing mechanical or electrical energy will be through the growth of natural products which can be turned into fuel for use in more-or-less conventional heat engines.

It can be readily shown that natural growth processes have a reasonable efficiency by determining the heat given off when a match is burnt. A known

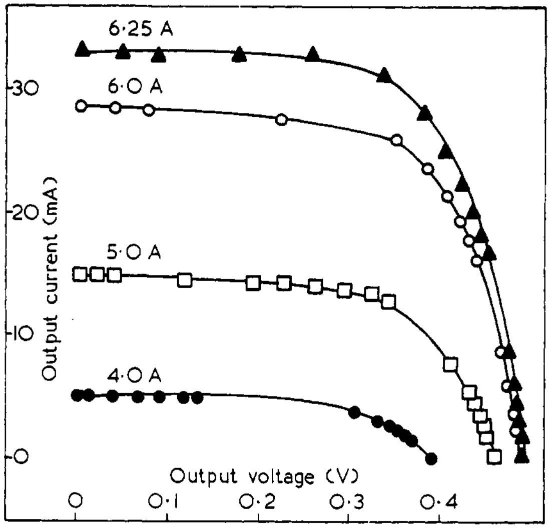


Figure 7 Current–voltage characteristics for a solar cell with different currents through the illuminating lamp

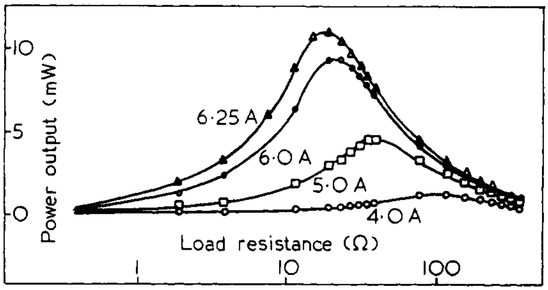


Figure 8 Power output from a solar cell plotted against load resistance for different lamp currents

amount of water (10^{-5} m^3) in a test-tube is held over the burning match and its rise of temperature found with a mercury-in-glass thermometer. We have found that this rise of temperature is about 10 K. The heat capacity of water is some $4{\cdot}2 \times 10^6$ J m^{-3} K^{-1}, so that a match can provide about 420 J. One must then estimate how much solar energy was used in growing the matchwood. This is done by estimating the solar energy falling on the area of ground occupied by a tree over its life and the number of matches in a tree.

Our estimates are as follows:

Volume of match = 40 mm $\times$ 2 mm $\times$ 2 mm = 16×10^{-8} m^3

Average diameter of tree = 0·4 m

Height of tree = 10 m

Volume of wood in tree = $10\pi \times 0{\cdot}2^2 = 1{\cdot}3$ m^3

Stored energy in tree = $\dfrac{420 \times 1{\cdot}3}{(16 \times 10^{-8})} = 3{\cdot}4 \times 10^9$ J

Time of growth = 20 years

Equivalent sunny days per year = 250 days

Hours of sunlight per day = 12 h

Radiant flux from sun = 1 kW m^{-2}

Area of land occupied by tree = 20 m^2

Total solar energy on land in 20 years = $20 \times 250 \times 12 \times 3600 \times 1000 \times 20 = 4{\cdot}3 \times 10^{12}$ J

Efficiency of storage of solar energy by tree = $3{\cdot}4 \times 10^9/(4{\cdot}3 \times 10^{12}) \approx 0{\cdot}1\%$.

This is probably quite a reasonable estimate for an average tree although it is appreciably less than the storage efficiency of specially selected plants.

Why is this a bad question?

London A-level physics, June 1975

A sealed bottle full of water is placed in a strong container full of air at standard atmospheric pressure, $1{\cdot}0 \times 10^5$ N m^{-2}, and at a temperature of 10°C. The temperature in the container is raised to and maintained at 100°C. Neglecting the expansion of the bottle and the container, what is the new pressure in the container? If the bottle breaks what will the pressure be?

For comments see page 423

Queries in physics

A354 (Why is ignition interference so much harder to suppress in an alternator circuit compared with the earlier (d.c. generator) circuits? Is it to do with solid state stabilization? What is the best approach?) (*from QIP* 38)

A correspondent writes: On several occasions I have been able to achieve a welcome reduction in the interference level on a car radio (whether from ignition or wiper motors) by having the earthed supply lead for the radio connected to the car chassis at one point, and *one point only*. That point must be where the aerial lead passes through the car chassis. If there are any other earth return routes, induced voltages from nearby varying magnetic fields will appear effectively in series with the signal reaching the aerial from the world outside.

The above item was selected from *QIP*, a thrice-yearly broadsheet edited by Mr W H Jarvis. It is available on subscription at £1·65 per annum from Trisagion Ltd, Rannoch Station, Perthshire PH17 2QH.