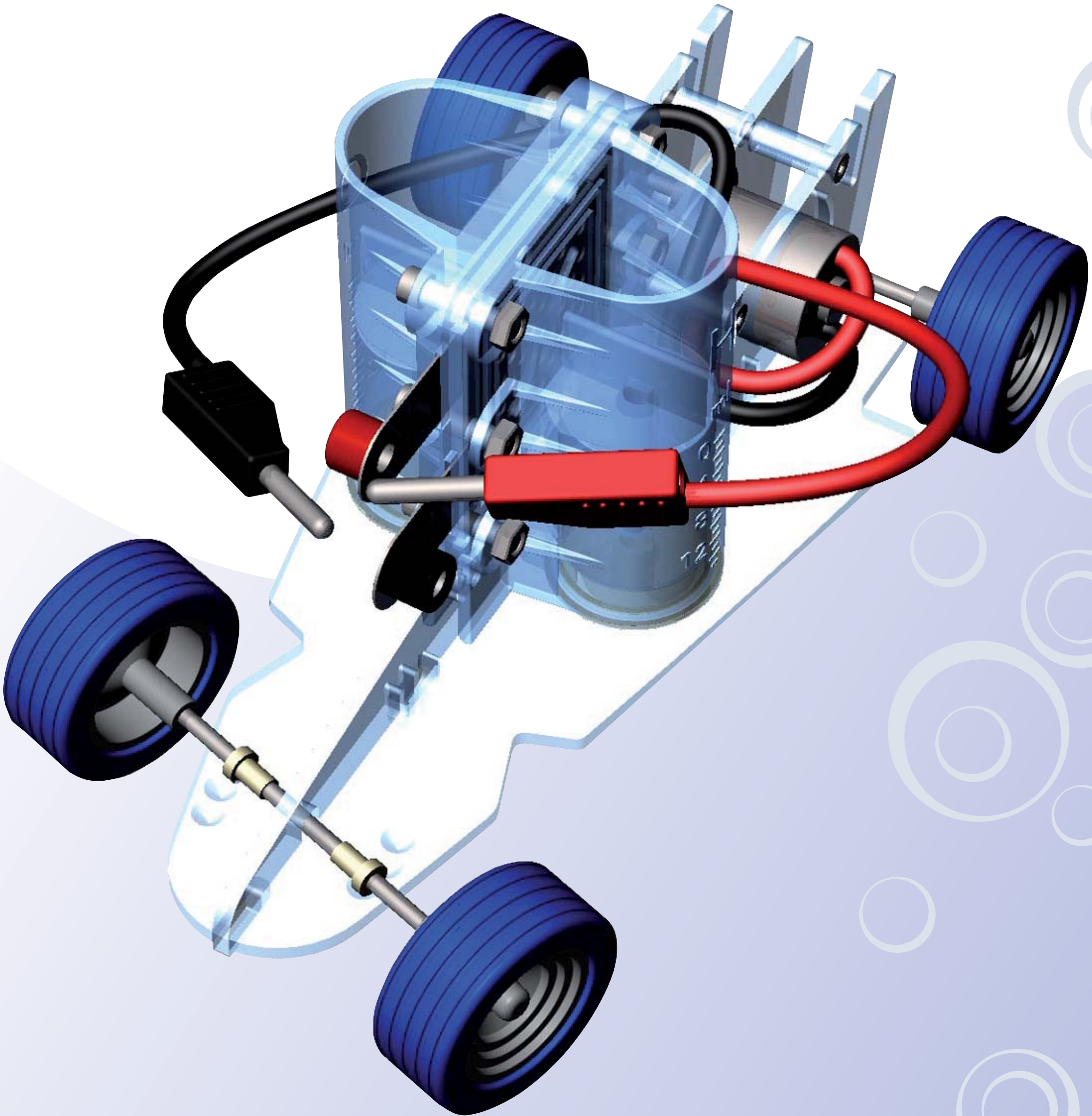
Heliocentris

Dr FuelCell™ Model Car

Teacher's Guide



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Teacher's Guide for Dr FuelCell™ Model Car kit

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Content

Preface

This book is intended to bring your students into contact with fuel cell technology. The basic principles of fuel cells are examined in a playful, fun filled manner, encouraging your students to examine this new technology.

Fuel cells use the chemical energy of hydrogen to generate electricity, cleanly and efficiently. Hydrogen fuel cells have the potential to

- Reduce the generation of greenhouse gases, air pollution and global climate changes
- Be an important part of energy security
- Propel hydrogen technology as the energy supply of the future

Teaching your students about this important technology will give them an edge in this developing field.

Curriculum aspects

Many curriculum aspects can be taught with this new technology:

- Concept of molecules
- Structure of atoms
- Chemical reactions
- Conversion of different types of energy
- Performing scientific inquiries
- Design and conduct scientific investigations
- Science and technology in local, national and global challenges

We hope your students will play an important part in making fuel cells part of our sustainable future.

2 About This Document

This document is designed to help prepare lessons about fuel cells. The investigations are organized in a sequential manner, nevertheless it is possible to perform them standalone.

Use this book to inspire lessons delivering the innovative and exciting technology of fuel cells to your students.

Each investigation contains a section with background information, providing the fundamentals of the topics dealt with. Furthermore, each investigation comprises a teacher's and a student's section.

The sections containing background information and instructions for students are explicitly designed for photocopying and handing out to the students.

This Teacher's Guide contains the following investigations:

Investigation	Main objective
Demonstrating the Dr FuelCell™ Model Car	Precise observation
Solar panel orientation	How electrical power production depends on the intensity of the energy input
Simple electrolysis	Basic principles of electrolysis
Understanding electrolysis	Breaking up of molecules
Hydrogen power!	Gaining electricity from combining hydrogen and oxygen – electrolysis is reversible
Hydrogen power in motion	Friction, work, power, energy
Energy efficiency	Energy efficiency
What is a hybrid?	Working independently on fuel cells, the hybrid concept

Table 2-1 Investigations and their main objectives

2.1 Using the Investigations in the Classroom

These investigations provide you with suggestions on how to set up lessons concerning fuel cells and the basic principles of physics and chemistry on which they are based.

Heliocentris has published correlations with the national curricula of some countries. These correlations can be found on our home page: www.heliocentris.com

If you wish to add correlations for your country, please e-mail to: info@heliocentris.com with the subject: correlations.

Teaching method

These investigations are designed to provide you with material to either conduct a chalk and talk, or a group work oriented approach. The approach you choose not only depends on the number of Model Car kits available but also on your students' abilities and your progress with the class. Additionally questions for homework, silent work or quizzes are part of each investigation.

Feedback

We at Heliocentris believe in continuous learning – if you do have suggestions to improve this Teacher's Guide you are more than welcome to supply us with suggestions and feedback.

Please send us your suggestions to: info@heliocentris.com with the subject: feedback.

2.1.2 Structure of the Chapters

The chapters of this Teacher's Guide consist of three sections; a section containing the teacher's essentials, a section outlining a chalk and talk lesson and a student's section containing a description of the investigation and a compendium of questions.

Teacher's essentials

In this section information for designing a lesson is given:

- An estimate of the time needed
- Information about the qualifications the students need to have
- The learning objectives
- Keywords to suggest related topics
- Background information on the theory behind the investigations, which you may photocopy and hand out to the students

The investigations – teachers

A chalk and talk lesson is outlined in this section, describing each step you need in order to demonstrate the investigation. Suggestions for student participation are given. At the end of this section the answers to the student questions are provided.

Student's section

Each of the investigations contains a student's section, which you may copy and hand out to the students. This section contains a description of how the student will conduct the investigation when it is undertaken as a group activity or as an individual task, and a compendium of questions. You may use these questions as homework, as in-class silent work or in any other way.

2.2 Symbols and Signs

2.2.1 Symbols

In this document the following symbols and signs are used to:

Symbol	Meaning
➔	Here you have to do something
1.	Here you have to do something and have to pay attention to the order
✓	This is a prerequisite you need to complete before starting the next step
•, -	Item of a list

Table 2-2 Symbols used in this document

2.2.2 Warning Signs

Even though no immediate dangers arise from these investigations, some safety measures should be heeded. When applicable, warning signs are placed in the investigation.

The warning signs appear as follows.

⚠ **RISK LEVEL**

Type and source of danger are described here!

Possible consequences if the safety measures are not heeded are described here.

➔ Safety measure to be heeded is given here.

2.2.3 Risk Levels

Following risk levels are present when working with the product:

⚠ CAUTION
Dangerous situation! If safety measures are not observed, minor injuries may occur.

! NOTICE
Dangerous situation! If safety measures are not observed, damage to equipment may occur.

2.2.4 Hints

Useful hints appear as follows:

TIP
Useful hint.

2.3 Further Applicable Documents

In addition to this Teacher's Guide the Dr FuelCell™ Model Car kit is delivered with the following documents:

- **Instruction Manual** providing information on how to use the Model Car kit. It must be read by the teacher prior to use of the Model Car kit.
- **Quick Guide** to be handed out to the students, containing a short synopsis of basic setups of the Model Car kit.

3 General Safety

The Model Car kit is constructed according to the highest standards. Nevertheless, improper operation or abuse can present danger to:

- The health of the operator and observers
- The unit itself and other items of property

3.1 For Your Safety

This information on general safety is supplemented by specific warnings throughout this Guide. These warnings explain how to act, in order to protect yourself or other persons or property from injury or damage.

➔ Read and completely understand experiments in this Guide.

➔ Adhere to the local statutory regulations.

➔ Follow safety instructions and warnings.

➔ Give this Guide to subsequent owners of the Model Car kit.

3.1.1 Intended Use

The Model Car kit is provided solely for experiments and demonstrations on hydrogen technology and its components. The Model Car kit may only be used for experimentation and demonstration purposes. It is only intended to be used as an electrolyzer and a fuel cell.

3.1.1.1 Prohibited Use

The Model Car kit may **not** be used for:

- Generating electricity and hydrogen for any other purposes than described in this Teacher's Guide or in the Instruction Manual
- Storing or collecting more than minimal amounts of hydrogen (appr. 30 mL)
- Measuring voltage and current with other than components of the Dr FuelCell™ package
- Continuous electrolysis

3.1.2 Operators

The Model Car kit is intended only for persons over age 12. Young persons over age 12 should use the kit only under the supervision and guidance of qualified adults. The adults must ensure appropriate handling. They must be aware of the possible dangers.

Students using the equipment must be supervised by experienced teaching staff. When students are performing experiments, the teacher should distribute the relevant student section of the Teacher's Guide for the Dr FuelCell™ Model Car kit and have available in the laboratory copies of the Quick Guide to the Dr FuelCell™ Model Car kit.

3.1.3 Protective Gear

- ➔ Wear protective goggles when conducting experiments.

3.2 Location Condition

The components of the Model Car kit must be assembled and operated on an even and stable, water resistant horizontal surface, at a recommended height of 75–85 cm (30–34").

The room must be well ventilated.

Room and equipment must meet the local statutory regulations.

3.3 Shipping and Transport

Prior to shipping or transporting the Model Car kit:

- ➔ Always empty the distilled water.

For shipping:

- ➔ Use only the original storage container.

3.4 Safety Measures

For your own safety:

- ➔ Only use Dr FuelCell™ components, unless stated otherwise in the experiment descriptions in the Teacher's Guide.
- ➔ Do not connect the Dr FuelCell™ components to AC power supplies.

The reversible fuel cell produces hydrogen, an explosive gas.

- ➔ Avoid open flames near the components.
- ➔ Do not smoke.

3.4.1 In Case of Emergency

If leaking hydrogen ignites:

1. Immediately disconnect the power supply from the reversible fuel cell to stop hydrogen production.
2. Initiate all fire-fighting measures.
3. Ensure that everyone keeps a safe distance from the components.

3.5 Electromagnetic Compatibility

The load measurement box complies with Electromagnetic Compatibility (EMC) Directive 89/336/EEC.

3.6 Warranty

The warranty period for the Dr FuelCell™ Model Car kit is 12 months from the date of delivery. The warranty covers only faults that occur in the context of proper use through no fault of the operator.

The guarantee covers missing components only at the time of delivery. Certain characteristics, such as the power and life span of the reversible fuel cell, are not guaranteed.

Warranty does not cover faults that occur if:

- The customer caused damage by improper operation
- The equipment was arbitrarily repaired or altered
- Third parties caused damage because the customer neglected his / her duty of supervision

4 Demonstrating the Dr FuelCell™ Model Car

The major goal of this investigation is to allow the students to begin to ask questions about the apparatus and what it is doing.

Students will observe the Model Car, will make assumptions about what is going on and will predict and formulate questions while watching the apparatus being set up and operated.

Discovery activity

O–P–Q stands for Observation, Prediction, and Question. These are the driving forces for the beginning of any scientific investigation. Discovery activities are open-ended explorations for students to whet their appetites to explore and learn more.

It is important for students to be allowed to practice these skills intentionally and with guidance from a teacher. This fits in well at the beginning of a unit and should be repeated intermittently throughout a school year to gauge student progress towards growth and mastery of these skills.

It is good to let students explore in any direction they choose, even if the ideas presented are incorrect. Students may end up arguing with each other about misguided concepts, but it is best you don't intervene, other than to encourage extended thinking about the concepts and to encourage students with differing views to support those views in a logical manner.

4.2 Teacher's Essentials

4.2.1 Objectives

Qualifications

The focus of this investigation is to have the students observe, predict and question – thus no prerequisites are needed. If you want to use this demonstration as the starting point for further investigations, your students may need to have certain qualifications, according to the focus you wish to set.

Learning objectives

Students will learn the importance of precise observation in science, and the importance of being able to articulate this observation in a concise manner.

TIP

It is good to let the students explore in any direction they choose, even if the ideas presented are incorrect. Students may end up arguing with each other about misguided concepts, but it is best you don't intervene, other than to encourage extended thinking about the concepts and to encourage students with differing views to support those views in a logical manner. This is quite important, as one vocal student with an incorrect idea may mislead less-sure students.

Outlook

This investigation serves as a starting point for a variety of different topics:

- Use of regenerative energy
- How fuel cells work
- The principles of physics, chemistry and mathematics accumulated in the set up of a solar panel connected to a reversible fuel cell:
  - Electric load
  - Voltage, current, Ohm's law
  - Concepts of atoms, electrons, molecules
  - Oxidation, Reduction
  - Breaking up of chemical compounds
  - Chemical reactions
  - How to plot graphs
  - and many more…

4.2.2 Time Table

The amounts of time are rough estimates.

Task	Time
Preparation prior to class	30 min
Introduction	15 min
Investigation (group work)	40 min

Table 4-1 Amount of time

4.2.3 Teaching Method

Method	Suitability
Group work	✓✓
Chalk and talk	✓✓✓✓
Silent work (student questions)	✓✓
Homework (student questions)	✓✓

Table 4-2 Teaching method (✓= poor … ✓✓✓✓=very good)

4.2.4 Background

Scientists look at their world and what happens in it carefully. Their observations usually begin with unusual or peculiar events – things that arouse their curiosity. One scientist said, "The cure for boredom is curiosity. There is no cure for curiosity!"

Curiosity as the motor for discoveries and subsequent inventions

Many inventions would not have been made if scientists were not curious about their findings and not interested in side effects of their studies. For instance features of the microwave were discovered that way and subsequently utilized in microwave ovens.

When working on a magnetron tube in 1946 Dr Percy Spencer reached into his pocket to search for a chocolate bar – he found the chocolate molten. Since he did not sense any heat coming from the magnetron, he needed to find out whether his body heat or the microwaves from the magnetron had melted his chocolate bar. He then placed popping corn and eggs in front of the magnetron – and when he returned, found a mess. Following this discovery the properties of the microwaves were utilized, as we know today.

The demonstration of the Model Car serves as a starting point for further in-depth investigations.

4.3 The Investigation – Teachers

4.3.1 Preparation

NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the fuel cell.

- ✓ Even and stable base has been chosen
- ✓ Reversible fuel cell
- ✓ Distilled water
- ✓ Model Car
- ✓ 2 patch cords
- ✓ Solar panel or hand generator
- ✓ 100–120 watts PAR lamp, or equivalent light source

1. Place the reversible fuel cell upside down (numbers facing down) on the flat surface.
2. Remove the stoppers.

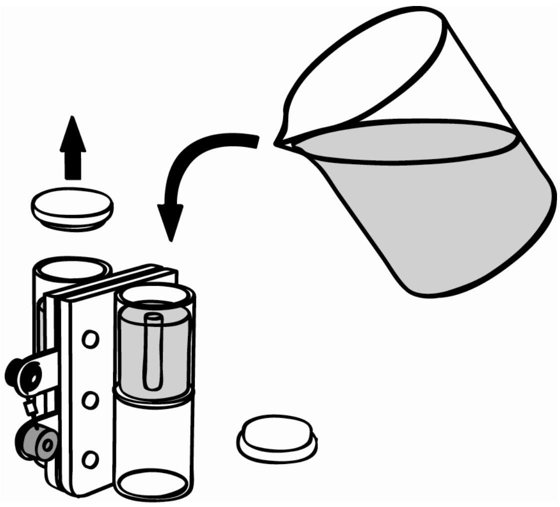


Fig. 4-1 Filling the reversible fuel cell with distilled water

3. Pour distilled water into both storage cylinders until the water reaches the tops of the small tubes in the center of the cylinders.

4. Tap the fuel cell lightly to help water flow into the area surrounding the membrane and metal current-collecting plates.
5. Add more water until it starts to overflow into the tubes in the cylinders.
6. Place the stoppers back onto the cylinders. Make sure no air is trapped inside the cylinders.

TIP
A small air bubble in the order of 0.5 mL will not cause problems and can be ignored.

7. If the membrane has not been used for a while and has dried out, leave it to soak for about 20 minutes.
8. Pour out the water if you wish to have the students to fill the reversible fuel cell themselves.

The membrane of the reversible fuel cell is now wet and ready for use.

It is advisable that you try out the investigation before class.

4.3.2 In Class

4.3.2.1 Chalk and Talk

Safety

➔ Always make your students aware of investigating safely and make yourself familiar with the potential hazards.

CAUTION

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

➔ No open flames.

➔ No smoking.

➔ Well ventilated workspace.

Demonstrate the whole process of getting the Model Car running, meanwhile encouraging the students to state their observations and assumptions about what is going on.

1. Put on goggles and encourage the students to write down their observations.

2. Fill the reversible fuel cell with distilled water, see *PREPARATION* on page 19.
3. Instead of step 7 in the preparation, turn the fuel cell right side up.

TIP

For this investigation it is recommended to use the solar panel as a source for electrical energy. Or you may also use the hand generator instead (see Instruction Manual).

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light.

2. Set up the solar panel and lamp.

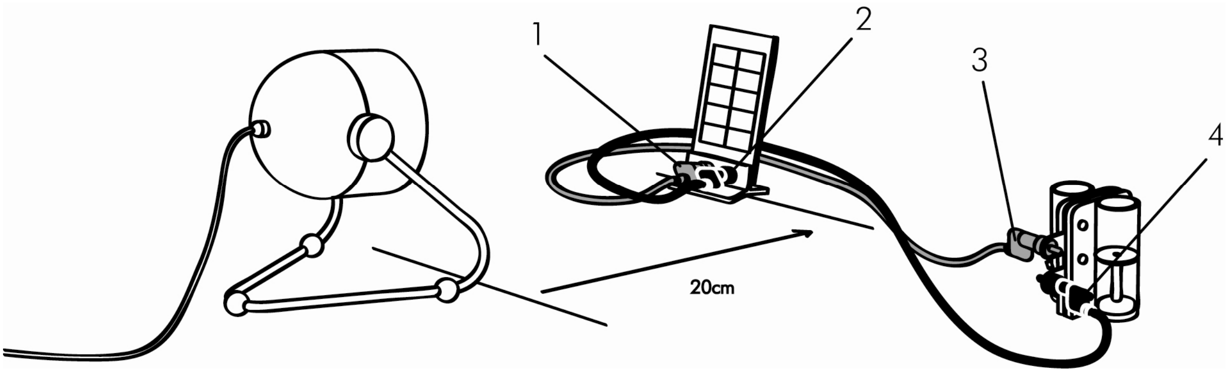


Fig. 4-2 Using the reversible fuel cell as an electrolyzer

Producing hydrogen

3. Plug the red banana jacks (1, 3) of the red patch cord into the red (positive) banana jack terminals of the solar panel (1) and the fuel cell (3).
4. Repeat step 3 with the black patch cord (2, 4) and the negative terminals.
5. Turn on the light.

The fuel cell is now connected to the energy source and will immediately start producing hydrogen and oxygen.

When the hydrogen has filled the whole storage cylinder:

6. Disconnect the fuel cell from the energy source by unplugging the banana jacks.

The reversible fuel cell stops producing hydrogen and oxygen.

> ⚠ **CAUTION**
>
> **Hot surface of solar panel and lamp!**
>
> Skin burns.
>
> ➔ Do not touch the hot surface of the solar panel or lamp.
>
> ➔ Allow solar panel / lamp to cool down before touching it.

7. Turn off the light.

The hydrogen production is now finished.

Running the car

8. Choose a suitable location: flat, smooth, and unobstructed.

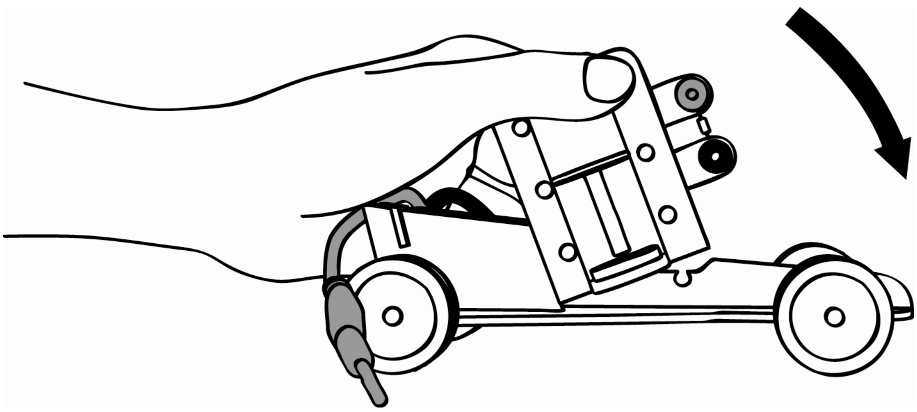


Fig. 4-3 Placing the reversible fuel cell onto the model car

9. With the red and black terminals facing towards the front of the car, place the reversible fuel cell into the notches on the model car until it audibly clicks into place.

NOTICE

Short circuit of reversible fuel cell!

Hot spots in the membrane, leading to deterioration of the membrane.

➔ Do not short circuit the reversible fuel cell.

10. Connect the red (positive) banana jack with the red (positive) terminal and the black (negative) banana jack with the black (negative) terminal.

The car will start running.

Making hydrogen audible

If you have time, you might try the following:

1. Set up the solar panel and the electrolyzer as in steps 2.–4. This time let the hydrogen fill the entire storage cylinder until hydrogen gas bubbles rise through the small tube, the upper reservoir and escape.

CAUTION

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

➔ Perform this experiment with uttermost care.

2. Hold a lit match above the escaping bubbles to see and hear the effects of burning hydrogen.
3. Have the students state their observations and start discussing them.

4.3.3 Homework

For this first investigation no special questions are designed, since the objective is to have the students observe, predict and question. Nevertheless these objectives can be met by writing down the observations, predictions and questions, possibly coming up with conclusions.

4.3.4 Silent Work

As for Homework.

5 Solar Panel Orientation

This investigation allows students to explore how the orientation of solar cells can result in maximizing the electrical power produced.

Your students will learn how electrical power production by solar panels depends on the intensity of the light source and how the intensity depends on the orientation of the solar cells.

5.1 Teacher's Essentials

5.1.1 Objectives

Qualifications

In order to ensure maximum learning success, your students should already be familiar with:

- Measuring electrical characteristics
- Knowledge of different forms of energy, electric charge, current, voltage
- Knowledge of how to draw a graph
- Knowledge of electrical circuits
- Geographical latitude, angle of the sun

Learning objectives

In this investigation your students will learn:

- How electrical power production depends on the intensity of the energy input
- Measuring short circuit current
- Energy conversion
- Solar radiation depends on the geographical latitude

Outlook

This investigation may serve as a starting point for a variety of different topics, for example:

- How does a solar cell work
- Concept of electrons, atoms etc.
- Semiconductors
- Renewable energy
- Resources
- Generation of electrical energy

5.1.2 Time Table

The amounts of time are rough estimates.

Task	Time
Preparation prior to class	10 min
Introduction	15 min
Investigation (group work)	35 min
Time students will need to answer questions	45 min

Table 5-1 Schedule

5.1.3 Teaching Method

Method	Suitability
Group work	✓✓✓✓
Chalk and talk	✓✓
Silent work (student questions)	✓✓
Homework (student questions)	✓✓✓✓

Table 5-2 Teaching method (✓= poor … ✓✓✓✓=very good)

5.1.4 Background

Individual solar cells convert the radiant energy of sunlight into electricity. The solar panel provided with the Model Car kit consists of several solar cells connected in series. The panel can generate enough electricity to power the electrolyzer of the Model Car kit.

Solar cells are examples of useful electrical technology as they can transform the sustainable energy of sunlight into electricity. The light source we will be using in our investigations is an incandescent lamp but in practical applications sunlight is used. Throughout the world we have sunlight at various times throughout the day. The sun is earth's nearest star and the sun seems to move across our sky each day. But in fact, earth travels in an orbit around the sun, spinning (once a day) as it goes. However, we often need electrical power when sunlight is not available, for example at night time. This means that if we want to collect the maximum sunlight with a stationary solar cell array, we have to place it in the best position to receive the maximum amount of energy available. If a solar cell is connected to an electrolyzer, the radiant energy of the sunlight can be stored as hydrogen and oxygen gas. A fuel cell can use these gases to make electricity when it is needed.

The principle of a solar cell is that it converts a stream of photons (the radiant energy of sunlight) into a stream of electrons (electricity). The conversion or transfer of energy from one form to electricity is the principle behind any electrical generator. Electrical generators include solar panels, diesel or gas engine generators, hydroelectric turbines and fuel cells.

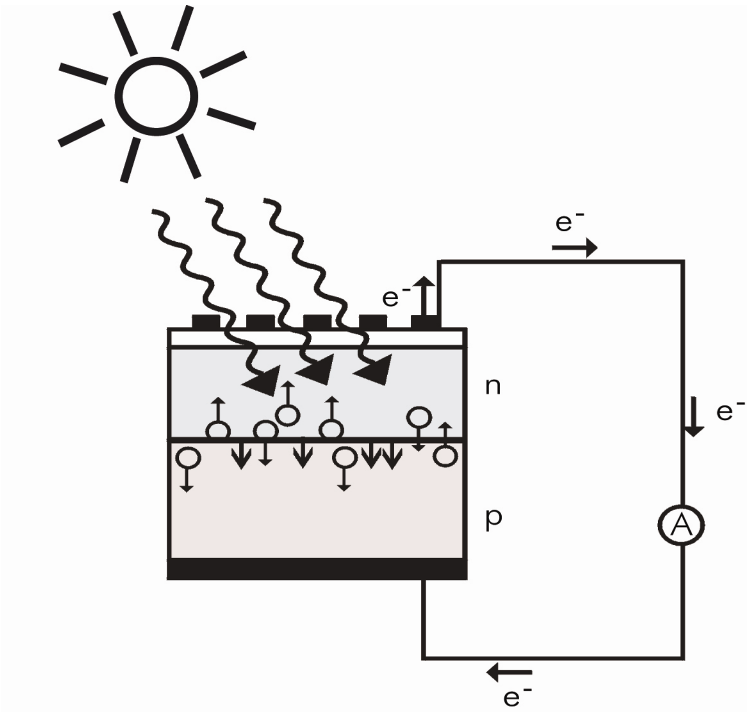


Fig. 5-1 Electron flow in solar cells

A solar cell contains layers of two types of silicon. Photons striking its surface knock electrons loose from one layer. The electrons are drawn to the other layer. If the two layers are connected through an external circuit, electrons will flow through that circuit. The flow of electrons is observed as an electric current. As more light is supplied to the solar cell, more photons are available to knock the electrons loose, and more current is generated.

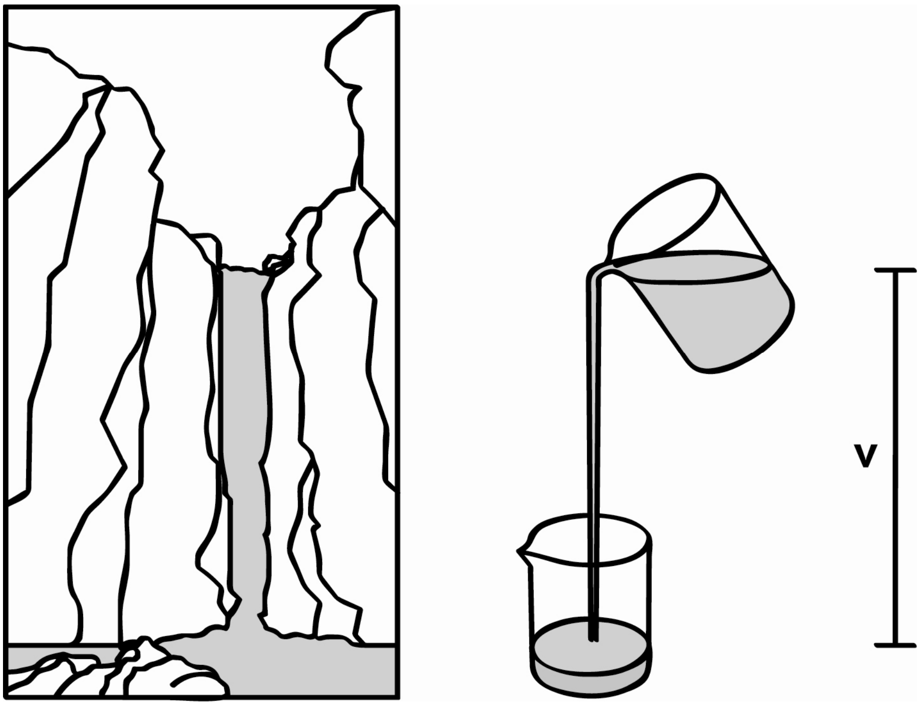


Fig. 5-2 Waterfall as image of current

This flow of electrons may be thought of as similar to a waterfall and has two values that are easily measured. One measurement is like the height of the waterfall, which is a fixed value. In electrical units, this is the electric potential, measured in volts. The other measurement is like the amount of water that falls down the waterfall, and allows us to actually do work with the water. In electrical units, this is called the current, measured in amperes (or simply amps). Thousandths of an ampere are called milliamperes, or mA.

5.2 The Investigation – Teachers

In this investigation the solar panel is connected to the load measurement box in order to obtain data illustrating the relationship between light intensity and current.

5.2.1 Preparation

Before class

Try out the investigation before class to ensure that the light source can be positioned so it will provide even illumination and steady, reproducible current from the solar panel, see *STUDENT'S SECTION* on page 39.

TIP

For group work it may be helpful to provide a large protractor, which students can place on the workbench as they adjust the solar panel. A template of such a protractor is provided here for you to copy, see *FIG. 5-10* on page 45.

5.2.2 In Class

Depending on your didactic approach and the number of solar panels at hand, you may either choose group work or chalk and talk teaching. Group work has the advantage to make science more tangible and understandable. Chalk and talk has the advantage that you need only one Model Car kit and you can lead your students more directly.

Safety

- ➔ Always make your students aware of investigating safely and make yourself familiar with the potential hazards.

For either approach a short introduction may be helpful.

Introducing the topic

With this short demonstration you can give an introduction to the investigation on the solar panel:

- ✓ Flashlight
- ✓ Chalk and chalk board

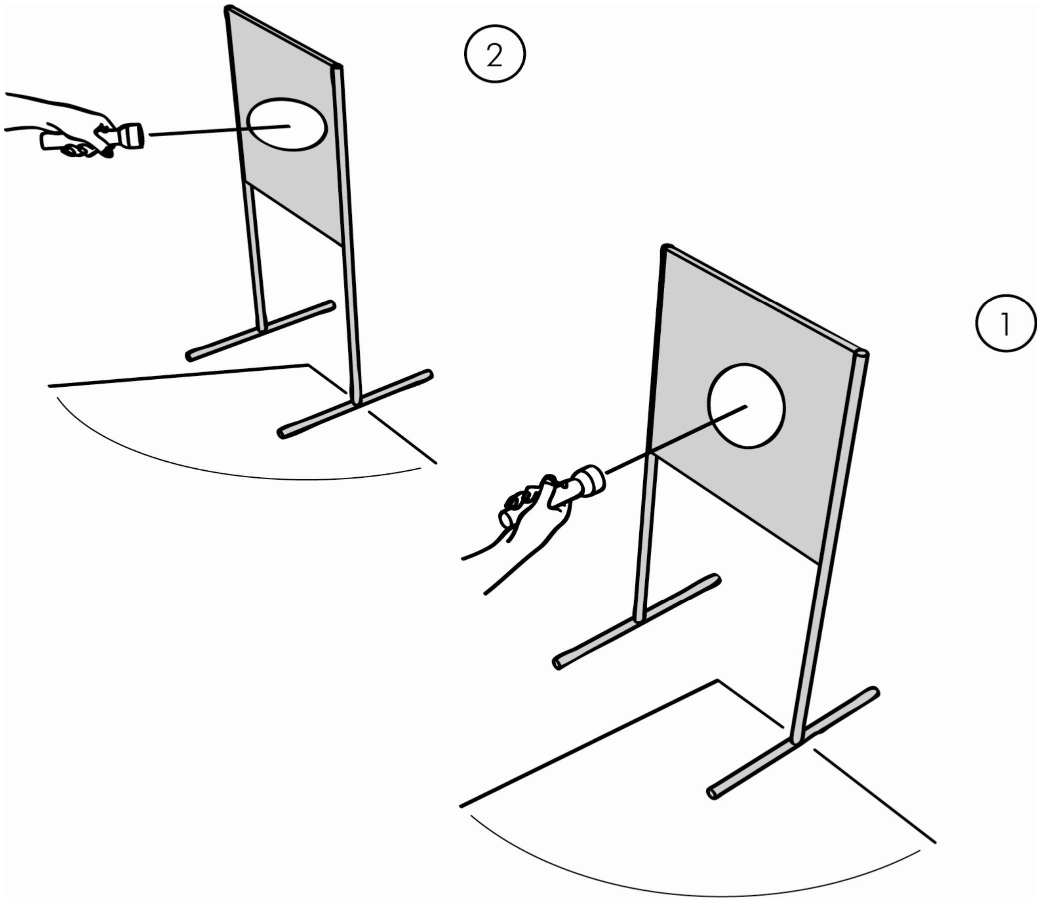


Fig. 5-3 Demonstrating the angle of incidence

1. Shine a flashlight directly at a chalkboard (see ①), so that it is exactly 1 meter away from the board and the angle at which the light strikes the chalkboard is 0 degrees (perpendicular, straight-on).

The angle of incidence is 0 degrees at a distance of 1 meter.

2. Mark the outline of this circular spot of light in chalk (see ①).
3. Change the angle of incidence to 45 degrees (see ②).
4. Mark the outline of the ellipse (see ②).
5. Have the students calculate the areas inside the ellipse / circle.

   The area of an ellipse is calculated: $A = (\pi/4) \times d \times D$
   The area of a circle is calculated: $A = \pi \times r^2$

6. Have the students compare the density of photons hitting the circle surface with the density of photons hitting the ellipse surface, assuming that the number of photons, the flashlight emits is constant.

   The density is the number of photons per area, since the number of photons is constant and since the origin of the photons is the same (same flashlight). The larger the area becomes, the smaller is the density of photons.

7. Let your students predict in which way the angle of incidence will influence the output of the solar module in the following investigation.

5.2.2.2 Group Work

In section *HOW CAN WE MAXIMIZE THE ELECTRICAL POWER COMING FROM THE SOLAR PANEL?* on page 39 you will find a description of the students' investigation.

For group work several Model Car kits are required.

➔ Distribute them among the students and have them work in small groups.

The questions on the investigation provided in section *HOW CAN WE MAXIMIZE THE ELECTRICAL POWER COMING FROM THE SOLAR PANEL?* on page 39 are designed for group work. While experimenting, the students are encouraged to question their actions and to write down their findings in a manner enabling them to make further assumptions and conclusions.

TIP

Remind your students to check the distance to the center of the panel each time so distance from the light source does not become another variable.

5.2.2.3 Chalk and Talk

➔ Do the investigation in front of the students and design the demonstration in such a manner that the students may participate with suggestions, assumptions and discussions, making the demonstration more engaging.

Investigation

- ✓ Solar panel
- ✓ Load measurement box
- ✓ Two patch cords, red and black
- ✓ 100–120 watts PAR lamp, or equivalent light source
- ✓ Measuring tape
- ✓ Protractor to measure angles (or make your own paper protractor from the template on page 45)

In this investigation, maximizing the current is not important. A current in the range 100–150 mA is sufficient. Probably this current will be obtained at 30–40 cm distance. Avoid lighting which has bright "spots" as slight movements of the light or panel will produce erratic changes in the current.

⚠ CAUTION
Hot surface of solar panel and lamp!
Skin burns.
➔ Do not touch the hot surface of the solar panel or lamp.
➔ Allow solar panel / lamp to cool down before touching it.

⚠ CAUTION
Ignition of hydrogen!
Skin burns and damage to the fuel cell.
➔ No open flames.
➔ No smoking.
➔ Well ventilated workspace.

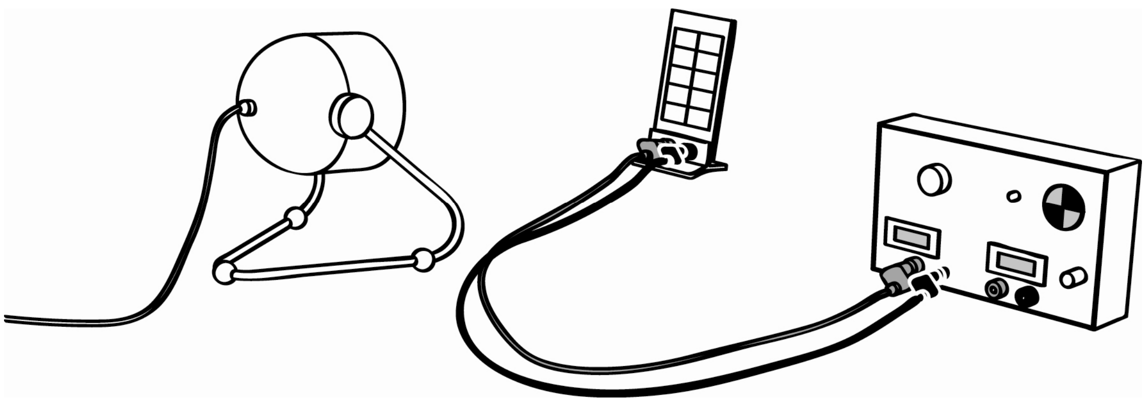


Fig. 5-4 Set up solar panel and load measurement box

1. With the patch cords connect the solar panel to the load measurement box current terminals – red to red and black to black.
2. Position the light source.
3. Turn the selectable *LOAD* knob to *SHORT CIRCUIT*.
4. Press the *ON / OFF button*.

5. Check if a number appears in the "A" window. If nothing appears, check your connections. If a negative number appears, you have the connections reversed and need to change them.

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light.

6. Adjust solar panel and light source so they are about 40 cm apart and the angle of incidence is exactly at 0 degrees. That is, the panel faces directly towards the light source.
7. Turn on the light.
8. Move the light towards or away from the solar panel, keeping the angle of incidence at 0 degrees, until the current shown in the "A" window is between .100 and .150 amperes. To prevent the solar panel from getting too hot, do not bring the light closer than 20 cm (8 inches).

Student participation

9. Have a student read out the current and measure the distance.

   Current: 150 mA
   Distance between the light and solar panel: 40 cm

TIP

The maximum current at 0 degrees will vary with lamp and distance, but the proportional change in current will be the same.

10. Have another student write down the results in a table on the chalk board.

TIP

Notice that the displayed number has a leading decimal point. For example the number .105 A represents a little more than a tenth of an ampere, or 105 milliamperes.

11. Place the solar panel so that the angle of incidence is exactly 90 degrees from the light source, taking care to keep the center of the solar panel exactly the same as before.

Student participation

12. Have a student write down the current displayed in the ammeter.
13. From the results so far, have the students predict what the current is at an angle of 10 degrees.
14. Have a student write down the predictions in the table on the chalk board.
15. Using the protractor template, have a student adjust the angle of incidence of the solar panel to 10 degrees still keeping the center of the solar panel exactly the same as before.
16. Have student record the actual current in the table on the chalk board.

Angle of inciden-ce (degrees)	**Predicted Current (mA) linear**	**Actual Cur-rent (mA)**
0°	–	150
10°	133	148
20°	117	143
30°	100	130
40°	83	123
50°	67	108
60°	50	88
70°	33	63
80°	17	38
90°	–	10

Table 5-3 Angle of incidence – sample of possible solutions (values are examples and can vary)

TIP

For advanced students point out the cosine relation of current and angle and have them additionally predict the values for the cosine relationship.

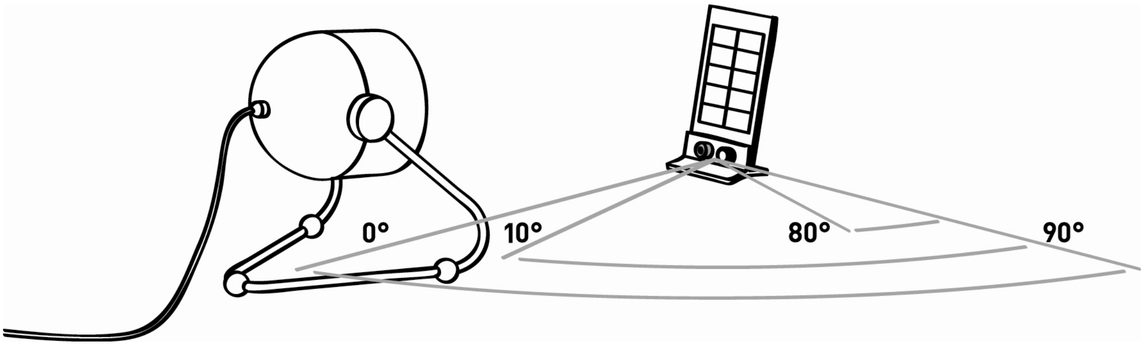


Fig. 5-5 Setting up the solar panel

17. Have students continue predicting and measuring in this way at 10 degree intervals until they reach 80 degrees.

Student participation

18. When they have made and recorded the measurements, have the students use the data from *TABLE 5-4 ANGLE OF INCIDENCE* to draw a graph indicating the findings.

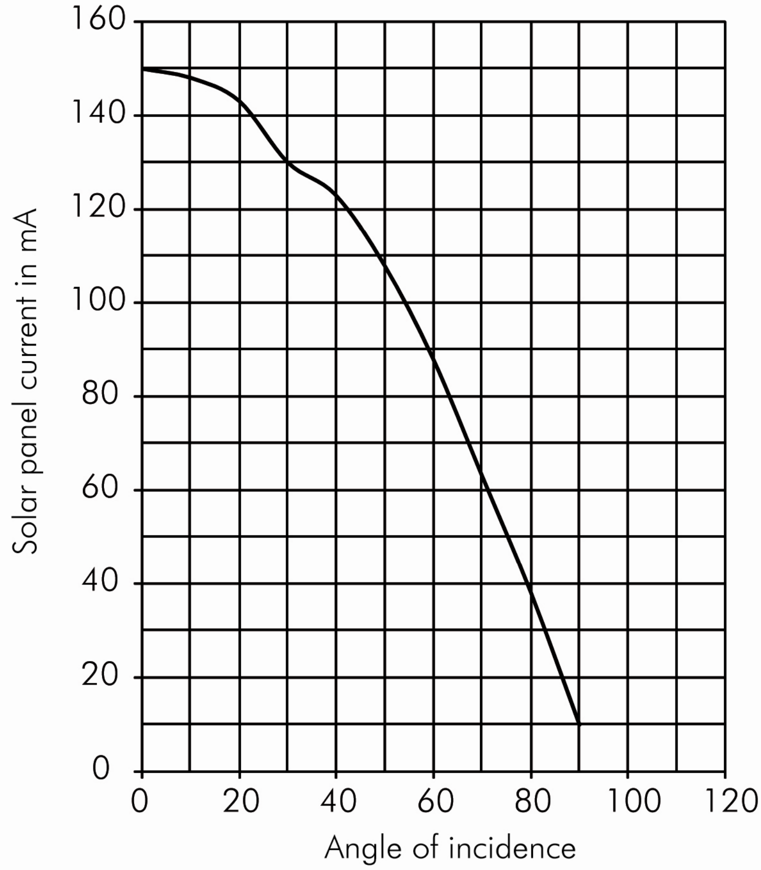


Fig. 5-6 Current as a function of the angel of incidence (results)

5.2.2.4 Silent Work

The students can be encouraged to answer the questions in section *QUESTIONS – STUDENTS* on page 44 in silent work or partner work. This depends on the students' abilities and your teaching approach.

5.2.2.5 Homework

The questions provided in section *QUESTIONS – STUDENTS* on page 44 can be used for homework as well, if the students do not need the teacher's assistance to answer them.

5.2.3 Questions and Answers

1. What is an ampere? What is a milliampere?

   An ampere is a measurement of electrical current . A milliampere is one one-thousandth of an ampere.

2. Is the milliampere a useful measure to see at which angle the solar panel works best?

   The milliampere is a useful measure of the best working angle of the solar panel as it is a small measure suited to the solar cell array and it is sensitive enough to allow us to see how the angle of incidence of the light source affects the current flowing from the solar panel.

3. What did you find out about the orientation of your solar panel to the light source?

   I found out that as the light source changed from a low angle of incidence to a higher angle of incidence, the current decreased.

4. Why is it important to keep the center of the solar panel exactly the same distance away from the light source for each different angle? Is this important when using sunlight as a source?

   It is important to keep the center of the solar panel exactly the same distance away from the light source for each different angle if we want to compare all the results. When we use sunlight as the light source, the sun is so far away from the solar panel that the distance on our tabletop is insignificant.

5. How did your prediction for the 10-degree angle compare with your actual result? How did you adjust your predictions for the other angles? Did they become more accurate as a result of your actual measurements?

   My prediction for the 10-degree angle was different from my actual result. I thought there would be a greater difference. The differences between each measurement grew larger as the angle of incidence increased so I increased the differences each time.

6. With your graph could you make a fairly accurate prediction of the current for 25 degrees or 75 degrees? Is there any way to check your predictions for 25° and 75°?

   We could check my predictions for 25 degrees and 75 degrees by actually doing it and getting the results from the ammeter.

7. To obtain the maximum current, we aimed the light source and the solar panel along the same line. The sun appears to move both horizontally and vertically. What would you need to know before you permanently attached a solar panel on top of your school?

I would need to determine my latitude and where geographic south is before I permanently attached a solar panel on top of my school. It would be like setting the position of a sundial.

8. Will the rate of electrical energy production be the same for every day of the year? Why or why not? How could you plan for this? Would your solution necessarily be a practical one?

   The rate of electrical energy production will not be the same for every day of the year because of the weather or time of the year. I might be able to make a motorized mount for a solar panel that would automatically track the sun wherever it is or find the brightest spot in an overcast sky. It might be too expensive to set it up this way and might present more problems or things that could go wrong.

9. How can we maximize the electrical power coming from the solar panel?

   We can maximize the electrical energy coming from the solar cell if we position it correctly.

Student's Section

5.3 Student's Section

In this investigation you will examine the influence the angle of incidence of the light source has on the electrical power coming from the solar panel.

5.3.1.1 How Can We Maximize the Electrical Power Coming from the Solar Panel?

➔ Wear goggles when experimenting.

✓ Solar panel
✓ Load measurement box
✓ Two patch cords, red and black
✓ 100–120 watts PAR lamp, or equivalent light source
✓ Measuring tape
✓ Protractor to measure angles (or make your own paper protractor from the template on page 45)

Safety

⚠ CAUTION
Hot surface of solar panel and lamp!
Skin burns.
➔ Do not touch the hot surface of the solar panel or lamp.
➔ Allow solar panel / lamp to cool down before touching it.

⚠ CAUTION
Ignition of hydrogen!
Skin burns and damage to the fuel cell.
➔ No open flames.
➔ No smoking.
➔ Well ventilated workspace.

1. With the patch cords connect the solar panel to the load measurement box CURRENT terminals – red to red and black to black.

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light.

2. Position the light source.
3. Turn the selectable *LOAD* knob to *SHORT CIRCUIT*.

Press the *ON / OFF* button.

4. Check if a number appears in the "A" window. If nothing appears, check your connections. If a negative number appears, you have the connections reversed and have to change them.

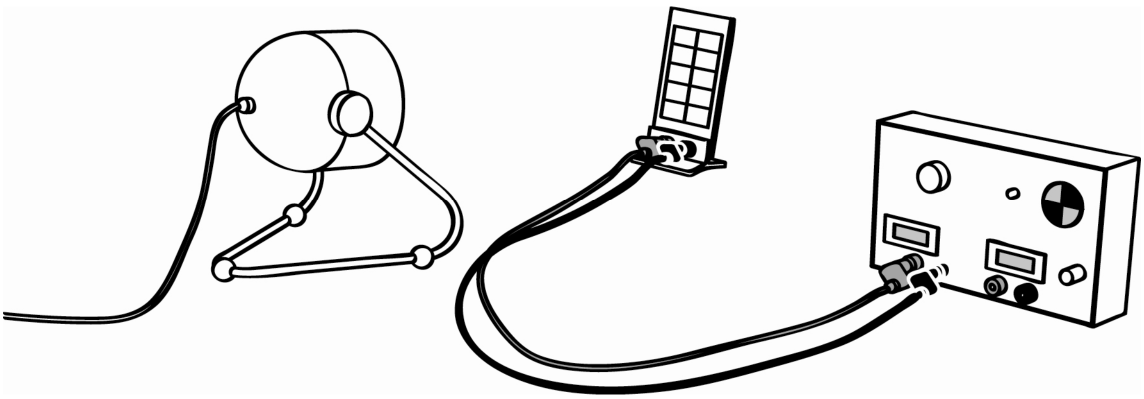


Fig. 5-7 Set up solar panel and load measurement box

5. Adjust solar panel and light source so they are about 40 cm apart and the angle of incidence is exactly at 0 degrees. That is, the panel faces directly toward the light source.
6. Turn on the light.
7. Move the light towards or away from the solar panel, keeping the angle of incidence at 0 degrees, until the current shown in the "A" window is between .100 and .150 amperes. To prevent the solar panel from getting too hot, do not bring the light closer than 20 cm (8 inches).

Get results!

8. Measure this distance and write it down.
9. Write the current displayed in the ammeter into the table below.

TIP

Notice that the displayed number has a leading decimal point. For example the number .105 A represents a little more than a tenth of an ampere, or 105 milliamperes.

Angle of incidence [degrees]	**Predicted current [mA]**	**Actual current [mA]**
0°		
10°		
20°		
30°		
40°		
50°		
60°		
70°		
80°		
90°		

Table 5-4 Angle of incidence

10. Place the solar panel so the angle of incidence is exactly 90 degrees from the light source, taking care to keep the center of the solar panel exactly the same as before.
11. Write down the current displayed in the ammeter window.

From the results so far, you may predict what the current is at an angle of 10 degrees:

12. What do you think the current will be at a 10-degree angle of incidence. Write down your prediction in *TABLE 5-4 ANGLE OF INCIDENCE*.
13. Using your protractor template (see *FIG. 5-10* on page 45), adjust the angle of incidence of the solar panel to 10 degrees still keeping the center of the solar panel exactly the same as before.
14. Record the actual current in *TABLE 5-4 ANGLE OF INCIDENCE*.

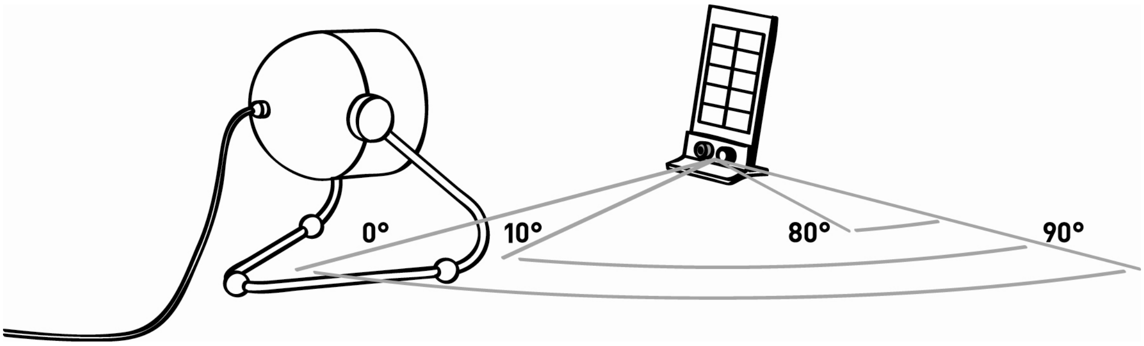


Fig. 5-8 Setting the solar panel

15. Continue predicting and measuring in this way at 10 degree intervals until you reach 80 degrees. Check the distance to the center of your solar panel for each measurement.
16. When you have made and recorded your measurements, use your data to draw a graph indicating your findings in the space below.

Your experimental part is finished – in order to gain more information, you have to process your data further:

17. Using the data from *TABLE 5-4 ANGLE OF INCIDENCE*, fill in your findings into the graph provided below.

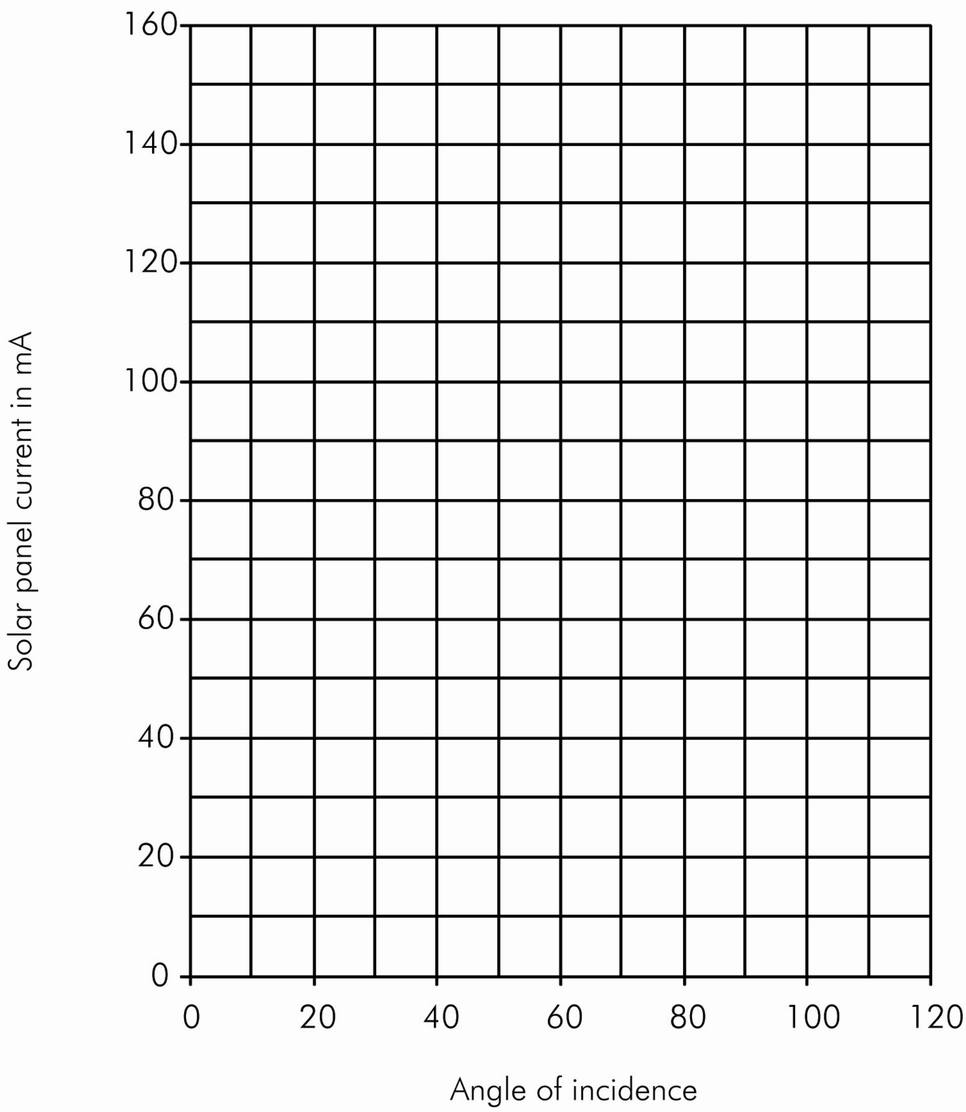


Fig. 5-9 Current as a function of the angle of incidence

Now your investigations and data gathering are finished. You can now go on interpreting your findings and checking your knowledge.

But before doing so:

- ➔ Turn off the light source.
- ➔ Let the solar panel cool down. Then disassemble the equipment carefully and return it.

5.3.2 Questions – Students

Use an extra sheet to answer the question.

1. What is an ampere? What is a milliampere?

2. Is the milliampere a useful measure to see at which angle the solar panel works best?

3. What did you find out about the orientation of your solar panel to the light source?

4. Why is it important to keep the center of the solar panel exactly the same distance away from the light source for each different angle? Is this important when using sunlight as a source?

5. How did your prediction for the 10-degree angle compare with your actual result? How did you adjust your predictions for the other angles? Did they become more accurate as a result of your actual measurements?

6. With your graph could you make a fairly accurate prediction of the current for 25 degrees or 75 degrees? Is there any way to check your predictions for 25° and 75°?

7. To obtain the maximum current, we aimed the light source and the solar panel along the same line. The sun appears to move both horizontally and vertically. What would you need to know before you permanently attached a solar panel on top of your school?

8. Will the rate of electrical energy production be the same for every day of the year? Why or why not? How could you plan for this? Would your solution necessarily be a practical one?

9. What is the answer to the question at the beginning of this investigation: How can we maximize the electrical power coming from the solar panel?

5.3.3 Template for Solar Panel Orientation

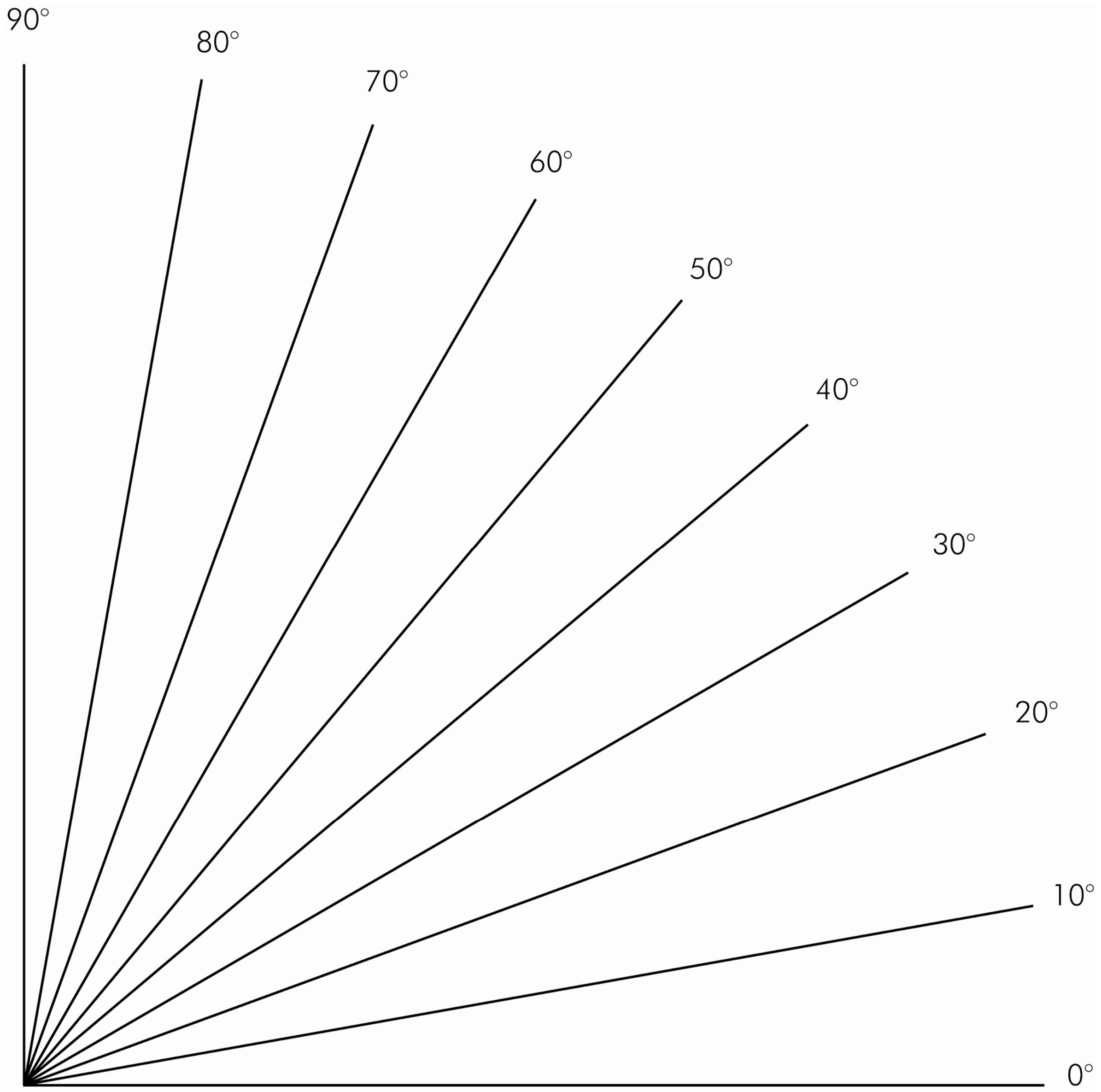


Fig. 5-10 Template for solar panel orientation

6 Simple Electrolysis

In this investigation the process of breaking up a compound will be examined. It will be investigated what happens when electricity flows through water.

The major goal of this investigation is to allow the students to begin to ask questions concerning energy and water. It is not a quantitative investigation that needs to be fully articulated into formulas and reactions as this will be developed in the next two investigations.

6.1 Teacher's Essentials

6.1.1 Objectives

Qualifications

In order to ensure maximum learning success, your students should already be familiar with:

- Electrical characteristics
- Different forms of energy
- Principle of molecules

Learning objectives

In this investigation your students will learn:

- Breaking up of molecules
- Chemical reactions
- Structure and properties of matter
- Behavior of ions
- Electrical charge, anode, cathode
- Electrolytes
- Oxidation, Reduction

Outlook

This investigation may serve as a starting point for a variety of different topics, for example:

- Which processes involve the taking apart of molecules
- Concept of electrons, atoms, etc.
- Renewable energies
- Autoprotolysis of water

6.1.2 Time Table

The amounts of time are rough estimates.

Task	Time
Preparation prior to class	10 min
Investigation	35 min
Time students will need to answer questions	35 min

Table 6-1:Schedule

6.1.3 Teaching Method

Method	Suitability
Group work	✓✓✓
Chalk and talk	✓✓✓✓
Silent work (student questions)	✓✓
Homework (student questions)	✓✓✓

Table 6-2:Teaching method (✓= poor … ✓✓✓✓=very good)

6.1.4 Background

Matter

Matter is made up of small particles that scientists call atoms. Atoms are often combined to form molecules. Ionic compounds such as sodium chloride are composed of particles that form when atoms lose or gain electrons. An element is a substance consisting of atoms of only one type.

Oxygen is an element and each molecule of oxygen is made up of two oxygen atoms joined chemically. In scientific shorthand oxygen is O and a molecule of oxygen is written as O_2.

In the same way, hydrogen is another element and each molecule of hydrogen is made up of two atoms of hydrogen joined chemically. A molecule of hydrogen is written as H_2.

Chemical compounds

A compound is described by its formula. For example, table salt is made up of one atom of the element sodium chemically joined with one atom of the element chlorine. This ionic compound is called sodium chloride. The shorthand for sodium is Na and the shorthand for chlorine is Cl. Therefore the formula for sodium chloride is written NaCl. Water is a compound containing two atoms of the element hydrogen and one atom of the element oxygen. The formula for water is H_2O.

Often, applying energy to a molecule can break it apart. The energy needed is usually heat, light, or electricity. The pulling apart is a type of change, called a chemical reaction. As the molecule breaks apart, its atoms may re-join to form different substances.

$2\ H_2O \leftrightarrow 2\ H_2 + O_2$

Later, these new substances might be used to make other compounds, or even make the original molecule again, and may give back some of the energy that was used in breaking apart the original molecule.

The Latin suffix -lysis means to dissolve or take apart. Therefore electrolysis is the use of an electron flow to take something apart.

This kind of thinking about the background of an investigation can often help with observations and allow us to understand what we are seeing.

Anode – oxidation

In general, the term anode refers to the electrode where the oxidation reaction takes place; that is, a reaction where there is a loss of electrons.

Cathode – reduction

Similarly, cathode refers to the electrode where the reduction reaction takes place; that is, a reaction where there is a gain of electrons. In this investigation, the electrode attached to the positive (red) side of the solar panel releases oxygen, and is the anode. The other electrode, attached to the negative (black) side of the solar panel, releases smaller hydrogen bubbles and is the cathode.

6.2 The Investigation – Teachers

6.2.1 Preparation

Try out the investigation before class to ensure that everything is working.

6.2.2 In Class

Depending on your didactic approach and the number of solar panels at hand, you may either choose group work or chalk and talk teaching.

Safety

- ➔ Always make your students aware of investigating safely and make yourself familiar with the potential hazards.
- ➔ Make sure to provide the students with goggles and to wear goggles yourself.

> ⚠ **CAUTION**
>
> **Ignition of hydrogen!**
>
> Skin burns and damage to the fuel cell.
>
> - ➔ No open flames.
> - ➔ No smoking.
> - ➔ Well ventilated workspace.

6.2.2.2 Group Work

For group work several solar panels are required.

While experimenting, the students are encouraged to question their actions and to write down their findings in a manner enabling them to make further assumptions and conclusions, see page 56.

6.2.2.3 Chalk and Talk

For chalk and talk (only one solar panel required):

It may be useful to magnify the investigation by using (instead of a beaker) a Petri dish placed on an overhead projector.

To save time steps 2.–6. may be done before class or by a student.

Investigation

- ✓ Goggles or eye protection
- ✓ Solar panel or hand generator

TIP
As an alternative to the solar panel you may also use the hand generator as a source for electrical energy (see Instruction Manual).

- ✓ Two patch cords
- ✓ Two 10 cm × 5 cm pieces of aluminum foil
- ✓ Pencil
- ✓ Clear 200 mL plastic cup or 250 mL beaker (or Petri dish)

TIP
If you don't have beakers and are using plastic cups, try to use plastic cups wide at the base as they are more stable.

- ✓ 150 mL distilled water
- ✓ 1 tablespoon of table salt
- ✓ 100–120 watts PAR lamp, or equivalent light source, or bright sunlight
- ✓ Utility tape to fasten aluminum foil
- ✓ Magnifying glass (optional)
- ✓ Overhead projector and Petri dish (optional)

1. Put on goggles.

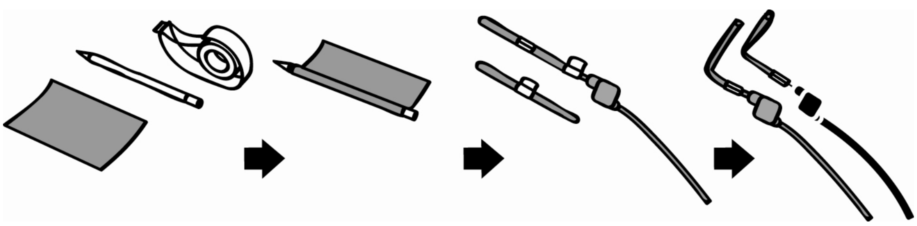


Fig. 6-1 Making simple electrodes

Making anode and cathode

2. Roll a piece of aluminum foil around a pencil.
3. Use a small piece of tape to hold the foil in a cylinder and slide it off the pencil.

4. Place one end of the cylinder over the metal tip of a patch cord, squeeze the foil and wrap that end tightly with tape so it is secure.
5. Flatten the other end of the foil cylinder, forming an electrode.
6. Repeat this step with another piece of foil and the other patch cord.
7. Pour 150 mL of distilled water into a small beaker or clear plastic cup (optionally Petri dish, which you can place onto an overhead projector to magnify the observation).

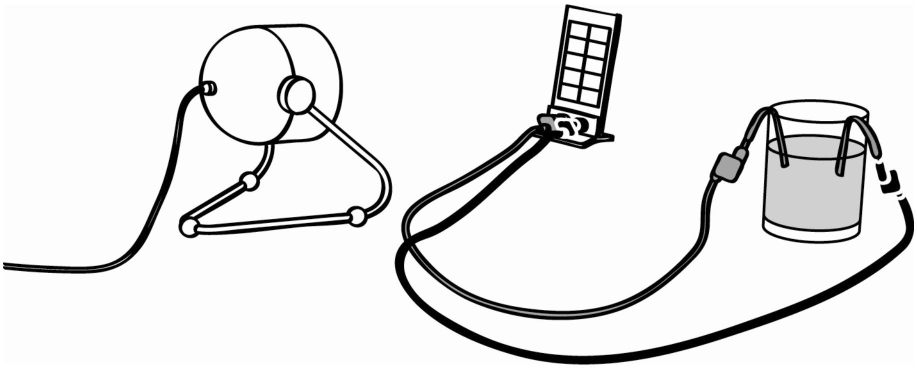


Fig. 6-2 Simple electrolysis

8. Bend the aluminum electrodes and hang them on the edge of the beaker or plastic cup (or Petri dish) with the electrodes immersed in the water. The metal ends of the patch cords should not touch the water directly.

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light.

9. Place the solar panel directly facing the light source, but not closer than 20 cm (8 inches).

⚠ **CAUTION**

Hot surface of solar panel and lamp!

Skin burns.

➔ Do not touch the hot surface of the solar panel or lamp.

➔ Allow solar panel / lamp to cool down before touching it.

10. Turn on the light, but do not connect the patch cords yet.

Student participation

11. Ask the students what they think is going to happen when the patch cords are connected to the solar panel and why?

    Electricity will pass through the water. Maybe it will break up the water into hydrogen and oxygen.

Electrolysis

12. Connect the patch cords to the solar panel – red to red and black to black. The connectors on the solar cell are colored in the usual way: red is positive, black is negative.

Student participation

13. Have the students observe what is happening under the water on the surface of each electrode. Let them make suggestions and hypotheses about what is happening.

    Nothing happens.

Explanation: No current flows in distilled water.

⚠ **CAUTION**

Formation of chlorine!

Irritations of skin and respiratory organs.

➔ Do not add more than one tablespoon of salt to 150 mL of distilled water. If too much salt is added, chlorine may form.

14. Lift the electrodes out of the water and set them aside. Add 1 tablespoon of ordinary table salt to the water and stir until the salt is completely dissolved.
15. Replace the electrodes in the water, now a salt solution.

Student participation

16. Have the students observe what is happening under the salt solution on the surface of each electrode. You may use a magnifying glass.

    Small bubbles are rising from the black electrode. Larger, fewer bubbles are rising from the red electrode.

Explanation: The water now contains ions which can conduct electricity. There are small bubbles (of hydrogen) at the black electrode (cathode) and larger, fewer bubbles (of oxygen) at the red side (anode).

17. Remove the electrodes from the salt solution and pull them off the patch cords.
18. Dispose of the aluminum foil responsibly.
19. Empty the salt-water solution and wash the cup or beaker so it is ready for use again.
20. Disconnect the patch cords.

6.2.2.4 Silent Work

The students can be encouraged to answer the questions in section *QUESTIONS* on page 59 in silent work or partner work. This depends on the students' abilities and your didactic approach.

6.2.2.5 Homework

The questions provided in section *QUESTIONS* on page 59 can be used for homework as well, if the students do not need the teacher's assistance to answer them.

6.2.3 Answers to the Student Questions

1. What is the reason for ensuring the solar panel is perpendicular to the light source and no closer than 20 cm?

    The solar panel is placed perpendicular to the light so the greatest amount of energy can be gained from the light source. The light source must be at least 20 cm away from the solar panel to avoid overheating.

2. Why is salt added to the water and how does it change. What happens when the electrodes are under the water and connected to the solar panel?

    Salt is added to the water to allow electricity to flow through it. When it is added the electricity begins to flow and bubbles begin to appear on the surface of the aluminum foil electrodes.

3. During electrolysis, the electrode attached to the black patch cord is called the CATHODE. Is the cathode positive or negative with respect to the other electrode?

    The cathode is more negative than the other electrode.

4. During electrolysis the electrode attached to the red patch cord is called the ANODE. Is the anode positive or negative with respect to the other electrode?

   The anode is more positive than the other electrode.

5. When the patch cords were connected to the solar panel what did you notice happening at the cathode when you observed carefully?

   When I connected the patch cords to the solar panel I noticed that the cathode was giving off lots of very small bubbles.

6. Was the same thing happening at the anode? What do you think is the reason for any differences in your observations?

   When I looked at the anode after connecting the patch cords to the solar panel I noticed that larger bubbles were forming on it but they didn't come to the surface as often. I think that there were different gases being produced at each electrode.

7. What evidence do we have that water can be taken apart using electricity?

   We have seen that when electricity flows through water, different gases are produced at the two points where the current enters the water. Probably these gases are the elements that water is composed of.

8. Looking at the scientific formula for water, H_2O, what do you think happened in this investigation? How can you be sure?

   Water is made up of two elements, hydrogen and oxygen. Both are gases and when water is taken apart by electricity the gases bubble up from the electrodes and escape into the air. I think we could collect the gases and test them to be sure of what they are.

9. What questions do you now have about this process?

Accept any questions the students suggest. The students may want to know what would happen if we used stronger light or more solar panels or added something else to the water such as sugar or more salt in the water or whatever they suggest. Some may notice that the gases seem to be coming off in a different manner with more rapid bubbling, smaller bubbles, and such.

The process here is to encourage questions beyond the immediate experience so as to allow the natural curiosity of the student to suggest further investigation that may be part of these experiences or extras that may add greatly to the unit. It may be helpful to ask questions during the investigation that would promote such questions.

10. What is the scientific name for this process?

    The scientific name for taking water apart by using electricity is electrolysis.

6.3 Student's Section

In this investigation you will learn whether it is possible to take apart water with electrical energy or not.

6.3.1 Can Electricity Take Apart Water?

In this investigation you will apply electrical power to water / salt solution and observe the findings.

Safety

➔ Wear goggles when experimenting.

⚠ **CAUTION**
Ignition of hydrogen! Skin burns and damage to the fuel cell. ➔ No open flames. ➔ No smoking. ➔ Well ventilated workspace.

- ✓ Goggles or eye protection
- ✓ Solar panel or hand generator

TIP
As an alternative to the solar panel your teacher may also ask you to use the hand generator as a source for electrical energy (see Instruction Manual).

- ✓ 2 patch cords
- ✓ Pencil
- ✓ 2 10 cm × 5 cm pieces of aluminum foil
- ✓ Clear 200 mL plastic cup or 250 mL beaker
- ✓ 150 mL distilled water
- ✓ 1 tablespoon of table salt
- ✓ 100–120 watts PAR lamp, or equivalent light source, or bright sunlight

- ✓ Utility tape to fasten aluminum foil
- ✓ Magnifying glass (optional)

1. Put on goggles.

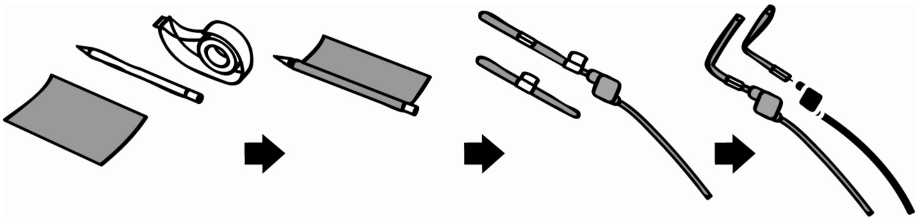


Fig. 6-3 Material for simple electrodes

Making anode and cathode

2. Roll a piece of aluminum foil around a pencil.
3. Use a small piece of tape to hold the foil in a cylinder and slide it off the pencil.
4. Place one end of the cylinder over the metal tip of a patch cord, squeeze the foil and wrap that end tightly with tape so it is secure.
5. Flatten the other end of the foil cylinder, forming an electrode.
6. Repeat this step with another piece of foil and the other patch cord.
7. Pour 150 mL of distilled water into a small beaker or clear plastic cup.
8. Bend the aluminum electrodes and hang them on the edge of the beaker or plastic cup with the electrodes immersed in the water. The metal ends of the patch cords should not touch the water directly.

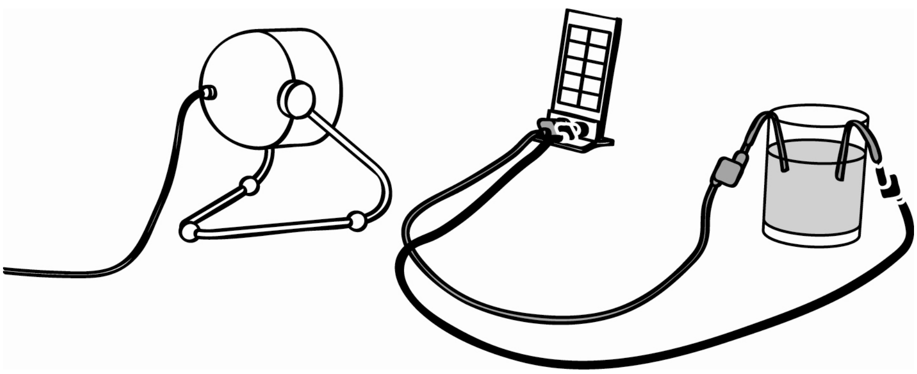


Fig. 6-4 Simple electrolysis

Student's Section

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

➔ Only use light sources with a maximum power of 120 W.

➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.

➔ Do not concentrate light.

9. Place the solar panel directly facing the light source, but not closer than 20 cm (8 inches).

CAUTION

Hot surface of solar panel and lamp!

Skin burns.

➔ Do not touch the hot surface of the solar panel or lamp.

➔ Allow solar panel/ lamp to cool down before touching it.

10. Turn on the light, but do not connect the patch cords yet.

Get results!

11. What do you think is going to happen when you connect the patch cords to the solar panel and why? Make an entry on your lab sheet before you continue.

Electrolysis

12. Connect the patch cords to the solar panel – red to red and black to black. The connectors on the solar cell are colored in the usual way: red is positive, black is negative.

Get results!

13. Observe what is happening under the water on the surface of each electrode and write it down on your lab sheet.

CAUTION

Production of chlorine!

Irritations of skin and respiratory organs.

➔ Do not add more than one tablespoon of salt.

14. Lift the electrodes out of the water and set them aside. Add 1 tablespoon of ordinary table salt to the water and stir until the salt is completely dissolved.
15. Replace the electrodes in the water, now a salt solution.

Get results!

16. Observe and write down what is happening under the salt solution on the surface of each electrode. You may wish to use a magnifying glass.
17. After recording your observations remove the electrodes from the salt solution and pull them off the patch cords.
18. Dispose of the aluminum foil responsibly.
19. Empty the salt-water solution and wash the cup or beaker so it is ready for use again.
20. Turn off the light source and let the solar panel cool down.
21. Disconnect the patch cords and return all equipment as directed by your teacher.
22. Take off your goggles and return them carefully.

6.3.2 Questions – Students

Use an extra sheet to answer the question.

1. What is the reason for ensuring the solar panel is perpendicular to the light source and no closer than 20 cm (8 inches)?
2. Why is salt added to the water and how does it change what happens when the electrodes are under the water and connected to the solar panel?
3. During electrolysis, the electrode attached to the black patch cord is called the CATHODE. Is the cathode positive or negative with respect to the other electrode?
4. During electrolysis, the electrode attached to the red patch cord is called the ANODE. Is the anode positive or negative with respect to the other electrode?
5. When the patch cords were connected to the solar panel what did you notice happening at the cathode when you observed carefully?
6. Was the same thing happening at the anode? What do you think is the reason for any differences in your observations?

7. What evidence do we have that water can be taken apart using electricity?

8. Looking at the scientific formula for water, H_2O, what do you think happened in this investigation? How can you be sure?

9. What questions do you now have about this process?

10. What is the scientific name for this process?

7 Understanding Electrolysis

This investigation is based on the investigation *SIMPLE ELECTROLYSIS*. It can of course be used without its predecessor – depending on your students and your needs.

In this investigation the electrolysis will be studied quantitatively, leading from the mere investigation to a more detailed analysis of what is happening when water is split.

7.1 Teacher's Essentials

7.1.1 Objectives

Qualifications

In order to ensure maximum learning success, your students should already be familiar with:

- Measuring electrical characteristics
- Knowledge of different forms of energy
- Knowledge of the principle of molecules
- Basic principle of electrolysis (see investigation *SIMPLE ELECTROLYSIS*)

Learning objectives

In this investigation your students will learn:

- Quantitative observation of electrolysis
- Breaking up of molecules
- Catalysts
- Electrolyzers
- Faraday's law of electrolysis
- Hydrogen test
- Identification of hydrogen and oxygen
- Exothermic and endothermic reactions

Outlook

This investigation may serve as a starting point for a variety of different topics, for example:

- Which processes involve the taking apart of molecules
- Catalysts

- Concept of electrons, atoms etc.
- Thermodynamics
- Ideal gas law
- Avogadro's constant
- Redox potentials
- Electrochemical series

7.1.2 Time Table

The amounts of time are rough estimates.

Task	Time
Preparation prior to class	30 min
Investigation	45 min
Time students will need to answer questions	45 min

Table 7-1 Schedule

7.1.3 Teaching Method

Method	Suitability
Group work	✓✓✓✓
Chalk and talk	✓✓✓
Silent work (student questions)	✓✓
Homework (student questions)	✓✓✓

Table 7-2 Teaching method (✓= poor … ✓✓✓✓=very good)

7.1.4 Background

In the previous investigation (*SIMPLE ELECTROLYSIS* on page 47) it was shown that electricity flowing through water with a little salt added produced gases at each electrode.

Breaking up water

Electricity is a flow of electrons and this flow needed to have the salt dissolved in the water in order to have these electrons complete their journey through the wires from the anode to the cathode. An interesting extra effect was that along the way the electron flow broke up water molecules to produce the bubbles of gas.

When you look at the formula for water (H_20) you probably have some idea of what these two gases might be. This investigation will introduce another way to break up water with electricity by having it flow through a special piece of equipment called an electrolyzer. The electricity to break up water will come from the solar panel.

Only distilled water

The electrolyzer is quite different from the electrolysis tank in investigation *SIMPLE ELECTROLYSIS* on page 47. We must not contaminate its special membrane by letting it contact damaging chemicals such as table salt. If the membrane becomes contaminated it will not work as well and the electrolyzer will not be able to break up water. Even tap water is not pure enough. You must use pure distilled water when you fill the electrolyzer or you could permanently damage the membrane.

In the previous investigation dissolving salt in water created charged particles called ions. Electricity was able to flow through the water using these ions.

The electrolyzer

The electrolyzer can break up water because it contains a special membrane containing a substance that allows hydrogen ions to jump between molecules and flow in one direction through the membrane.

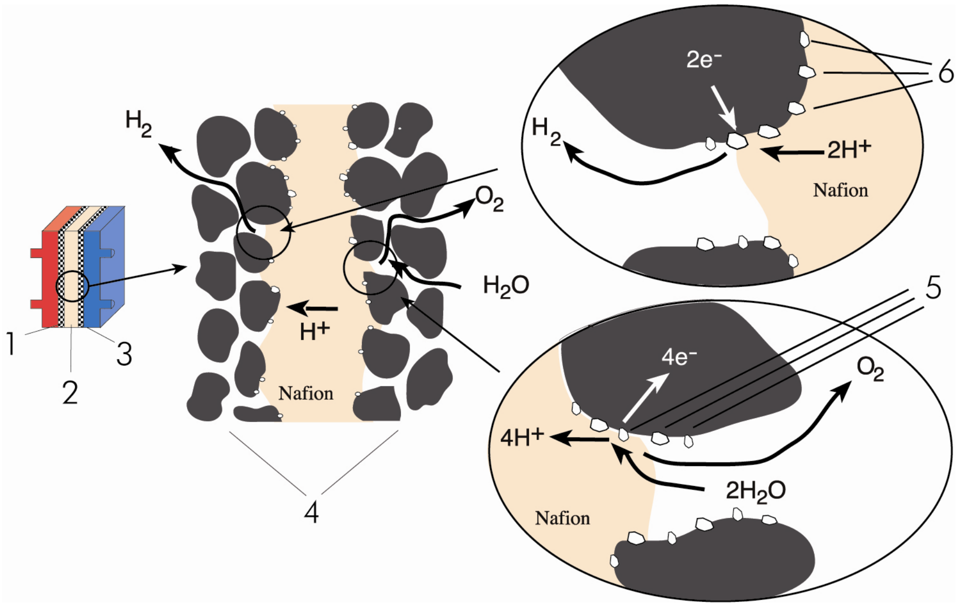


Fig. 7-1 Principle electrolyzer in reversible fuel cell

1	Cathode	4	Carbon layer
2	Polymer electrolyte membrane (Nafion)	5	Platinum catalyst
3	Anode	6	Platinum-iridium catalyst

This substance is held inside two very thin layers of carbon that have had tiny amounts of the element platinum added to them on one side and tiny amounts of platinum plus another element, iridium on the other side. These microscopic amounts of platinum and iridium allow the water molecules to break apart when the membrane is being used as an electrolyzer.

The platinum and iridium do not change in the electrolysis reaction but remain in place to continue helping with the reaction. Substances that change reaction rates but do not change themselves are called catalysts and are a very important part of fuel cells and electrolyzers.

Catalysts

The concept of a catalyst is an important one. Catalysis means the acceleration of a reaction with help of a catalyst, which does not change in the process of the reaction. A baseball bat is used to propel the ball a long distance but hitting the ball does not materially change the bat. Swim fins allow a swimmer to go faster but do not change while they are being worn. These examples are not usually considered catalysts but perhaps you can see how platinum and iridium allow a reaction to happen much faster than if they weren't there. Pure water is very difficult to break apart so the platinum catalyst is needed.

7.2 The Investigation – Teachers

7.2.1 Preparation

It is advisable that you try out this investigation before class.

Since the electrolyzer takes about 10 minutes to fill the hydrogen cylinder with hydrogen and another 5 minutes to fill the test tube with hydrogen (oxygen takes twice as long), it may be helpful to start electrolysis before class.

7.2.2 In Class

Depending on your didactic approach and the number of Model Car kits at hand, you may either choose group work or chalk and talk teaching.

Safety

- ➔ Always make your students aware of investigating safely and make yourself familiar with the potential hazards.
- ➔ Make sure to provide the students with goggles and to wear goggles yourself.

⚠ **CAUTION**

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

- ➔ No open flames.
- ➔ No smoking.
- ➔ Well ventilated workspace.

⚠ **CAUTION**

Ignition of hydrogen!

Skin burns.

- ➔ Perform the investigation with great care since this investigation includes the ignition of hydrogen.

CAUTION

Overpressure in reversible fuel cell!

Injuries due to objects shooting out, when the top of the overflow compartments of the gas storage cylinders is obstructed.

➔ Do not block the top of the overflow compartments of the gas storage cylinders.

➔ Always wear eye protection.

7.2.2.2 Group Work

For group work several Model Car kits are required.

For this investigation it is recommended to undertake the investigation in front of the class prior to having the students perform the investigation themselves.

Make the students aware that while testing the hydrogen a small explosion will take place.

7.2.2.3 Chalk and Talk

For chalk and talk only one Model Car kit is required.

TIP

This investigation is described with the use of the solar panel as the source for electrical energy. In order to speed up the investigation or to demonstrate students how to gain electrical energy from mechanical work, you may use the hand generator. See the Instruction Manual and provide your students with the information.

Investigation

- ✓ Goggles or eye protection
- ✓ Solar panel or hand generator
- ✓ 2 patch cords
- ✓ Reversible fuel cell, used here as an electrolyzer
- ✓ Load measurement box
- ✓ Distilled water
- ✓ 100–120 watts PAR lamp, or equivalent light source
- ✓ 2 small test tubes, 1 cm by 10 cm
- ✓ Matches

- ✓ Wooden splints (thin sticks, approximately 2 mm by 6–10 cm)
- ✓ Tray to place under fuel cell or paper towels
- ✓ Watch

1. Put on your goggles.
2. Place the fuel cell upside down (numbers facing down) on the flat surface.
3. Remove the stoppers.

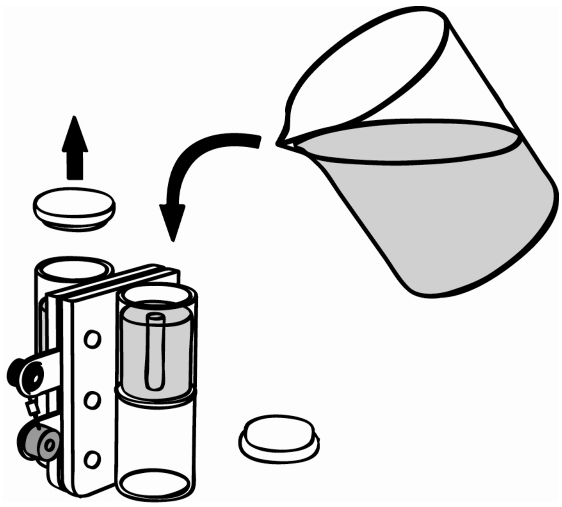


Fig. 7-2 Filling the reversible fuel cell with distilled water

NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the reversible fuel cell.

4. Pour distilled water into both storage cylinders until the water reaches the tops of the small tubes in the center of the cylinders.
5. Tap the fuel cell lightly to help water flow into the area surrounding the membrane and metal current-collecting plates.
6. Add more water until it starts to overflow into the tubes in the cylinders.
7. Place the stoppers back onto the cylinders. Make sure no air is trapped inside the cylinder.

TIP

A small air bubble in the order of 0.5 mL will not cause problems and can be ignored.

8. If the reversible fuel cell has not been used for a while, leave it to rest for 20 min; if has been used recently, turn it right side up.

TIP

Place the fuel cell on a tray or folded paper towels to catch the water that will overflow in the later steps of this investigation.

Student participation

9. Have the students closely watch the top of the small tubes for half a minute to see if any water comes out.

   No water comes up the tubes.

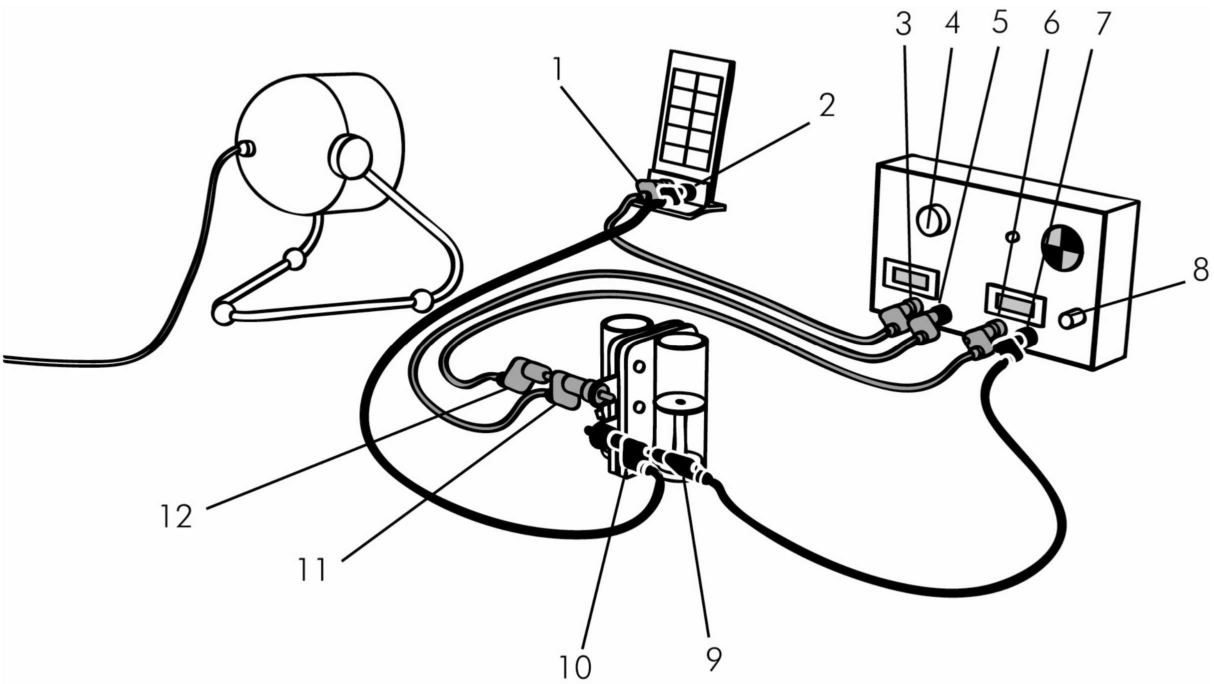


Fig. 7-3 Connecting solar panel, reversible fuel cell and load measurement box

10. Connect the red (positive) terminal of the solar panel (1) to the red (positive) terminal of the ammeter (3).
11. Connect the black (negative) terminal of the solar panel (2) to the black (negative) terminal of the reversible fuel cell (10).

12. Connect the red (positive) terminal of the reversible fuel cell (11) with the black (negative) terminal of the ammeter (5).
13. Connect the black (negative) terminal of the reversible fuel cell (9) with the black (negative) terminal (7) of the voltmeter.
14. Connect the red (positive) terminal of the reversible fuel cell (12) with the red (positive) terminal of the voltmeter (6).
15. Set the *LOAD* knob (4) to *SHORT CIRCUIT*.
16. Push the *ON / OFF* button (8).

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light.

17. Align the solar panel with the light source, keeping a minimum distance of 20 cm (8 inches).

CAUTION

Hot surface of solar panel and lamp!

Skin burns.

- ➔ Do not touch the hot surface of the solar panel or lamp.
- ➔ Allow solar panel/ lamp to cool down before touching it.

18. Turn on the light.
19. Position the solar panel and light so that the current is 150 mA or more, but they are not closer than 20 cm.

Student participation

20. Have a student watch the top of the small tubes again. Have him / her suppose what is pushing the water out?

    Gas, apparently coming from the electrolyzer membrane, is collecting in the top of each storage cylinder, pushing water up the tube into the reservoir.

21. Have the students continue observing and recording the amount of gas collected in each storage cylinder every two minutes.

Time from start [minutes]	**Cathode (black) gas volume [mL]**	**Anode (red) gas volume [mL]**
0	0	0
2	2.5	1
4	5	2
6	7	3.5
8	9.5	5
8:30	10	5

Table 7-3 Gas volumes – example (values are examples and can vary)

22. When 10 mL of gas is collected in one cylinder, have the time recorded and the amount of gas in the other cylinder.

This completes the table.

23. Let the electrolyzer continue working until all the water has moved into the upper portion of one of the cylinders. (With optimum lighting, it will take 5–10 minutes to displace all the water into the upper hydrogen cylinder.)
24. If necessary, add more distilled water to the upper part of the cylinder so it is overflowing.
25. Wash and rinse your hands carefully. Avoid using soap.

Hydrogen test

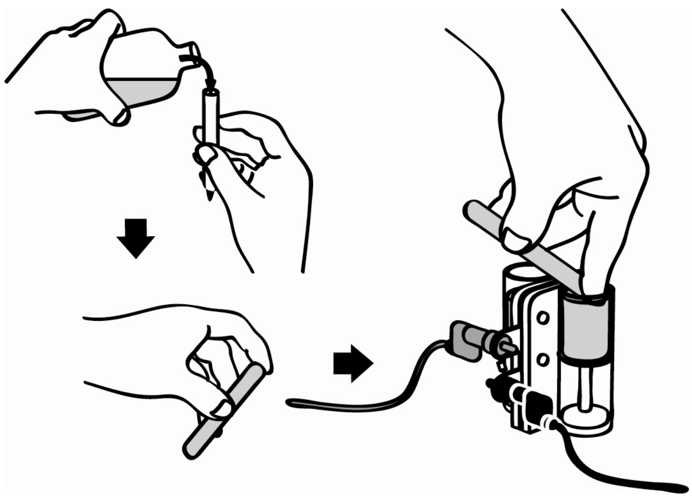


Fig. 7-4 Filling test tubes with hydrogen

26. Completely fill one of the small test tubes with distilled water.

CAUTION

Formation of oxyhydrogen!

Injuries and damage to property due to uncontrolled explosion and breaking glass.

- ➔ To make the explosion in this investigation as small as possible, be sure to keep the amount of air in the test tube smaller than 0.5 mL.
- ➔ Perform the investigation with great care since this investigation includes an explosion.

TIP

A small amount of air, less than 0.5 mL in the test tube will not matter. But if there is more you should repeat the procedure, perhaps asking someone with smaller fingers to help.

27. Cover the end of the tube with your finger, turn the tube upside down and, keeping it covered, place it under the surface of the water as quickly as you can, trying to prevent any air getting into the tube.

TIP

When removing the tube filled with hydrogen from the reservoir, hold it as close to the bottom as you can so that your index finger is extended. When pulled away this will allow the students to see the reaction.

You may want to darken the room so the students can see the light blue flash of the combustion.

- ➔ Do not point the tube at yourself or a student.

28. Remove your finger from the end of the tube and position it so the bubbles of gas will be collected in the inverted test tube.
29. When the test tube is filled with hydrogen, cover the end with your finger, trapping the collected gas, before you remove the tube from the water.

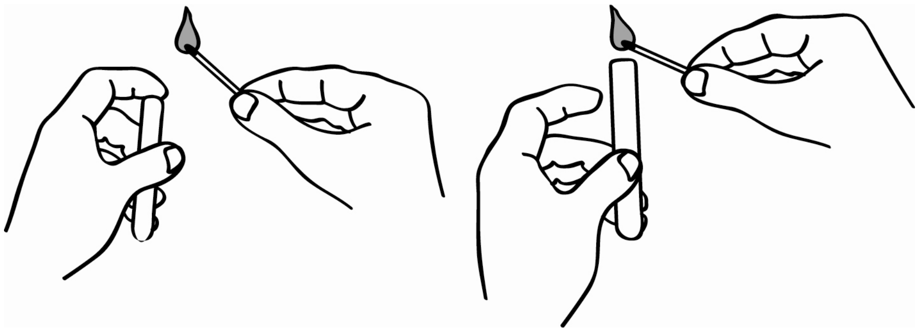


Fig. 7-5 Hydrogen test

30. Still keeping the tube closed, turn it right side up.

> ⚠ **CAUTION**
>
> **Formation of oxyhydrogen!**
>
> Skin burns, cuts from glass fragments.
>
> ➔ Perform the investigation with great care since this investigation includes the ignition of hydrogen.
>
> ➔ Do not point the test tube at anybody.

31. Hold the flame of a lit splint just above the tube and release your finger. There will be a visible and audible reaction.

Student participation

32. Have the students look carefully at the inside of the mouth of the tube immediately after, encourage them to state their investigations.

There was an immediate flash and pop. There appeared to be water condensed inside the mouth of the tube.

Oxygen test

33. When bubbles of gas start to escape in the other cylinder, repeat steps 26, 27 and 28 for the oxygen cylinder.
34. When the test tube is filled with oxygen, cover the end with your finger, trapping the collected gas before you remove the tube from the water.

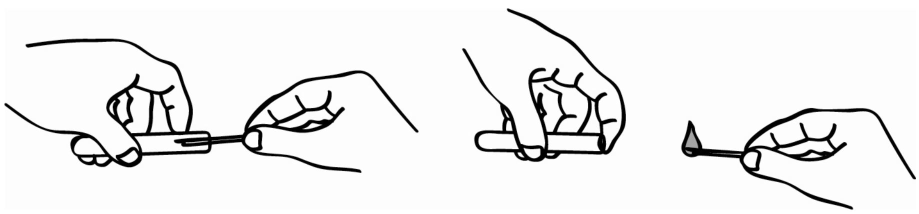


Fig. 7-6 Oxygen test

35. Still keeping the tube closed, hold it horizontally.

CAUTION

Hot test tube!

Skin burns.

➔ Hold the tube in such a way you will not get burned.

TIP

As soon as the splint re-ignites and burns brightly remove it from the tube to show the students it is burning again. Do not insert it a second time into the tube of oxygen. Gases from the vaporized resins, with remaining oxygen could produce a large pop. Although not dangerous, it may cause you to drop the tube.

36. Light a wooden splint and when it is burning well, blow out the flame, leaving a visibly glowing ember on the end of the splint.
37. Quickly release your finger and insert the glowing splint half way into the tube.

Student participation

38. Have the students look carefully at the inside of the mouth of the tube immediately after and encourage them to state their investigations.

    When it entered the tube the glowing splint started to burn again, brighter than it had in air. There was no water inside the mouth of the test tube.

39. Remove the splint and do not insert it again.
40. Disassemble the equipment and put it away.

7.2.2.4 Silent Work

The students can be encouraged to answer the questions in section *QUESTIONS* on page 86 in silent work or partner work. This depends on the students' abilities and your didactic approach.

7.2.2.5 Homework

The questions provided in section *QUESTIONS* on page 86 can be used for homework as well, if the students do not need teacher's assistance to answer them.

7.2.3 Answers to the Student Questions

1. Why is it important to ensure there are no large bubbles of air remaining when we fill the gas storage cylinders with water?

   It is important to ensure there are no large bubbles of air remaining when we fill the gas storage cylinders so we can get an accurate measure of the gas collected.

2. Using the information provided by the labels on the gas storage cylinders, which electrode is attached to which cylinder?

   The H_2 gas-collecting cylinder is attached to the cathode (black, negative) and the O_2 gas collecting cylinder is attached to the anode (red, positive).

3. Is gas produced at similar rates at each electrode? What evidence do you have of this?

   The gases are not produced at similar rates at each electrode. Our table shows that in six minutes we collected 7 mL at the cathode but only 3.5 mL of gas at the anode.

4. What simple ratio can you use for this gas production?

   Our table shows us that for every two milliliters of gas collected at the cathode there is one milliliter collected at the anode. The ratio is 2:1.

5. Why do we test the gas from the cathode first?

   We test the gas collected at the cathode first because it is the gas that is produced more quickly and the test tube will be filled first.

6. Do you have any evidence that the labels on the cylinders are placed on the correct cylinder?

   I think the labels are placed correctly because there is twice as much gas in the hydrogen storage cylinder. The formula for water, H_2O shows that there is twice as much hydrogen as oxygen.

7. Looking at the scientific formula for water, H_2O, what do you think happened in this investigation?

   When I look at the formula for water, H_2O, I think that water is being broken up into hydrogen and oxygen with twice as much hydrogen being produced as oxygen.

8. Use the data from your table to create a simple graph. How much gas would be produced if you ran your electrolyzer for one hour? How long would it take you to collect a liter of cathode gas? Of anode gas?

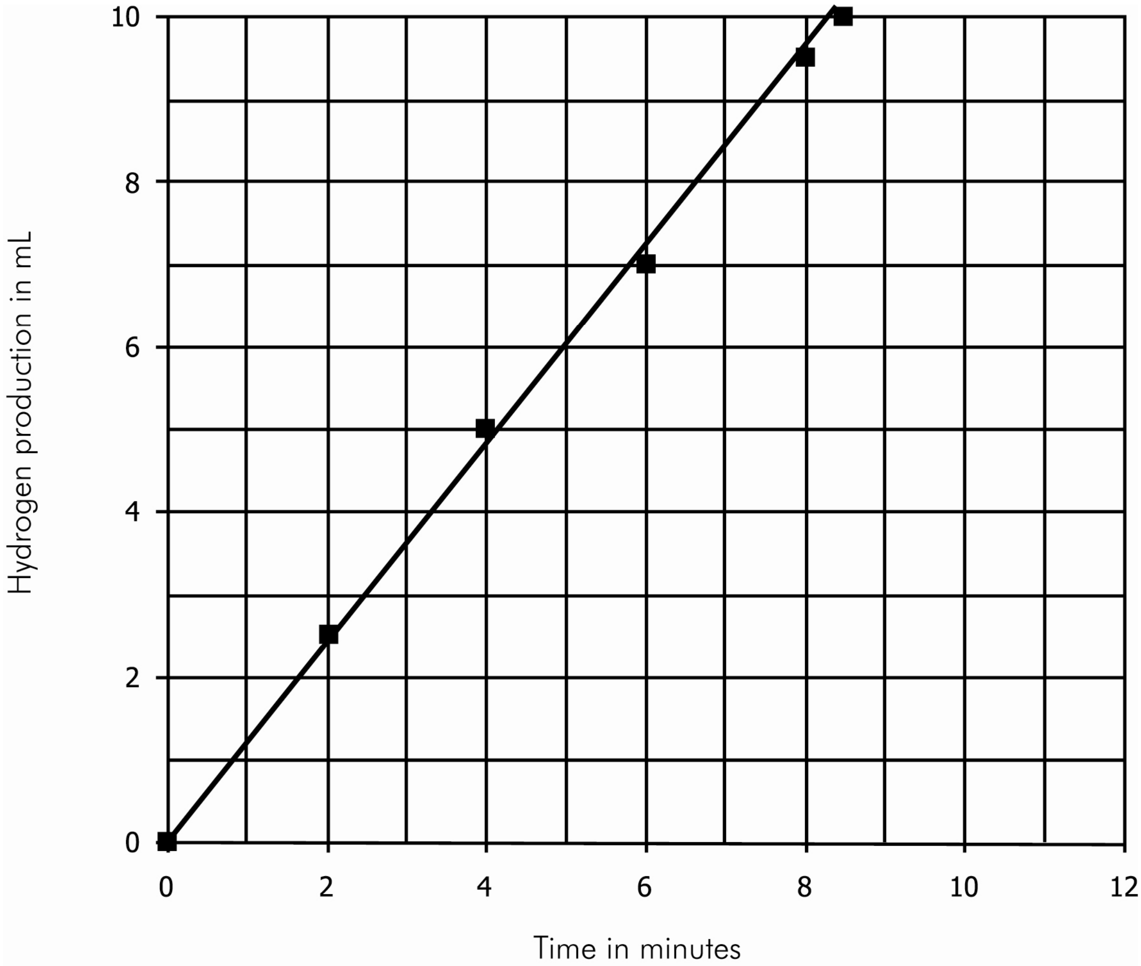


Fig. 7-7 Possible result hydrogen production rate (values are examples and can vary)

10 mL hydrogen was collected in 8.5 minutes. Therefore 71 mL would be collected in 60 minutes. The collection rate is 71 mL/hr.

Collecting a liter of cathode gas (hydrogen) would take 14 hours.

Collecting a liter of anode gas (oxygen) would take exactly twice as long, 28 hours.

9. From the results you obtained from this investigation:
   What is an electrolyzer and what does it do?

   An electrolyzer is a device that allows us to break water into hydrogen and oxygen using electricity. Its solid electrolyte in the membrane between the electrodes makes it work like the simple electrolysis process that used a dissolved-salt electrolyte.

Only when the Simple Electrolysis investigation has been performed

10. Looking back at investigation Simple Electrolysis can you make any inferences about the gases you saw being produced at each electrode? Did you observe any differences when you watched the gases being produced by simple electrolysis and by the electrolyzer?

    I think that in the other electrolysis investigation that hydrogen gas was being produced at the cathode and oxygen gas was being produced at the anode. The bubbles of hydrogen gas appeared smaller in size.

11. Is hydrogen a good name for the gas collected over the cathode?

    As hydrogen means water former it is a good name for this gas which produces water when burned with oxygen.

7.3 Student's Section

In this investigation you will examine electrolysis in a quantitative manner. This means you will observe closely what is going on in the electrolyzer and will offer some suggestions as to what is happening.

7.3.1 What Is an Electrolyzer and What Does It?

You will analyze the products of electrolysis.

Safety

- ➔ Wear goggles when experimenting.

⚠ **CAUTION**

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

- ➔ No open flames.
- ➔ No smoking.
- ➔ Well ventilated workspace.

⚠ **CAUTION**

Ignition of hydrogen!

Skin burns.

- ➔ Perform the investigation with great care since this investigation includes the ignition of hydrogen.

⚠ **CAUTION**

Overpressure in reversible fuel cell!

Injuries due to objects shooting out, when the top of the overflow compartments of the gas storage cylinders is obstructed.

- ➔ Do not block the top of the overflow compartments of the gas storage cylinders.
- ➔ Always wear eye protection.

- ✓ Goggles or eye protection
- ✓ Solar panel or hand generator

TIP

As an alternative to the solar panel your teacher may also ask you to use the hand generator as a source for electrical energy (see Instruction Manual).

- ✓ 2 patch cords
- ✓ Reversible fuel cell, used here as an electrolyzer
- ✓ Load measurement box
- ✓ Distilled water
- ✓ 100–120 watts PAR lamp, or equivalent light source
- ✓ 2 small test tubes, 1 cm by 10 cm
- ✓ Matches
- ✓ Wooden splints (thin sticks, approximately 2 mm by 6–10 cm)
- ✓ Tray to place under fuel cell, or paper towels
- ✓ Watch

1. Put on your goggles.
2. Place the fuel cell upside down (numbers facing down) on the flat surface.
3. Remove the stoppers.

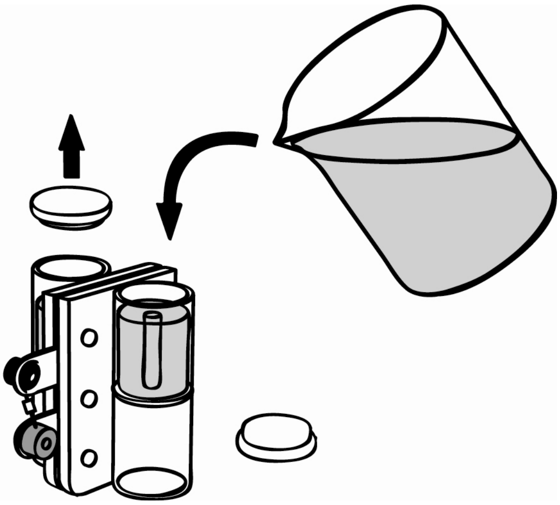


Fig. 7-8 Filling the reversible fuel cell with distilled water

NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the reversible fuel cell.

4. Pour distilled water into both storage cylinders until the water reaches the tops of the small tubes in the center of the cylinders.
5. Tap the fuel cell lightly to help water flow into the area surrounding the membrane and metal current-collecting plates.
6. Add more water until it starts to overflow into the tubes in the cylinders.
7. Place the stoppers back onto the cylinders. Make sure no air is trapped inside the cylinder.

TIP

A small air bubble in the order of 0.5 mL will not cause problems and can be ignored.

8. Turn the fuel cell right side up.

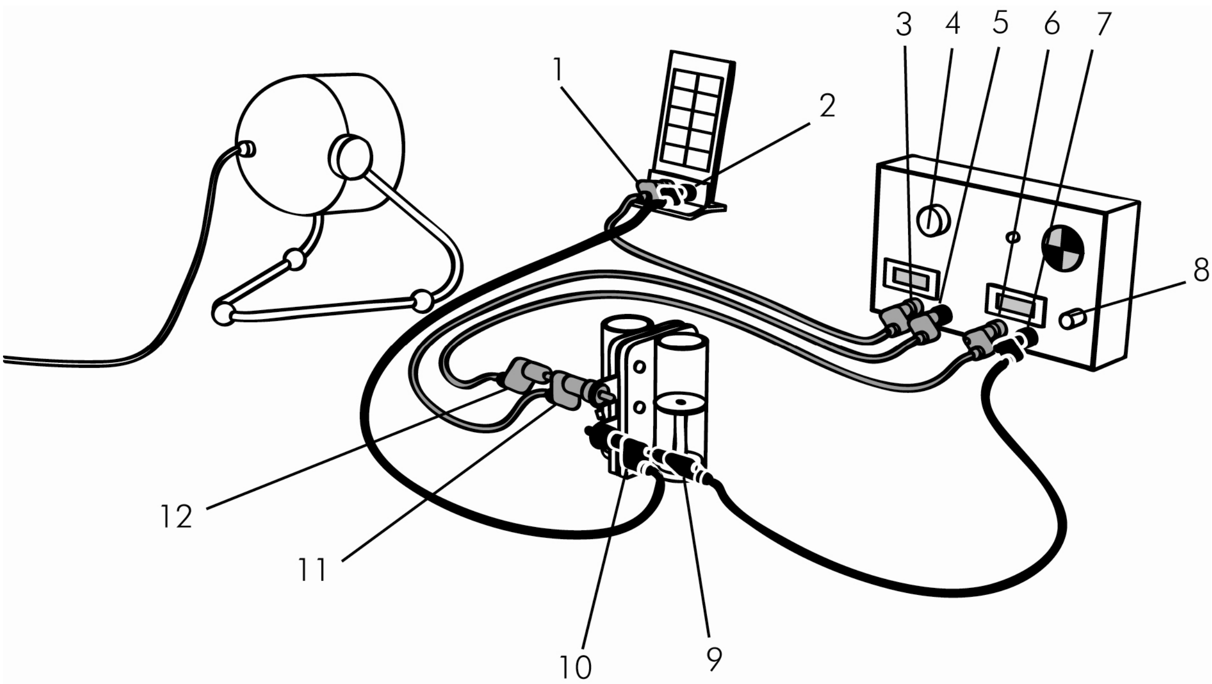


Fig. 7-9 Connecting solar panel, reversible fuel cell and load measurement box

TIP

Place the fuel cell on a tray or folded paper towels to catch the water that will overflow in the later steps of this investigation.

Get results!

9. Watch the top of the small tubes for half a minute. Does any water come out? Write down your observation.
10. Connect the red (positive) terminal of the solar panel (1) to the red (positive) terminal of the ammeter (3).
11. Connect the black (negative) terminal of the solar panel (2) to the black (negative) terminal of the reversible fuel cell (10).
12. Connect the red (positive) terminal of the reversible fuel cell (11) with the black (negative) terminal of the ammeter (5).
13. Connect the black (negative) terminal of the reversible fuel cell (9) with the black (negative) terminal (7) of the voltmeter.
14. Connect the red (positive) terminal of the reversible fuel cell (12) with the red (positive) terminal of the voltmeter (6).
15. Set the *LOAD* knob (4) to *SHORT CIRCUIT*.
16. Push the *ON / OFF* button (8).

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light.

17. Align the solar panel with the light source, keeping a minimum distance of 20 cm (8 inches).

Student's Section

⚠ **CAUTION**

Hot surface of solar panel and lamp!

Skin burns.

- ➔ Do not touch the hot surface of the solar panel or lamp.
- ➔ Allow solar panel/ lamp to cool down before touching it.

18. Turn on the light.
19. Position the solar panel and light so that the current is 150 mA or more, but they are not closer than 20 cm.

Get results!

20. Watch the top of the small tubes for half a minute again. Does any water come out? What do you think pushes the water out? Write down your suggestions.
21. Continue observing and every two minutes record the amount of gas collected in each storage cylinder in *TABLE 7-4*.

Time from start [minutes]	Cathode (black) gas volume [mL]	Anode (red) gas volume [mL]
0		
2		
4		

Table 7-4 Gas volumes

22. When 10 mL of gas is collected in one cylinder, have the time recorded and the amount of gas in the other cylinder.

This completes the table.

23. Let the electrolyzer continue working until all the water has moved into the upper portion of one of the cylinders. (With optimum lighting, it will take 5–10 minutes to displace all the water into the upper hydrogen cylinder.)
24. If necessary, add more distilled water to the upper part of the cylinder so it is overflowing.
25. Wash and rinse your hands carefully. Avoid using soap.

Hydrogen test

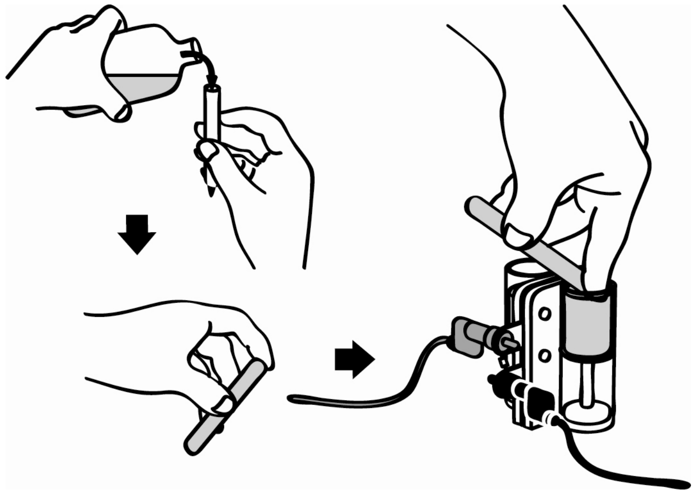


Fig. 7-10 Filling test tubes with hydrogen

26. Completely fill one of the small test tubes with distilled water.

CAUTION

Formation of oxyhydrogen!

Explosion.

- ➔ To make the explosion in this investigation as small as possible, be sure to keep the amount of air in the test tube smaller than 0.5 mL.
- ➔ Perform the investigation with great care since this investigation includes an explosion.

TIP

A small amount of air, less than 0.5 mL in the test tube will not matter. But if there is more you should repeat the procedure, perhaps asking someone with smaller fingers to help!

27. Cover the end of the tube with your finger, turn the tube upside down and keeping it covered place it under the surface of the water as quickly as you can, trying to prevent any air getting into the tube.
28. Remove your finger from the end of the tube and position it so the bubbles of gas will be collected in the inverted test tube.

29. When the test tube is filled with hydrogen, cover the end with your finger, trapping the collected gas, before you remove the tube from the water.

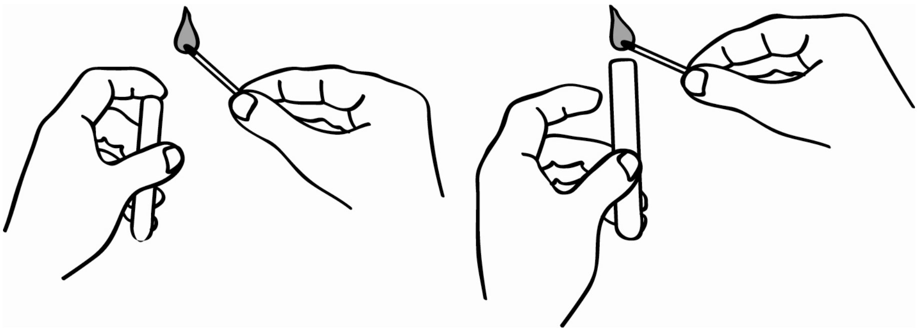


Fig. 7-11 Hydrogen test

TIP

When removing the tube filled with hydrogen from the reservoir, hold it as close to the bottom as you can so that your index finger is extended. Do not point the tube at yourself or anyone else.

CAUTION

Ignition of hydrogen!

Skin burns.

➔ Perform the investigation with great care since this investigation includes the ignition of hydrogen.

30. Still keeping the tube closed, turn it right side up.

CAUTION

Formation of oxyhydrogen!

Skin burns, cuts from glass fragments.

➔ Perform the investigation with great care since this investigation includes the ignition of hydrogen.

➔ Do not point the test tube at anybody.

31. Hold the flame of a lit splint just above the tube and release your finger. There will be a visible and audible reaction.

Get results!

32. Look at the inside of the mouth of the tube immediately after, what do you see? Write down your observation.

Oxygen test

33. When bubbles of gas start to escape in the other cylinder, repeat steps 26, 27 and 28 for the oxygen cylinder.
34. When the test tube is filled with oxygen, cover the end with your finger, trapping the collected gas before you remove the tube from the water.

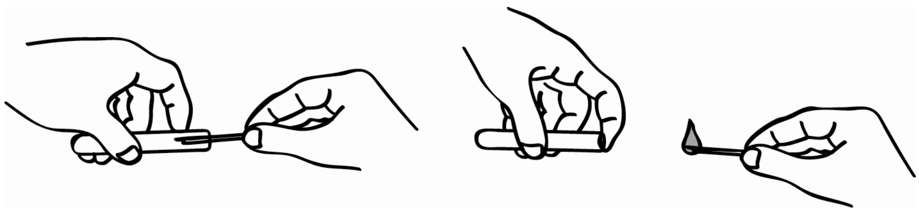


Fig. 7-12 Oxygen test

35. Still keeping the tube closed, hold it horizontally.

⚠ CAUTION
Hot test tube! Skin burns. ➔ Hold the tube in such a way you will not get burned.

! TIP
As soon as the splint re-ignites and burns brightly remove it from the tube. Do not insert it a second time into the tube of oxygen. Gases from the vaporized resins, with remaining oxygen could produce a large pop. Although not dangerous, it may cause you to drop the tube.

36. Light a wooden splint and when it is burning well, blow out the flame, leaving a visibly glowing ember on the end of the splint.
37. Quickly release you finger and insert the glowing splint half way into the tube.

Get results!

37. Look at the inside of the mouth of the tube immediately after, what do you see?
38. Remove the splint and do not insert it again.
39. Write down your observations.
40. Disassemble the equipment and return it.

7.3.2 Questions – Students

Use an extra sheet to answer the question.

1. Why is it important to ensure there are no large bubbles of air remaining when we fill the gas storage cylinders with water?

2. Using the information provided by the labels on the gas storage cylinders, which electrode is attached to which cylinder?

3. Is gas produced at similar rates at each electrode? What evidence do you have of this?

4. What simple ratio can you use for this gas production?

5. Why do we test the gas from the cathode first?

6. Do you have any evidence that the labels on the cylinders are placed on the correct cylinder?

7. Looking at the scientific formula for water, H_2O, what do you think happened in this investigation?

8. Use the data from your table to create a simple graph. How much gas would be produced if you ran your electrolyzer for one hour? How long would it take you to collect a liter of cathode gas? Of anode gas?

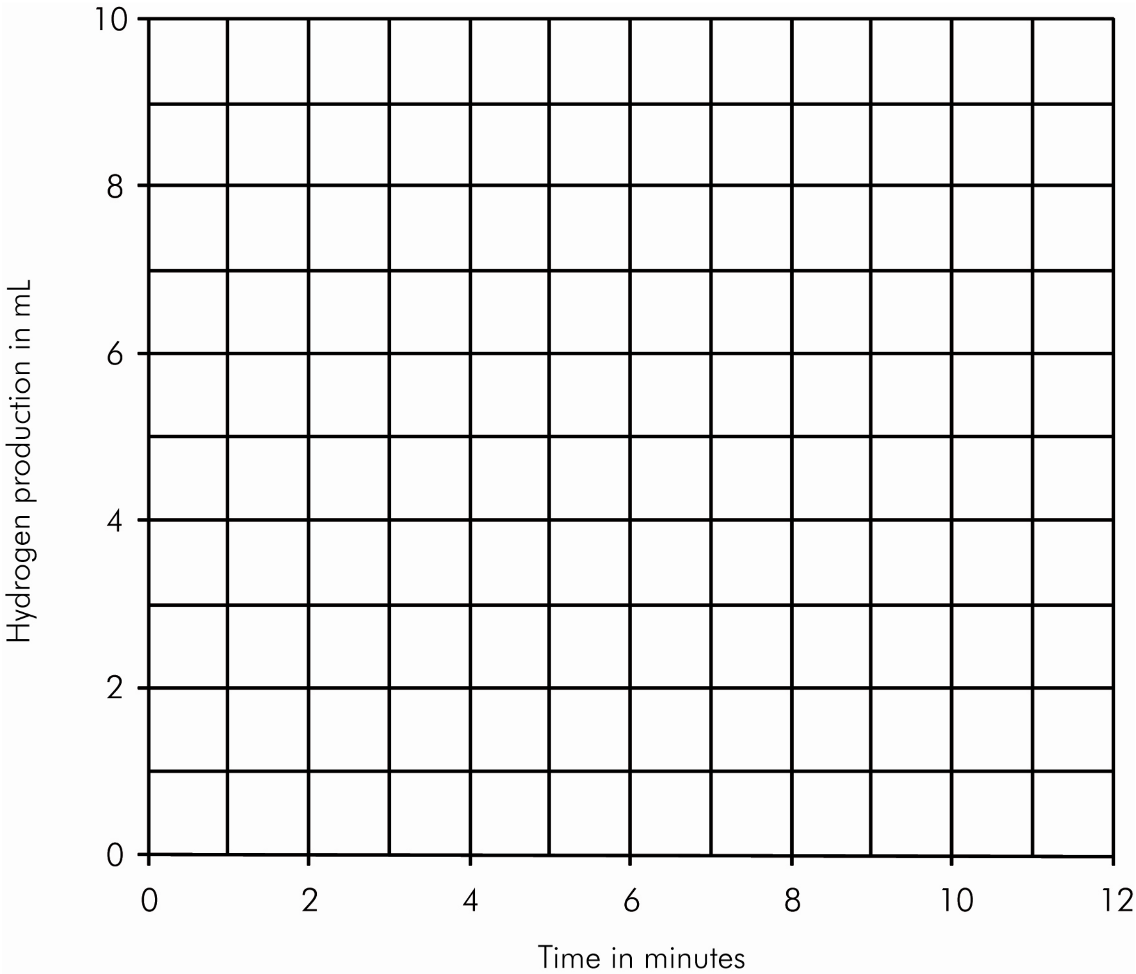


Fig. 7-13 Hydrogen production rate

9. From the results you obtained from this investigation:
   What is an electrolyzer and what does it do?

10. Is hydrogen a good name for the gas collected over the cathode?

Only when the Simple Electrolysis investigation has been performed

11. Looking back at investigation 3 can you make any inferences about the gases you saw being produced at each electrode? Did you observe any differences when you watched the gases being produced by simple electrolysis and by the electrolyzer?

Student's Section

8 Hydrogen Power!

In this investigation the students will explore how to gain electrical energy from combining hydrogen and oxygen.

This investigation is a continuation of the previous ones but it is not essential that the students have actually performed them.

8.1 Teacher's Essentials

8.1.1 Objectives

Qualifications

In order to ensure maximum learning success, your students should already be familiar with:

- Breaking up of chemical compounds
- Redox reaction
- Batteries
- Hydrogen test
- Linearity and extrapolation

Learning objectives

In this investigation your students will learn:

- Gaining electricity from combining hydrogen and oxygen
- Conversion of energy
- Power as the product of current and voltage
- Faraday's first law of electrolysis
- Need for reproducibility of scientific investigations
- Hydrogen is stored chemical energy

Outlook

This investigation may serve as a starting point for a variety of different topics, for example:

- Concept of catalysts
- Concept of electrons, atoms, etc.
- Power industries
- Greenhouse effect
- Avogadro's constant

8.1.2 Time Table

The amounts of time are rough estimates.

Task	Time
Preparation prior to class	20 min
Investigation	90 min
Time students will need to answer questions	35 min

Table 8-1 Schedule

8.1.3 Teaching Method

Method	Suitability
Group work	✓✓✓✓
Chalk and talk	✓
Silent work (student questions)	✓✓
Homework (student questions)	✓✓✓

Table 8-2 Teaching method (✓= poor … ✓✓✓✓=very good)

8.1.4 Background

Powering a car with hydrogen?

In the electrolyzer we have used in the previous experiments we have a source of hydrogen and a way of storing it in the gas cylinder. We also have a source of oxygen, although we could simply use air, as it contains 21 % oxygen. Now we need a way to change the hydrogen and oxygen back into electricity that will power an electric motor to move the car.

Fuel cell

In the Model Car kit a device to change hydrogen and oxygen back into water is provided. In investigation *UNDERSTANDING ELECTROLYSIS* we used the main component in this kit – the reversible fuel cell – as an electrolyzer. But if you supply hydrogen on one side of the fuel cell and oxygen on the other, the reversible fuel cell produces an electric current. The hydrogen unites with the oxygen to produce water again, which is the material we started with. You could write this as follows:

Electricity + Water → Hydrogen + Oxygen

Hydrogen + Oxygen → Water + Electricity

This could be a wonderful solution to the air pollution problem as hydrogen fuel cell power would release only water or water vapor into the atmosphere, using water and electricity as the source of the hydrogen needed to power the fuel cell.

Astronauts already use this technology in space stations. With solar cells, electrolyzers, fuel cells, and an initial supply of water, the astronauts have a source of electricity and oxygen as well as an abundant supply of hydrogen. As the hydrogen is used as fuel to produce electricity, it also produces water.

Recall the reaction within a fuel cell:

$2\ H_2 + O_2 \rightarrow 2\ H_2O$

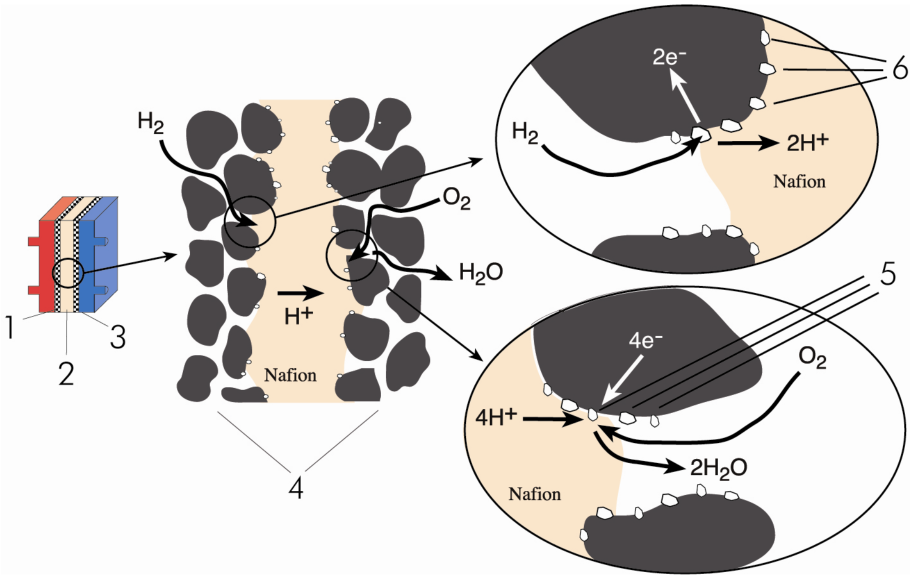


Fig. 8-1 Principle fuel cell

1	Anode	4	Carbon layer
2	Polymer electrolyte membrane (Nafion)	5	Platinum-iridium catalyst
3	Cathode	6	Platinum catalyst

The electron flow can be used by a consumer load.

With the Model Car we can use stored hydrogen to produce electricity to power the motor. Because the electric motor spins very quickly it has gearing to reduce the speed of the motor shaft and carry power the rear wheels of the car

Power

When describing electrical events, the power (in watts) going into or out of a device can be determined by multiplying the current (in amperes) passing through the device by the voltage (in volts) that exists across that device. Power describes the strength of a process. We can write:

$I \times V = P \quad (\text{amperes} \times \text{volts} = \text{watt})$

Anode / Cathode

When we used the reversible fuel cell as an electrolyzer, we observed the polarity: negative (black) = hydrogen=cathode, and positive (red) = oxygen = anode. Now that we are using the reversible fuel cell as a fuel cell, it is convenient that the polarity is almost the same. The hydrogen side (black) produces a negative voltage; the oxygen side (red) produces a positive voltage. However in keeping with the definition of anode / cathode (electrons are lost at the anode), the hydrogen side is now called the anode and the oxygen side is called the cathode.

8.2 The Investigations – Teachers

8.2.1 Preparation

It is advisable that you try out this investigation before class.

8.2.2 In Class

Depending on your didactic approach and the number of Model Car kits at hand, you may either choose group work or chalk and talk teaching.

Safety

- ➔ Always make your students aware of investigating safely and make yourself familiar with the potential hazards.
- ➔ Make sure to provide the students with goggles and to wear goggles yourself.

⚠ CAUTION

Overpressure in reversible fuel cell!

Injuries due to objects shooting out, when the top of the overflow compartments of the gas storage cylinders is obstructed.

- ➔ Do not block the top of the overflow compartments of the gas storage cylinders.
- ➔ Always wear eye protection.

⚠ CAUTION

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

- ➔ No open flames.
- ➔ No smoking.
- ➔ Well ventilated workspace.

TIP

Students may observe that the motor stops before all the hydrogen is used up, or conversely, the motor continues to run after the hydrogen appears to be gone. You could offer the following explanations:

- Motor stops before all the hydrogen is used up:
  - This may be the result of air left in the system when it was filled with water. What's left in the hydrogen side is not completely hydrogen.
- Motor continues to run after the hydrogen is gone:
  - Although no hydrogen is visible in the storage cylinder, hydrogen can still be present around the membrane.

8.2.2.2 Group Work

For group work several Model Car kits are required.

8.2.2.3 Chalk and Talk

For chalk and talk only one Model Car kit is required.

To present the investigation you will need the following:

Investigation

- ✓ Goggles or eye protection
- ✓ Solar panel or hand generator

TIP

As an alternative to the solar panel you may also use the hand generator as a source for electrical energy (see Instruction Manual).

- ✓ 2 or 5 patch cords (5 if you wish to investigate how much power the fuel cell can deliver)
- ✓ Reversible fuel
- ✓ Car with motor
- ✓ Load measurement box (if you wish to investigate how much power the fuel cell can deliver)
- ✓ Distilled water
- ✓ 100–120 watts PAR lamp, or equivalent light source
- ✓ Block of wood or other support for the car

✓ Watch with second hand or stopwatch function

1. Put on your goggles.

Filling the reversible fuel cell with distilled water

2. Place the fuel cell upside down (numbers facing down) on the flat surface.
3. Remove the stoppers.

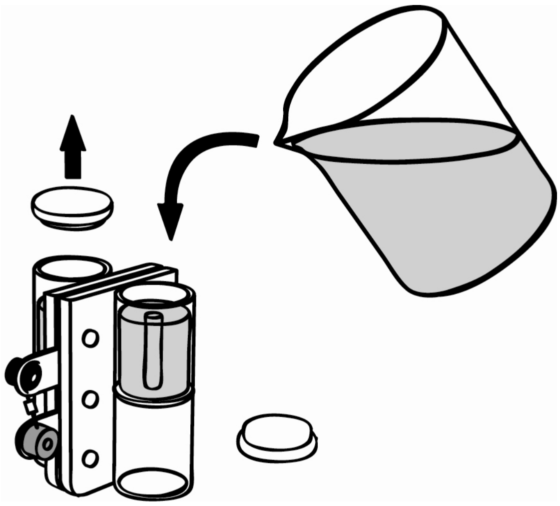


Fig. 8-2 Filling the reversible fuel cell with distilled water

NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the reversible fuel cell.

4. Pour distilled water into both storage cylinders until the water reaches the tops of the small tubes in the center of the cylinders.
5. Tap the fuel cell lightly to help water flow into the area surrounding the membrane and metal current-collecting plates.
6. Add more water until it starts to overflow into the tubes in the cylinders.
7. Place the stoppers back onto the cylinders. Make sure no air is trapped inside the cylinder.

TIP

A small air bubble in the order of 0.5 mL will not cause problems and can be ignored.

8. If the reversible fuel cell has not been used for a while, leave it to rest for 20 min; if has been used recently, turn it right side up.

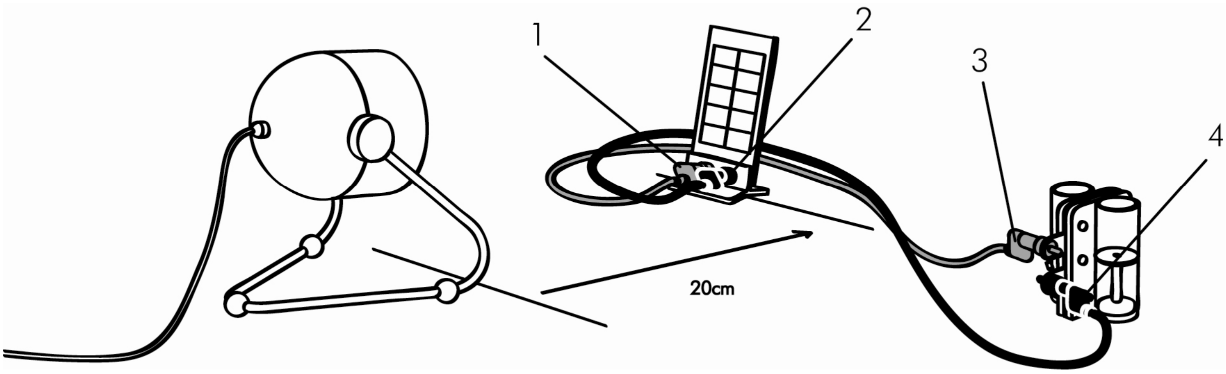


Fig. 8-3 Connecting solar panel and fuel cell

Producing hydrogen

9. Plug the red banana jacks of the red patch cord into the red (positive) banana jack terminals of the solar panel (1) and the fuel cell (3).

NOTICE

Short circuit of reversible fuel cell!

Hot spots in the membrane, leading to deterioration of the membrane.

➔ Do not short circuit the reversible fuel cell.

10. Repeat step 9 with the black patch cord and the negative terminals (2, 4).

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

➔ Only use light sources with a maximum power of 120 W.

➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.

➔ Do not concentrate light.

11. Align the solar panel with the light source, keeping a minimum distance of 20 cm (8 inches).

⚠ **CAUTION**
Hot surface of solar panel and lamp! Skin burns. ➔ Do not touch the hot surface of the solar panel or lamp. ➔ Allow solar panel / lamp to cool down before touching it.

12. Turn on the light.

The fuel cell starts producing hydrogen.

13. When the hydrogen storage cylinder is filled to a little more than 12 ml:
    - Turn off the light.
    - Unplug the patch cords from the reversible fuel cell.

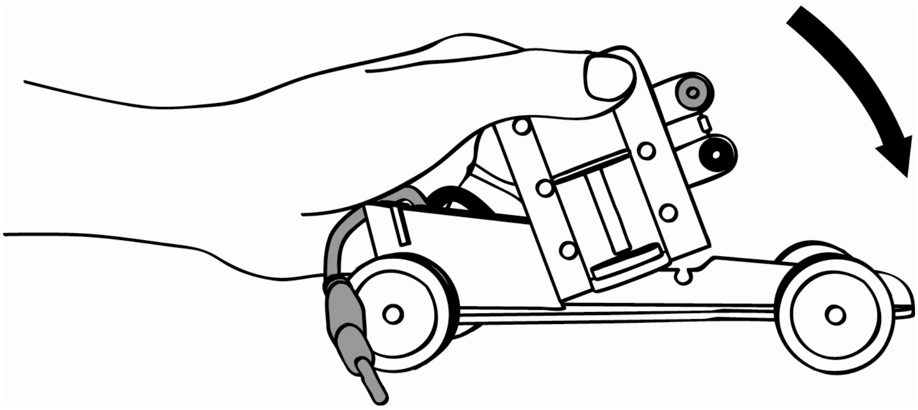


Fig. 8-4 Placing reversible fuel cell onto Model Car

Running the car

14. With the red and black terminals facing towards the front of the car, place the reversible fuel cell into the notches on the model car until it audibly clicks into place.

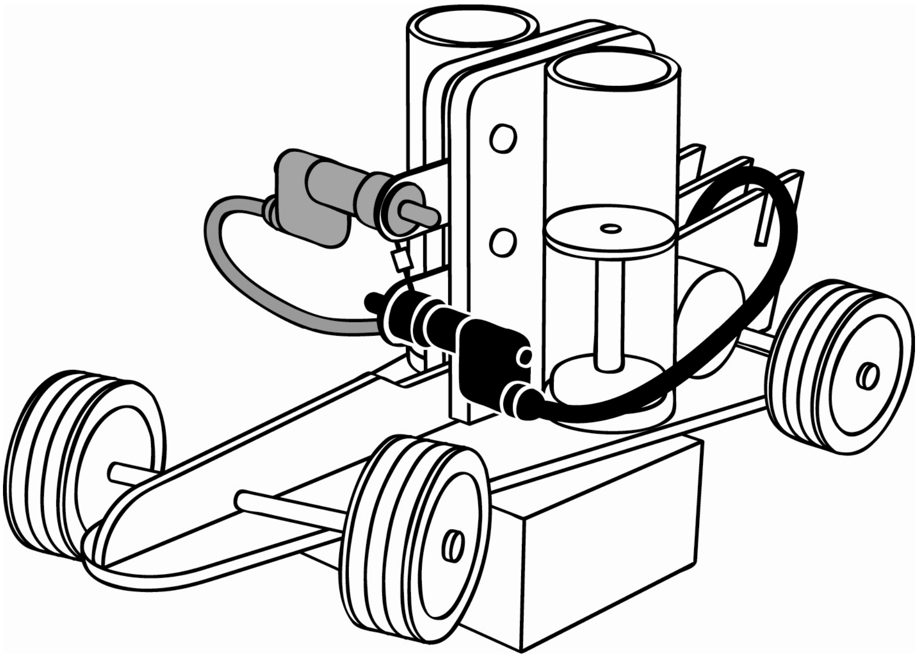


Fig. 8-5 Placing Model Car on block

15. Place the block of wood under the car base, so that the wheels on the car are free to turn.
16. Connect the red (positive) banana jack with the red (positive) terminal and the black (negative) banana jack with the black (negative) terminal.

Student participation

17. Have the students watch the level of gas in the hydrogen storage cylinder and when the gas level reaches exactly 12 mL, have them start a stopwatch (or record the time to the nearest second).
18. Have them record the time after each milliliter that has been consumed.
19. Have a student keep record in a table (on chalk board).

Hydrogen consumed [mL]	Elapsed time [s] Trial 1	Elapsed time [s] Trial 2	Elapsed time [s] Trial 3	Average elapsed time of all trials
0	0	0	0	0
1	60	60	60	60
2	120	110	120	117
3	170	160	170	167
4	220	210	210	213
5	270	260	260	263
6	320	310	300	310
7	370	360	350	360
8	420	410	400	410
9	470	460	450	460
10	520	510	490	507
11	570	550	550	557
12	–	–	–	–
When wheels stop	580	550	550	560

Table 8-3 Example for hydrogen consumption (values are examples and can vary)

20. Continue until the motor stops.
21. Disconnect fuel cell and car and connect the fuel cell to the solar panel to produce hydrogen again.
22. Turn on the light.
23. Repeat production of hydrogen and consumption by the car as many times as you think it makes sense (at least once).
24. Have one student draw a graph onto the chalk board, resulting in a graph showing the volume of hydrogen used as a function of the duration of time the wheels turn.

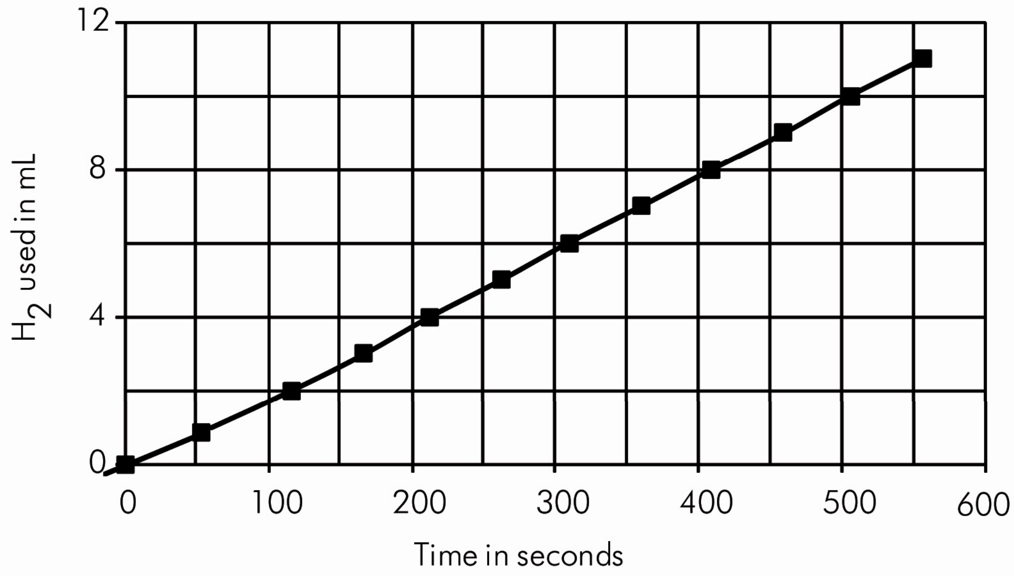


Fig. 8-6 Hydrogen volume as function of time wheels run (values are examples and can vary)

How much power can the fuel cell deliver

You can stop the investigation at this point, if you do not have any time left or if you wish to continue differently. You may however, continue with the investigation on how much power a fuel cell can deliver:

1. Fill the reversible fuel cell with distilled water (if necessary) and produce hydrogen, see steps 2.–13. on pages 95–96.

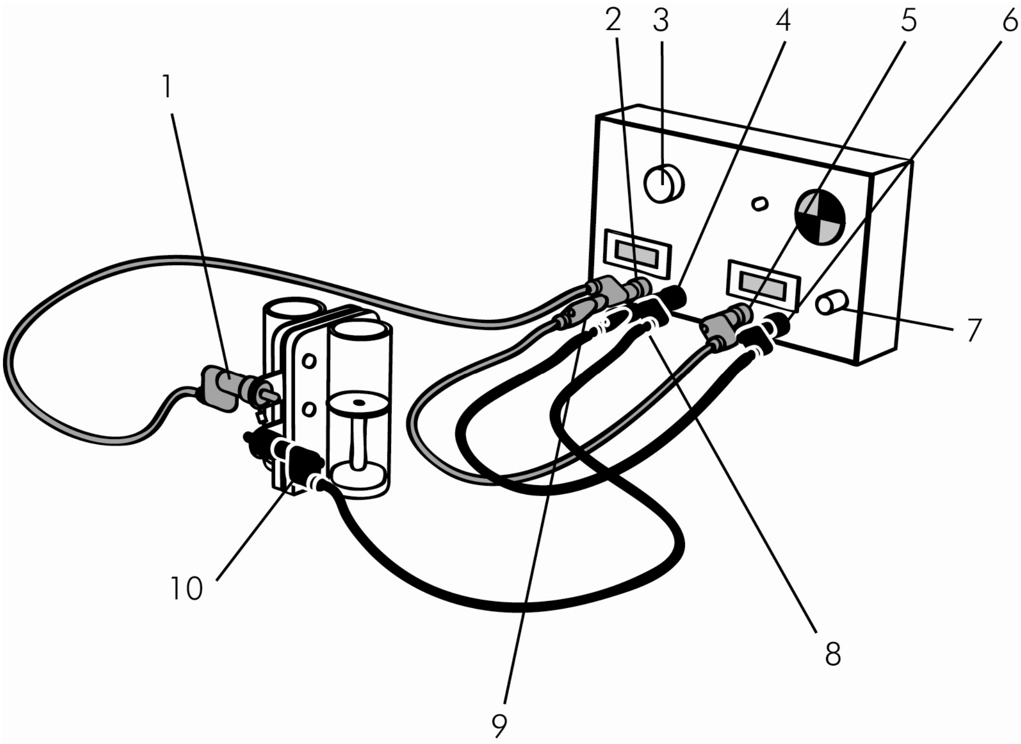


Fig. 8-7 Connecting reversible fuel cell and load measurement box

2. Set the *LOAD* knob (3) to *OPEN*.
3. Connect the red (positive) terminal of the reversible fuel cell (1) to the red (positive) terminal of the ammeter at the load measurement box (2).
4. Connect the black (negative) terminal of the reversible fuel cell (10) to the black (negative) terminal of the ammeter at the load measurement box (4).
5. Connect the red (positive) terminal of the ammeter at the load measurement box (9) with the red (positive) terminal of the voltmeter (5) at the load measurement box.
6. Connect the black (negative) terminal of ammeter at the load measurement box (8) with the black (negative) terminal of the voltmeter at the load measurement box (6).
7. Push the *ON* / *OFF* button (7).
8. Set the *LOAD* knob (3) to 10 Ω.

Measuring current and voltage

9. Observe the current and the voltage for a few seconds.

TIP

You might see the voltage start at a value even higher than 1.23 V (theory says this is the maximum possible voltage of a hydrogen-oxygen fuel cell) and then slowly fall. This happens because of surface layers left on the catalyst after electrolysis.

Student participation

10. When current and voltage appear to have settled, encourage the students to write them in the following table (here with typical results).

Load [Ω]	Current [A]	Voltage [V]	Power [W] (calculated)
10	0.080	0.840	0.067
5	0.145	0.780	0.113
3	0.237	0.750	0.178
1	0.497	0.640	0.318

Table 8-4 Typical results power output of fuel cell (values are examples and can vary)

11. Change the load setting to 5 Ω, 3 Ω and then to 1 Ω and at each point have the students record the current and voltage.
12. Have students calculate the power output of the fuel cell.
13. Disconnect the load measurement box and turn it off.
14. Disassemble the equipment and put it away.

8.2.2.4 Silent Work

The students can be encouraged to answer the questions in *QUESTIONS – STUDENTS* on page 113 in silent work or partner work. This depends on the students' abilities and the didactic approach.

8.2.2.5 Homework

The questions provided in section *QUESTIONS – STUDENTS* on page 113 can be used for homework as well, if your students do not need teacher's assistance to answer them.

8.2.3 Questions and Answers

1. Why is it important to have the hydrogen gas cylinder filled with the same amount each time we start to measure the length of time the wheels turn for each mL of gas?

If we want to compare the duration of the wheels turning for each mL of hydrogen gas used it is important to begin our timing with the same amount of hydrogen each time.

2. What happens to the level of gas in the hydrogen storage cylinder as the wheels turn? Why does this occur?

   The volume of gas in the hydrogen storage cylinder decreases because as the wheels turn they use electricity to power the electric motor and this electricity comes from the hydrogen gas combining with the oxygen gas to form water and produce electricity.

3. Could you power the electric motor with electricity produced by the solar panel? What is the advantage of powering a car with hydrogen fuel rather than a solar panel connected directly to the electric motor?

   Yes, I think you could power the electric motor with electricity produced by the solar panel. Powering a car with hydrogen fuel rather than a solar panel would mean that you could drive the car in the dark when there is not enough light to allow a solar panel to work.

4. What is the advantage of having hydrogen combine with oxygen in this way rather than having it burn and explode as it does in the hydrogen test?

   The advantage of having the hydrogen combine with oxygen in this way rather than having it burn and explode is that it produces a much more controlled energy flow in the form of electricity. This electricity can be turned on and off so you can use it a little at a time. With an explosion a lot of the energy is released in the form of heat and cannot easily be used to power the car.

5. Predict how long the wheels would rotate for 20 mL of hydrogen gas. Refer to your graph and extrapolate an answer.

   [individual results will vary]

   Because the wheels rotated 507 seconds for 10 mL of hydrogen, I predict they will rotate two times 507 seconds (1014 seconds or 17 minutes) for 20 mL of hydrogen. The relation between hydrogen consumption and wheel rotation is linear.

6. What is the answer to the question at the start of the investigation: Can we use stored hydrogen to produce electricity? Explain.

   Yes, we can use stored hydrogen to produce electricity. We have seen the fuel cell use hydrogen while making electrical energy.

7. When you decreased the resistance from 10 to 1 Ω, what happened to the current? What happened to the voltage? What is the maximum power output from the fuel cell you determined?

   [individual results will vary]

   When I decreased the resistance, the current increased but the voltage decreased. The maximum power I measured was 0.318 watts with the 1 Ω resistor.

8. The dependence of current and voltage you have determined is typical for batteries too. Can we say the fuel cell is a battery? Please discuss this.

   Yes we can say that a fuel cell is a battery because it makes electricity out of a chemical reaction, which is separated in two half-cells having a minus pole anode and a plus pole cathode.

   Batteries show a similar behavior. They have a no-load voltage, which decreases with increasing current. For example the no-load voltage for a NiCd battery is 1.2 volts.

8.3 Student's Section

In this investigation you will examine if you can use hydrogen as a fuel.

8.3.1 Can We Use Stored Hydrogen to Produce Electricity?

Safety

➔ Wear goggles when experimenting.

⚠ CAUTION

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

- ➔ No open flames.
- ➔ No smoking.
- ➔ Well ventilated workspace.

⚠ CAUTION

Overpressure in reversible fuel cell!

Injuries due to objects shooting out, when the top of the overflow compartments of the gas storage cylinders is obstructed.

- ➔ Do not block the top of the overflow compartments of the gas storage cylinders.
- ➔ Always wear eye protection.

- ✓ Goggles or eye protection
- ✓ Solar panel or hand generator

TIP

As an alternative to the solar panel your teacher may also ask you to use the hand generator as a source for electrical energy (see Instruction Manual).

- ✓ 2 or 4 patch cords
- ✓ Reversible fuel cell

- ✓ Car with motor
- ✓ Load measurement box
- ✓ Distilled water
- ✓ 100–120 watts PAR lamp, or equivalent light source
- ✓ Block of wood or other support for the car
- ✓ Watch with second hand or stopwatch function

1. Put on your goggles.
2. Place the fuel cell upside down (numbers facing down) on the flat surface.
3. Remove the stoppers.

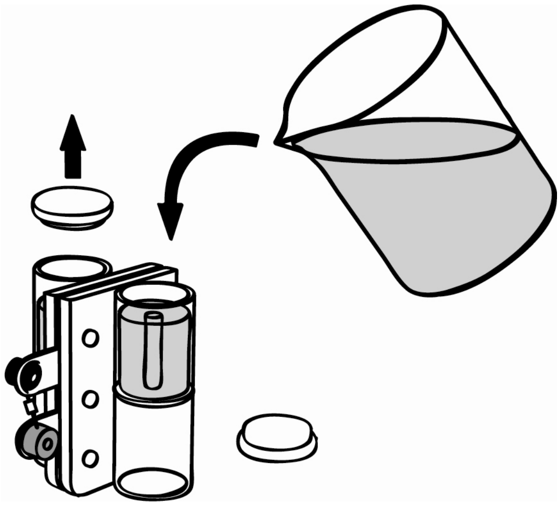


Fig. 8-8 Filling the reversible fuel cell with distilled water

NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the reversible fuel cell.

4. Pour distilled water into both storage cylinders until the water reaches the tops of the small tubes in the center of the cylinders.
5. Tap the fuel cell lightly to help water flow into the area surrounding the membrane and metal current-collecting plates.
6. Add more water until it starts to overflow into the tubes in the cylinders.
7. Place the stoppers back onto the cylinders. Make sure no air is trapped inside the cylinder.

TIP

A small air bubble in the order of 0.5 mL will not cause problems and can be ignored.

8. Turn the reversible fuel cell right side up.

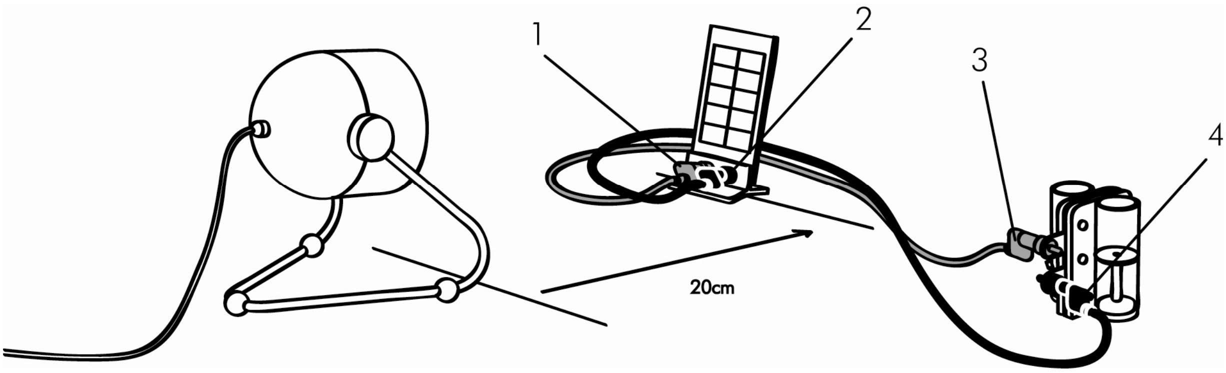


Fig. 8-9 Connecting solar panel and fuel cell

9. Plug the red banana jacks of the red patch cord into the red (positive) banana jack terminals of the solar panel (1) and the fuel cell (3).

NOTICE

Short circuit of reversible fuel cell!

Hot spots in the membrane, leading to deterioration of the membrane.

➔ Do not short circuit the reversible fuel cell.

10. Repeat step 9 with the black patch cord and the negative terminals (2, 4).

Student's Section

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light.

11. Align the solar panel with the light source keeping a minimum distance of 20 cm (8 inches).

CAUTION

Hot surface of solar panel and lamp!

Skin burns.

- ➔ Do not touch the hot surface of the solar panel or lamp.
- ➔ Allow solar panel / lamp to cool down before touching it.

12. Turn on the light.
13. When the hydrogen storage cylinder is filled to a little more than 12ml:
    - – Turn off the light.
    - – Unplug the patch cords from the reversible fuel cell.

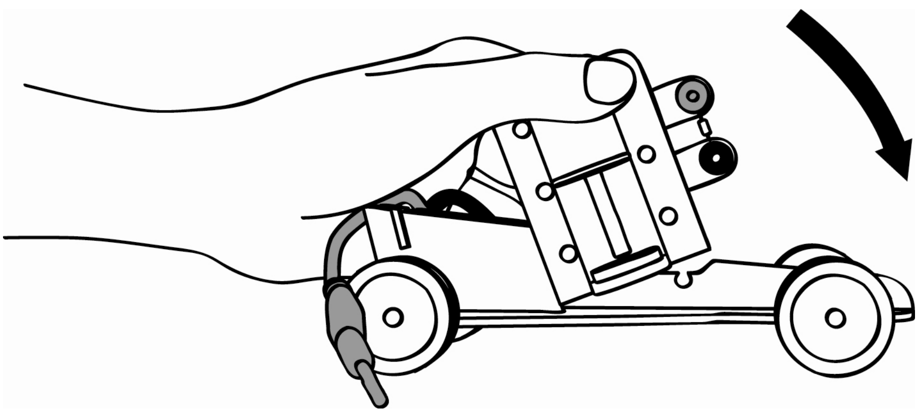


Fig. 8-10 Placing reversible fuel cell onto Model Car

14. With the red and black terminals facing towards the front of the car, place the reversible fuel cell into the notches on the model car until it audibly clicks into place.

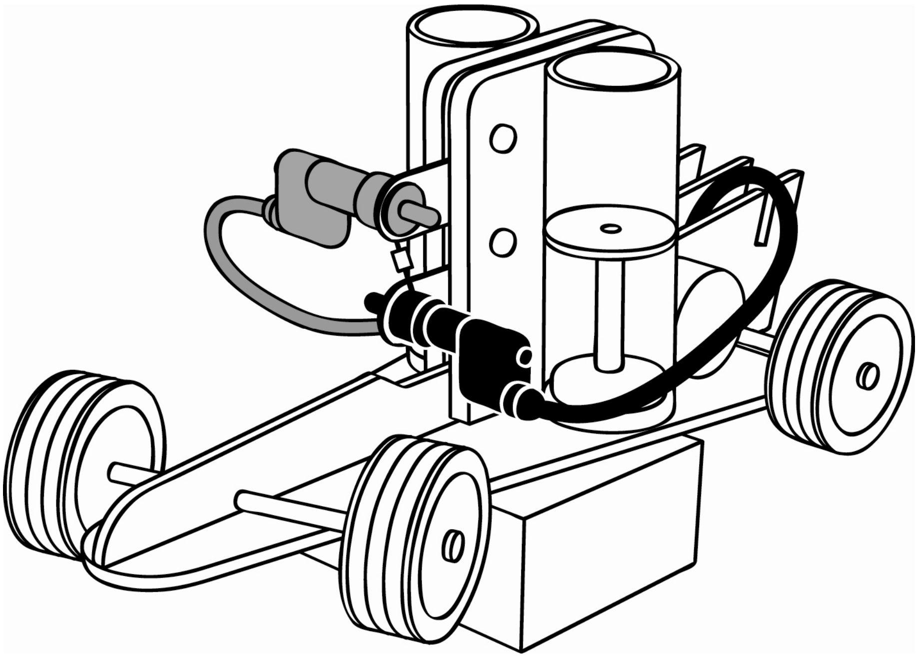


Fig. 8-11 Car on block

15. Place the block of wood under the car base, so that the wheels on your car are free to turn.
16. Connect the red (positive) banana jack with the red (positive) terminal and the black (negative) banana jack with the black (negative) terminal.
17. Watch the level of gas in the hydrogen storage cylinder, and when the gas level reaches exactly 12 mL, start a stopwatch (or record the time to the nearest second).
18. Record the time after each milliliter that has been consumed, keeping record in the table below.

Hydrogen consumed [mL]	Elapsed time [s] Trial 1	Elapsed time [s] Trial 2	Elapsed time [s] Trial 3	Average elapsed time of all trials [s]
0				
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
When wheels stop				

Table 8-5 Hydrogen volume and time the car runs

19. Continue until the motor stops.
20. Disconnect fuel cell and car and connect the fuel cell to the solar panel.

To produce hydrogen again:

21. Turn on the light
22. Repeat production of hydrogen and consumption by the car as many times as you think it makes sense (at least once).
23. Draw a graph into the chart below, resulting in a graph showing the volume of hydrogen used as a function of the duration of time the wheels turn.

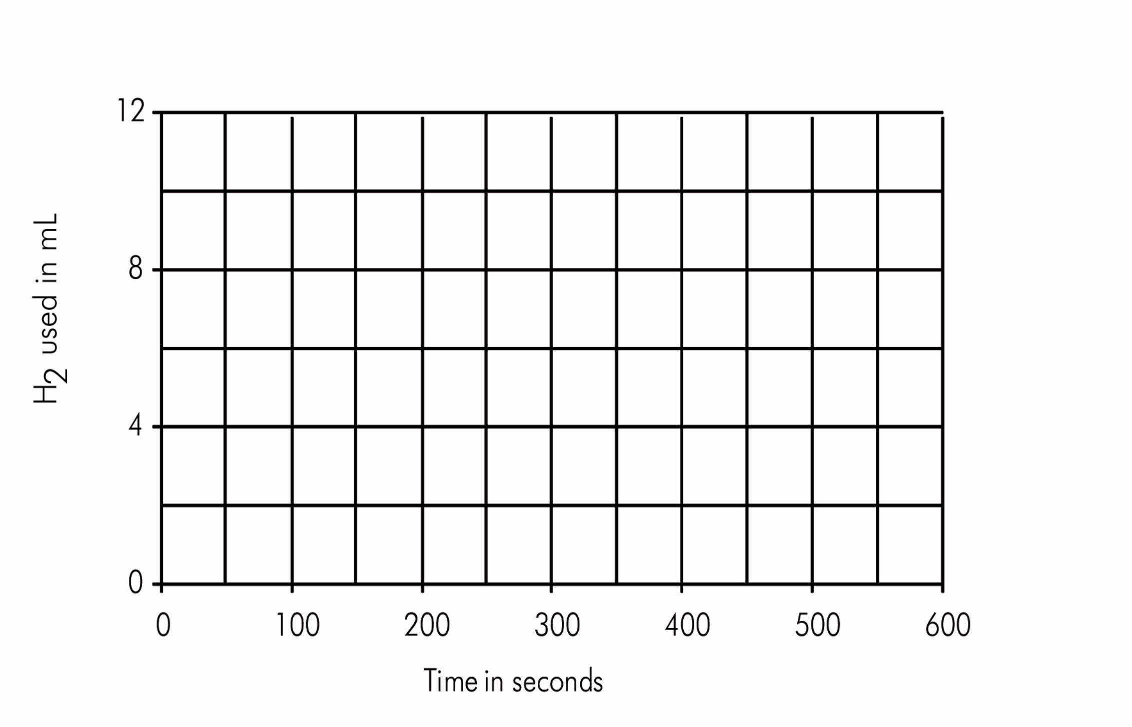


Fig. 8-12 Hydrogen volume as function of time wheels run

The first part of the investigation is finished. Check with your teacher whether you may continue or not.

How much power can a fuel cell deliver

1. Fill the reversible fuel cell with distilled water (if necessary) and produce hydrogen, see steps 2.–13. on pages 106–108.

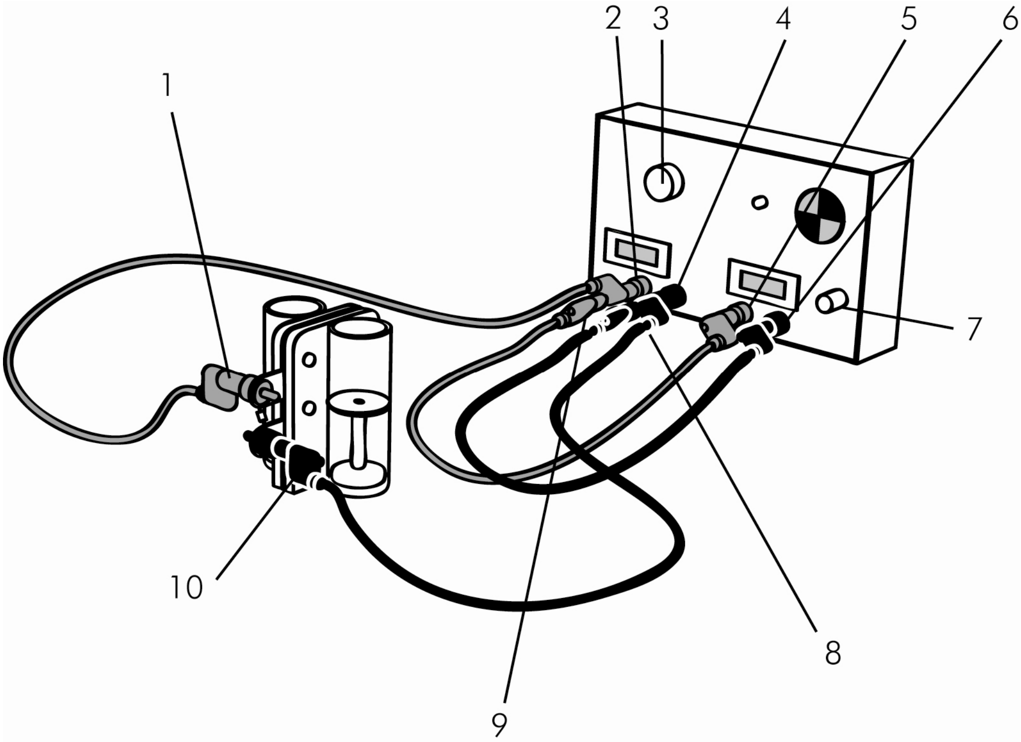


Fig. 8-13 Connecting reversible fuel cell and load measurement box

2. Set the *LOAD* knob (3) to *OPEN*.
3. Connect the red (positive) terminal of the reversible fuel cell (1) to the red (positive) terminal of the ammeter at the load measurement box (2).
4. Connect the black (negative) terminal of the reversible fuel cell (10) to the black (negative) terminal of the ammeter at the load measurement box (4).
5. Connect the red (positive) terminal of the ammeter at the load measurement box (9) with the red (positive) terminal of the voltmeter (5) at the load measurement box.
6. Connect the black (negative) terminal of ammeter at the load measurement box (8) with the black (negative) terminal of the voltmeter at the load measurement box (6).
7. Push the *ON / OFF* button (7).
8. Set the *LOAD* knob (3) to 10 Ω.

TIP

You might see the voltage start at a value even higher than 1.23 V (theory says this is the maximum possible voltage of a hydrogen-oxygen fuel cell) and then slowly fall. This happens because of surface layers left on the catalyst after electrolysis.

9. When current and voltage appear to have settled, write them into the following table.

Load [Ω]	Current [A]	Voltage [V]	Power [W]
10			
5			
3			
1			

Table 8-6 Determination of power output of fuel cell

10. Change the load setting to 5 Ω, 3 Ω and then to 1 Ω and at each point record the current and voltage.
11. Calculate the power output of the fuel cell.
12. Disconnect the load measurement box and turn it off.
13. Disassemble the equipment, put it away and then take off your goggles and return them carefully.

8.3.2 Questions – Students

Use an extra sheet to answer the question.

1. Why is it important to have the hydrogen gas cylinder filled with the same amount each time we start to measure the length of time the wheels turn for each mL of gas?

2. What happens to the level of gas in the hydrogen storage cylinder as the wheels turn? Why does this occur?

3. Could you power the electric motor with electricity produced by the solar panel? What is the advantage of powering a car with hydrogen fuel rather than a solar panel connected directly to the electric motor?

4. What is the advantage of having hydrogen combine with oxygen in this way rather than having it burn and explode as it does in the hydrogen test?

5. Predict how long the wheels would rotate for 20 mL of hydrogen gas. Refer to your graph and extrapolate an answer.

6. What is the answer to the question at the start of the investigation: Can we use stored hydrogen to produce electricity? Explain.

7. When you decreased the resistance from 10 to 1 Ω, what happened to the current? What happened to the voltage? What is the maximum power output from the fuel cell you determined?

8. The dependence of current and voltage you have determined is typical for batteries too. Can we say the fuel cell is a battery? Please discuss this.

9 Hydrogen Power in Motion

Because fuel cells can deliver convenient and pollution-free energy they are an ideal energy source for the future.

In recent decades car companies have been researching for alternatives to the use of gasoline. News reports state, that within the next couple of years, fuel cell cars will be produced in quantity. This investigation will focus on running a car with hydrogen – but also on the problems and limits of hydrogen power.

9.1 Teacher's Essentials

9.1.1 Objectives

Qualifications

In order to ensure maximum learning success, your students should already be familiar with:

- Investigation *HYDROGEN POWER!*, see page 89.
- Calculation of circumference

Learning objectives

In this investigation your students will learn:

- Friction
- Work, power, energy
- Stating hypotheses and substantiating them

Outlook

This investigation may serve as a starting point for a variety of different topics, for example:

- Hydrogen power in everyday life
- Combined heat and power units
- Hybrid cars

9.1.2 Time Table

The amounts of time are rough estimates.

Task	Time
Preparation prior to class	20 min
Investigation	45 min
Time students will need to answer questions	25 min

Table 9-1 Schedule

9.1.3 Teaching Method

Method	Suitability
Group work	✓✓✓✓
Chalk and talk	✓
Silent work (student questions)	✓✓
Homework (student questions)	✓✓✓

Table 9-2:Teaching method (✓= poor … ✓✓✓✓=very good)

9.1.4 Background

Air pollution caused by transport emissions amounts to 60 % of the total air pollution in our cities today.

Emissions from combustion of carbon-based fuels are considered to be mainly responsible for the climate change. Fuel cells offer an ideal cycle, in principle leaving no pollution.

In 2006 approximately 600 million cars were on the roads worldwide and the prognosis for 2050 is that between1.4 and 2.7 billion cars will cruise the roads and highways. In 2006 road traffic was responsible for almost 4 billion tons of carbon dioxide. Not only the effects on the climate through increased emission of greenhouse gases has to be taken into account, but also the health hazards imposed by noxious exhaust gases such as nitrogen oxides.

By contrast, the reaction between hydrogen and oxygen produces merely water (even though the total emissions also depend on the source of the hydrogen). The need for alternative and clean sources of energy is vital.

Since the early 1960s car companies have been working on fuel cell cars, producing prototypes with quite impressive features, for example a travelling distance of 200 km with one hydrogen filling. Although little has been done towards commercializing a hydrogen powered vehicle, the recent threat of California's zero-emission policy has caused car companies to respond.

Today the car companies are on the verge of producing fuel cell cars in quantity. These cars meet all the needs today's customers demand.

Several police and fire departments in the USA possess fuel cell powered vehicles. Some European towns have changed part of their public transportation bus fleet to fuel cell powered busses.

British Columbia, Canada plans to have the first hydrogen bus fleet ready for public transportation during the Winter Olympics 2010.

9.2 The Investigation – Teachers

9.2.1 Preparation

It is advisable that you try out this investigation before class.

9.2.2 In Class

Depending on your didactic approach and the number of kits at hand, you may either choose group work or chalk and talk teaching.

Safety

- ➔ Always make your students aware of investigating safely and make yourself familiar with the potential hazards.
- ➔ Make sure to provide the students with goggles and to wear goggles yourself.

⚠ **CAUTION**

Overpressure in reversible fuel cell!

Injuries due to objects shooting out, when the top of the overflow compartments of the gas storage cylinders is obstructed.

- ➔ Do not block the top of the overflow compartments of the gas storage cylinders.
- ➔ Always wear eye protection.

⚠ **CAUTION**

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

- ➔ No open flames.
- ➔ No smoking.
- ➔ Well ventilated workspace.

TIP

Students may observe that the motor stops before all the hydrogen is used up, or conversely, the motor continues to run after the hydrogen appears to be gone. You could offer the following explanations:

- Motor stops before all the hydrogen is used up:
  - This may be the result of air left in the system when it was filled with water. What's left in the hydrogen side is not completely hydrogen.
- Motor continues to run after the hydrogen is gone:
  - Although no hydrogen is visible in the storage cylinder, hydrogen can still be present around the membrane.

9.2.2.2 Group Work

For group work several Model Car kits are required.

For this investigation it is recommended to have the students perform the investigation themselves, see *STUDENT'S SECTION* on page 129. You may have them state a hypothesis and discuss it afterwards.

9.2.2.3 Chalk and Talk

Investigation

- ✓ Goggles or eye protection
- ✓ Solar panel or hand generator

TIP

As an alternative to the solar panel you may also use the hand generator as a source for electrical energy (see Instruction Manual).

- ✓ 2 patch cords
- ✓ Reversible fuel cell
- ✓ Car with motor
- ✓ Distilled water
- ✓ 100–120 watts PAR lamp, or equivalent light source (only when you use the solar panel)
- ✓ Watch with second hand or stopwatch function

Filling the reversible fuel cell with distilled water

1. Put on your goggles.
2. Place the fuel cell upside down (numbers facing down) on the flat surface.
3. Remove the stoppers.

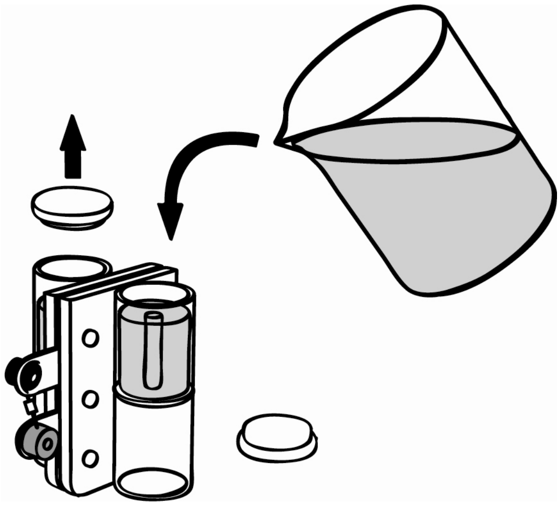


Fig. 9-1 Filling the reversible fuel cell with distilled water

NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the reversible fuel cell.

4. Pour distilled water into both storage cylinders until the water reaches the tops of the small tubes in the center of the cylinders.
5. Tap the fuel cell lightly to help water flow into the area surrounding the membrane and metal current-collecting plates.
6. Add more water until it starts to overflow into the tubes in the cylinders.
7. Place the stoppers back onto the cylinders. Make sure no air is trapped inside the cylinder.

TIP

A small air bubble in the order of 0.5 mL will not cause problems and can be ignored.

8. If the reversible fuel cell has not been used for a while, leave it to rest for 20 min; if has been used recently, turn it right side up.

Producing hydrogen

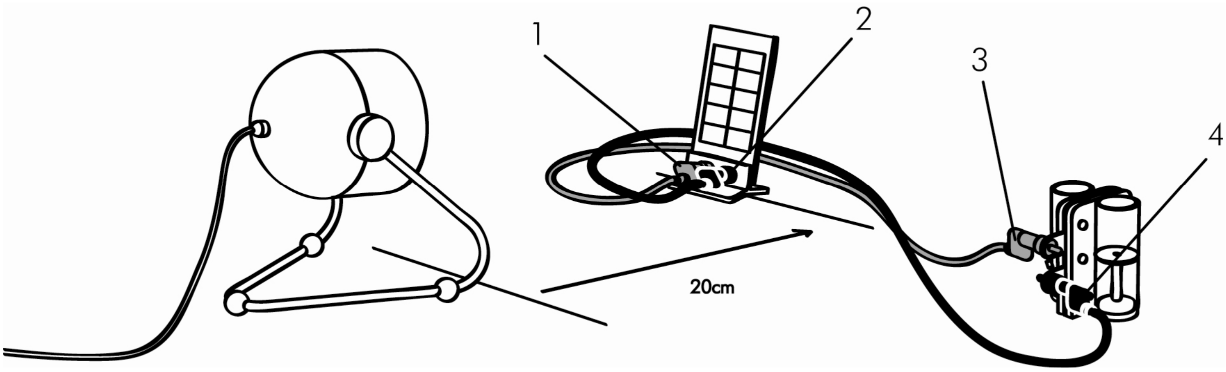


Fig. 9-2 Producing hydrogen

9. Plug the red banana jacks of the red patch cord into the red (positive) banana jack terminals of the solar panel (1) and the fuel cell (3).

!	NOTICE

Short circuit of reversible fuel cell!

Hot spots in the membrane, leading to deterioration of the membrane.

➔ Do not short circuit the reversible fuel cell.

10. Repeat step 9 with the black patch cord and the negative terminals (2, 4).

!	NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

➔ Only use light sources with a maximum power of 120 W.

➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.

➔ Do not concentrate light with a reflector.

11. Align the solar panel with the light source keeping a minimum distance of 20 cm (8 inches).

⚠ CAUTION
Hot surface of solar panel and lamp!
Skin burns.
➔ Do not touch the hot surface of the solar panel or lamp.
➔ Allow solar panel / lamp to cool down before touching it.

12. Turn on the light.
13. When the hydrogen storage cylinder is filled to a little more than 12 mL:
    - Turn off the light.
    - Unplug the patch cords from the reversible fuel cell.

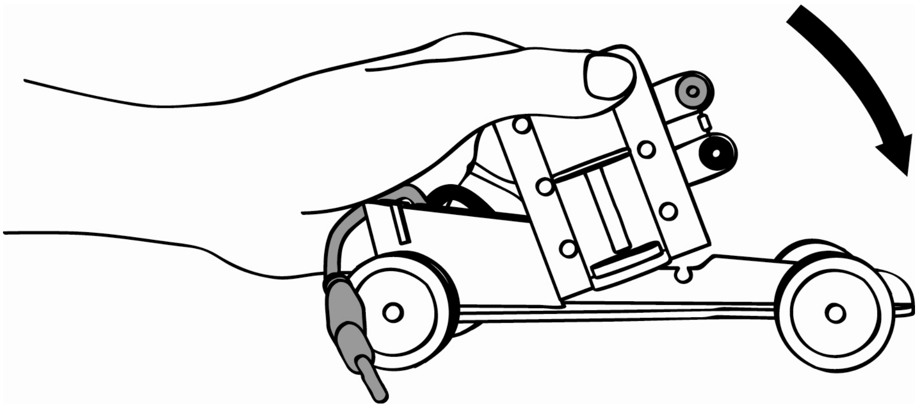


Fig. 9-3 Placing reversible fuel cell onto Model Car

14. With the red and black terminals facing towards the front of the car, place the reversible fuel cell into the notches on the model car until it audibly clicks into place.
15. Considering the space you have available, decide if you want to run the car in a straight line, or in a circle. If you will run the car in a circle:
    - Position the car on the floor and turn the front wheels so that the car will run in a fairly small circle without hitting anything.

Running the car

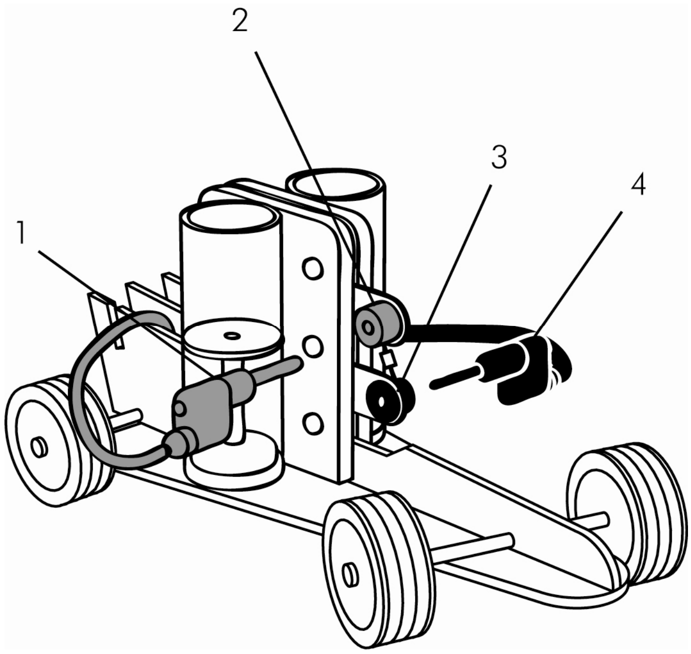


Fig. 9-4 Connecting the model car

Student participation

16. Have a student connect the red (positive) banana jack (1) with the red (positive) terminal (2) and the black (negative) banana jack (4) with the black (negative) terminal (3).

The car starts running.

17. Have the student adjust the front wheels and the car position until you are satisfied with the circle the car is making.
18. Have a student use chalk or a piece of tape to mark a point on the circle and another point exactly opposite. Have him / her mark where the center of the car travels, not the outside or inside wheels.
19. Have a student disconnect one of the patch cords so the motor stops.

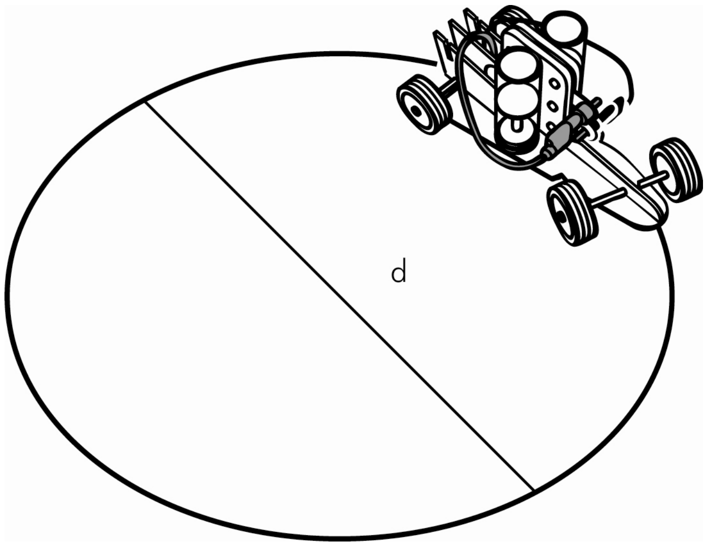


Fig. 9-5 Diameter of the driving circle (values for the example below: Diameter of circuit (d) in m: 0.8
Length of circuit in m: 2.51)

Trial	H_2 at start [mL]	H_2 at end [mL]	H_2 used in 1 minute [mL]	H_2 used in 2 minutes [mL]	Number of circuits	Distance travelled [m]
1	12	9.0	3.0	–	6.00	15.1
2	9.0	5.5	3.5	–	6.75	17.0
3	5.5	2.5	3.0	–	6.5	16.3
4	12	8.0	4.0	–	straight	18.0
5	12	6.0	–	6.0	12.00	30.2
6	12	5.0	–	7.0	13.5	33.89
7	12	6.0	–	6.0	12.00	30.2
8	12	4.0	–	8.0	straight	37

Table 9-3 Typical results (values are examples and can vary)

20. Have a student measure the diameter of the driving circle and write it down in a table on the chalk board.
21. Have a student note the amount of hydrogen in the storage cylinder, and record it in the table.
22. Have a student position the car on the floor.
23. Have a stopwatch ready at hand.
24. Have a student connect the black and red patch cords from the motor to the fuel cell and let the car run. If the car does not move immediately give it a push to overcome the starting friction.
25. Have a student start the stopwatch or note the time.

26. Let the car run for exactly one minute and have students count the number of circles it makes, or keep track of the straight-line distance travelled.

TIP
If the car runs into a wall quickly turn it around, send it back and let it continue until one minute is up.

27. Have a student disconnect one of the patch cords so the motor stops.
28. Have a student note the amount of hydrogen in the storage cylinder, write it in the table, and calculate the amount used in one minute. Have students write the number of circuits and calculate the distance, or write down the straight-line distance the car travelled.

Repeating the experiment with 2 minutes intervals

29. Go back to step 21, and repeat the procedure, this time letting the car run for two minutes. If necessary, produce more hydrogen (see steps 9.–12.).
30. If you have time, go back to step 21, and repeat the procedure several times. If necessary, produce more hydrogen (see steps 9.–12.).
31. Have students fill in the graph.

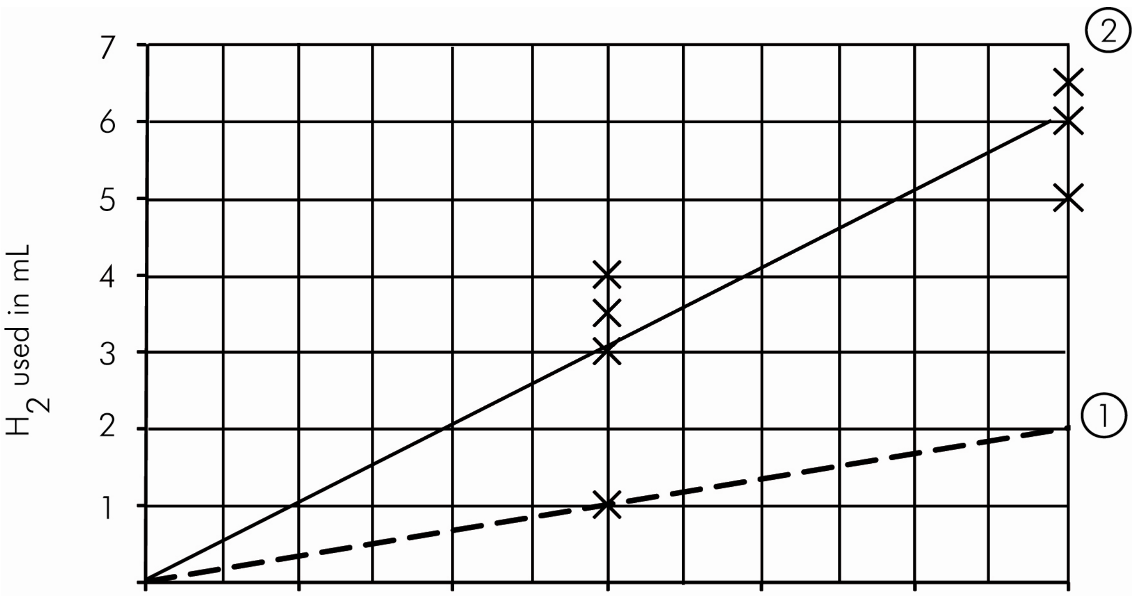


Fig. 9-6 Result Hydrogen consumption, with ① indicating the car stationary (investigation Hydrogen Power!) and ② indicating the car in motion (values are examples and can vary)

32. If you have the results from Investigation Hydrogen Power! (when the wheels were turning but the car was not moving), have students take from it the rate of H_2 use. Add this information to the above graph (①).
33. On the following graph, have students mark the point describing distance traveled and hydrogen used for each trial.

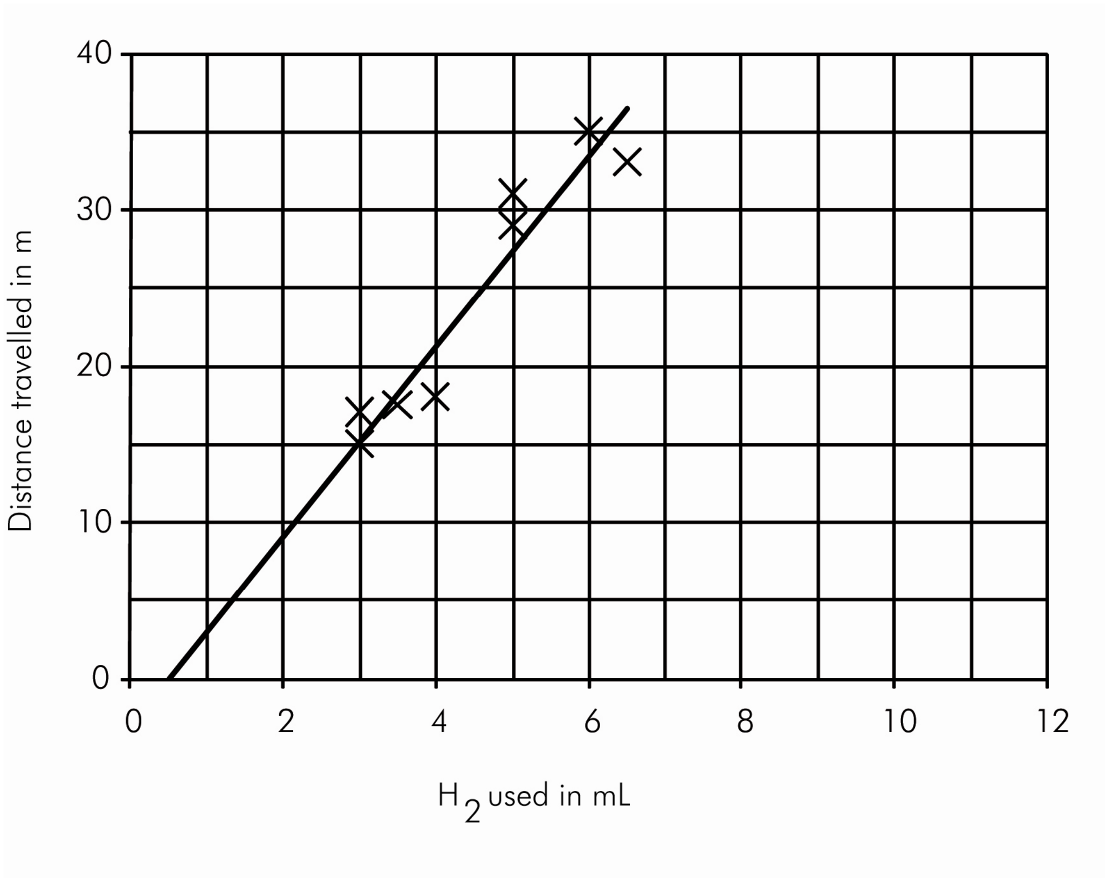


Fig. 9-7 Distance travelled as a function of hydrogen used (values are examples and can vary)

34. Disassemble the equipment, put it away and then take off your goggles.

9.2.3 Silent Work

The students can be encouraged to answer the questions on page 138 in silent work or partner work. This depends on the students' abilities and the didactic approach.

9.2.4 Homework

The questions provided on page 138 can be used for homework as well, if the students do not need teacher's assistance to answer them.

9.2.5 Questions and Answers

Only when investigation Hydrogen Power! was performed before

1. What did you find when you compared the rate of hydrogen consumption in this investigation with investigation *HYDROGEN POWER*?

   When the car moves, the rate at which hydrogen is used is greater than when the car is stationary. That is, when moving, the car used more hydrogen in the same amount of time.

2. If you found a difference, what do you think caused this?

   We did find a change and we think it is because the electric motor had not only to turn the wheels but it had to get the wheels to drive the car over the ground. This would need more work from the motor and would use up the hydrogen faster.

3. Can you think of any other examples of this from your personal experience?

   [Individual answers will vary; assess them all for reasonableness.]

   When I ride a bicycle on flat ground it is a lot easier than when I go up a hill. When I turn it upside down and just run the wheels in the air I can turn the pedals really easily with my hand and the wheel can go around really fast.

4. How do you think this would affect cars in the future if they drove on flat or hilly roads? Is this effect similar to what happens to the cars we drive now?

   I think that cars used on hilly roads would use up the hydrogen faster than cars running on flat surfaces. I think cars on hilly roads use up the gasoline faster than cars running on flat roads. The principle is the same – more work requires more fuel.

5. Using your data on the distance your car travelled, how far did your car travel on 4 mL of hydrogen? How much hydrogen would you need to have your car travel exactly one kilometer? Show all your calculations.

   [Individual results will vary.]

   Our car traveled 21 m on 4 mL of hydrogen. The rate of hydrogen consumption is:

   4 ml / 21 m = 0.19 mL/m

   To travel 1 km, we would need:

   Distance × rate of hydrogen consumption =
   1000 m × 0.19 mL/m = 190 mL

9.3 Student's Section

You may already have some idea of what you will see in this investigation, but think some more and come up with some reasons to support your thinking. This thinking about an investigation is called a hypothesis by scientists and is usually a written description of what you expect to happen and why. By writing down a hypothesis and then asking the appropriate questions in investigations, scientists get answers, adding to the information they already have. They might then revise the previous information, or form a new hypothesis and ask more questions.

9.3.1 Will the Wheels Turn for the Same Period of Time when Used to Power the Car on a Flat Surface?

Safety

➔ Wear goggles when experimenting.

⚠ **CAUTION**

Overpressure in reversible fuel cell!

Injuries due to objects shooting out, when the top of the overflow compartments of the gas storage cylinders is obstructed.

➔ Do not block the top of the overflow compartments of the gas storage cylinders.

➔ Always wear eye protection.

⚠ **CAUTION**

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

➔ No open flames.

➔ No smoking.

➔ Well ventilated workspace.

✓ Goggles or eye protection

✓ Solar panel or hand generator

Student's Section

TIP

As an alternative to the solar panel your teacher may also ask you to use the hand generator as a source for electrical energy (see Instruction Manual).

- ✓ 2 patch cords
- ✓ Reversible fuel cell
- ✓ Car with motor
- ✓ Distilled water
- ✓ 100–120 watts PAR lamp, or equivalent light source (only when you use the solar panel)
- ✓ Watch with second hand or stopwatch function

Filling the reversible fuel cell with distilled water

1. Put on your goggles.
2. Place the fuel cell upside down (numbers facing down) on the flat surface.
3. Remove the stoppers.

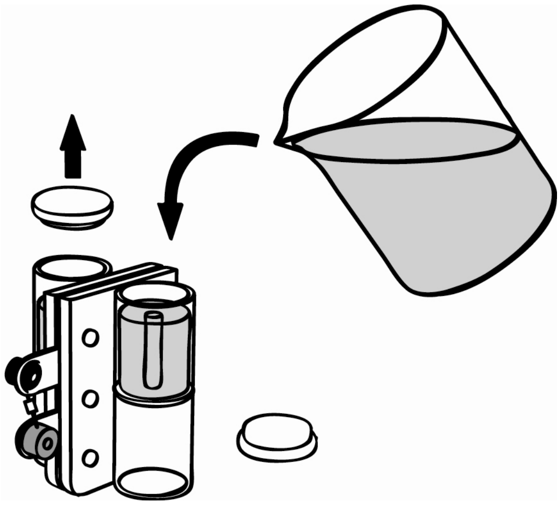


Fig. 9-8 Filling the reversible fuel cell with distilled water

NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the reversible fuel cell.

4. Pour distilled water into both storage cylinders until the water reaches the tops of the small tubes in the center of the cylinders.
5. Tap the fuel cell lightly to help water flow into the area surrounding the membrane and metal current-collecting plates.
6. Add more water until it starts to overflow into the tubes in the cylinders.
7. Place the stoppers back onto the cylinders. Make sure no air is trapped inside the cylinder.

TIP

A small air bubble in the order of 0.5 mL will not cause problems and can be ignored.

8. Turn the reversible fuel cell right side up.

Producing hydrogen

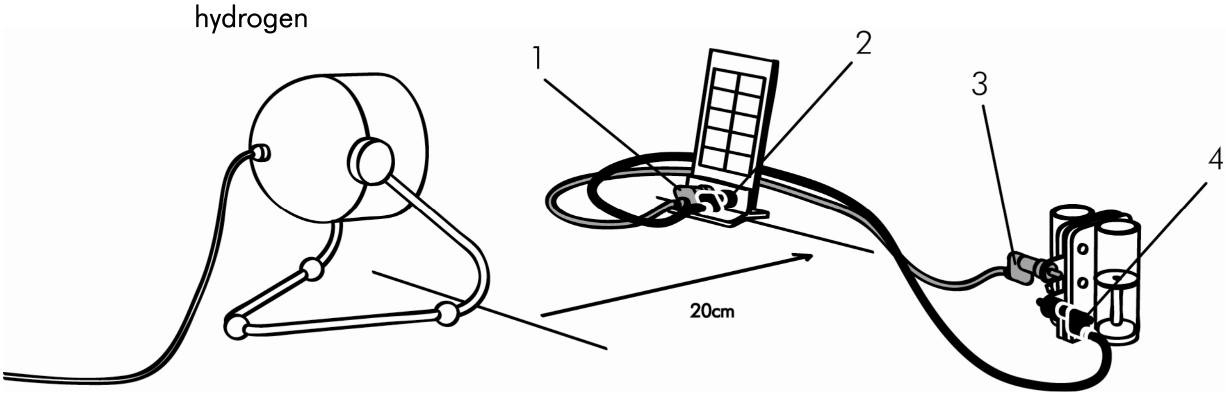


Fig. 9-9 Producing hydrogen

9. Plug the red banana jacks of the red patch cord into the red (positive) banana jack terminals of the solar panel (1) and the fuel cell (3).

NOTICE

Short circuit of reversible fuel cell!

Hot spots in the membrane, leading to deterioration of the membrane.

➔ Do not short circuit the reversible fuel cell.

10. Repeat step 9 with the black patch cord and the negative terminals (2, 4).

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light with a reflector.

11. Align the solar panel with the light source, keeping a minimum distance of 20 cm (8 inches).

CAUTION

Hot surface of solar panel and lamp!

Skin burns.

- ➔ Do not touch the hot surface of the solar panel or lamp.
- ➔ Allow solar panel / lamp to cool down before touching it.

12. Turn on the light.
13. When the hydrogen storage cylinder is filled to a little more than 12 mL:
    - Turn off the light.
    - Unplug the patch cords from the reversible fuel cell.

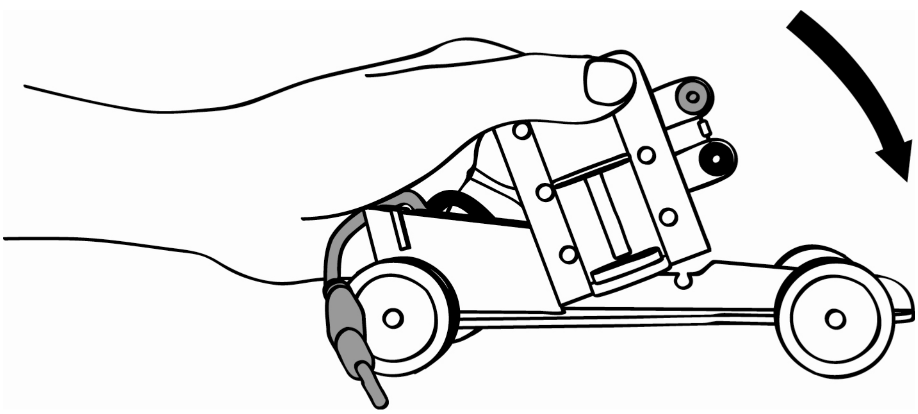


Fig. 9-10 Placing reversible fuel cell onto Model Car

14. With the red and black terminals facing towards the front of the car, place the reversible fuel cell into the notches on the model car until it audibly clicks into place.
15. Considering the space you have available, decide if you want to run the car in a straight line, or in a circle. If you will run the car in a circle:
    – Position the car on the floor and turn the front wheels so that the car will run in a fairly small circle without hitting anything.

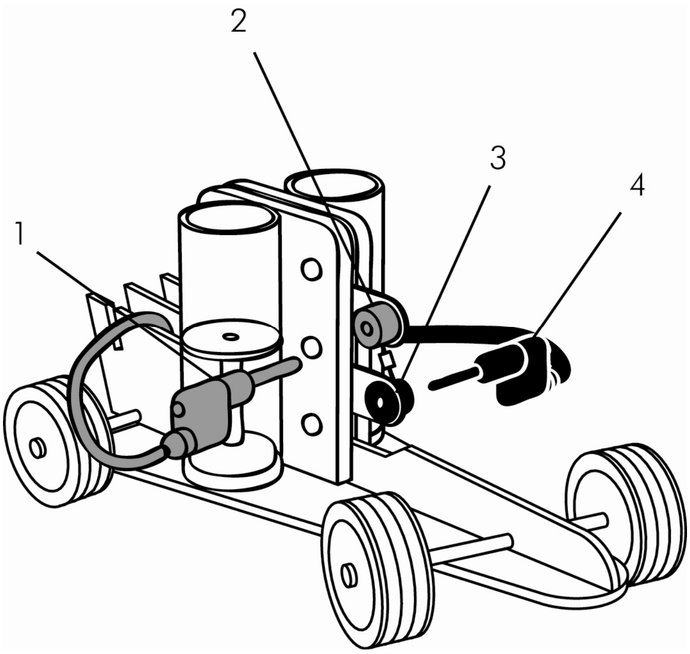


Fig. 9-11 Connecting the car

Running the car

16. Connect the red (positive) banana jack (1) with the red (positive) terminal (2) and the black (negative) banana jack (4) with the black (negative) terminal (3).

The car starts running.

17. Adjust the front wheels and the car position until you are satisfied with the circle the car is making.
18. Use chalk or a piece of tape to mark a point on the circle and another point exactly opposite. Mark where the center of the car travels, not the outside or inside wheels.
19. Disconnect one of the patch cords so the motor stops.

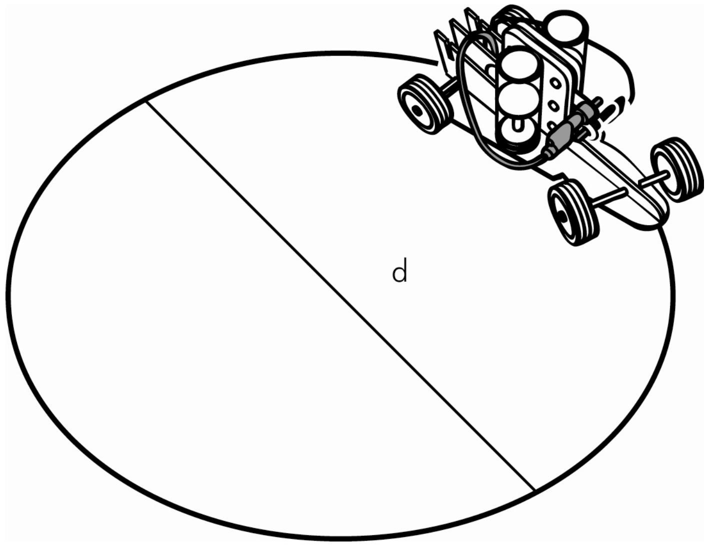


Fig. 9-12 Diameter of the driving circle

Trial	H_2 at start [mL]	H_2 at end [mL]	H_2 used in 1 minute [mL]	H_2 used in 2 minutes [mL]	Number of circuits	Distance travelled [m]
1				–		
2				–		
3				–		
4				–		
5			–			
6			–			
7			–			
8			–			

Table 9-4 Data

Get results!

20. Measure the diameter of the driving circle and write it down and calculate the length of the circuit.
21. Note the amount of hydrogen in the storage cylinder and record it in the table.
22. Position the car on the floor.
23. Have a stopwatch ready at hand.
24. Connect the black and red patch cords from the motor to the fuel cell and let the car run. If your car does not move immediately give it a push to overcome the starting friction.
25. Start the stopwatch or note the time.
26. Let the car run for exactly one minute and count the number of circles it makes, or keep track of the straight-line distance travelled.

TIP

If the car runs into a wall quickly turn it around, send it back and let it continue until one minute is up.

Student's Section

27. Disconnect one of the wires so the motor stops.

Get results!

28. Note the amount of hydrogen in the storage cylinder, write it in the table, and calculate the amount used in one minute. Write the number of circuits and calculate the distance, or write the straight-line distance the car travelled.
29. If you have time, go back to step 3, and repeat the procedure several times.
30. Mark your "H_2 used in 1 minute" points in the graph.

Repeat the experiment with 2 minutes

31. Go back to step 26, and repeat the procedure, this time letting the car run for two minutes. If necessary, produce more hydrogen (see steps 9–13).
32. If you have time, go back to step 31, and repeat the procedure several times. If necessary, produce more hydrogen (see steps 9–13).
33. Mark your "H_2 used in 2 minutes" points in the graph.

Student's Section

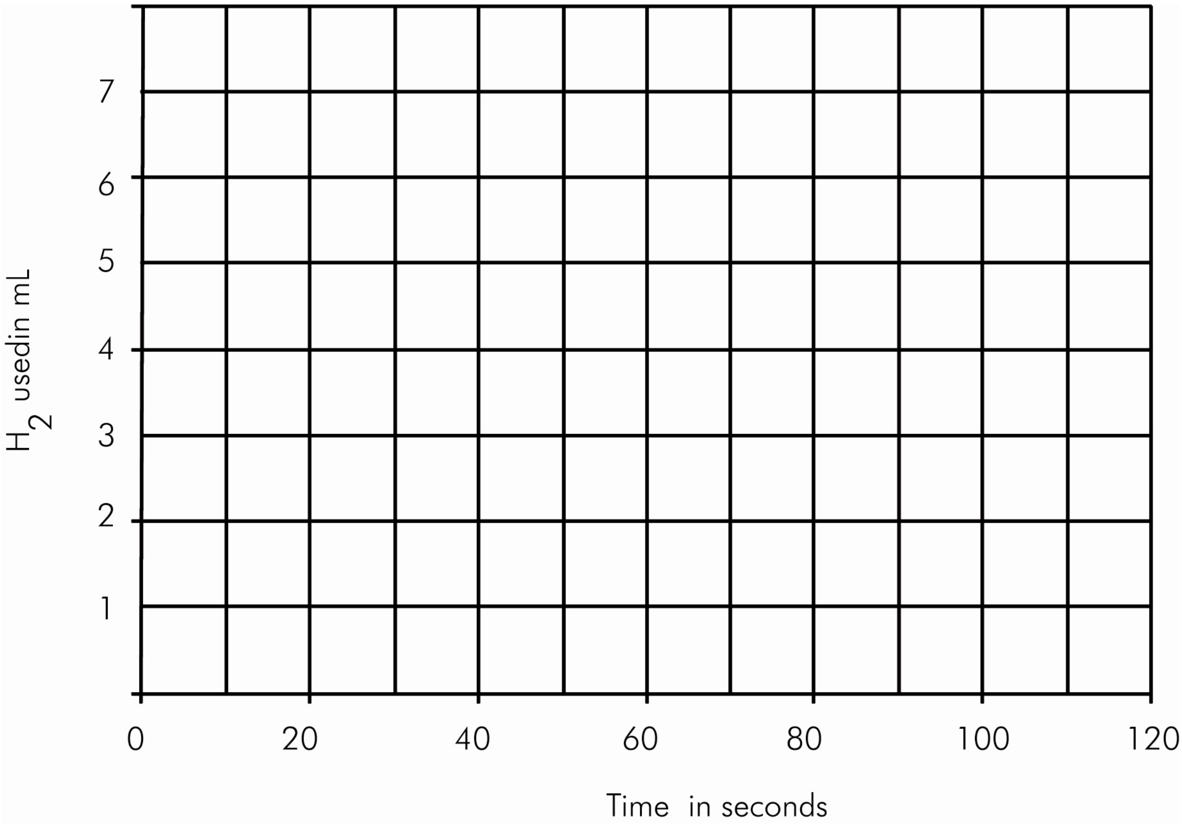


Fig. 9-13 Hydrogen consumption

34. If you have the results from Investigation Hydrogen Power! (when the wheels were turning but the car was not moving), take from it the rate of H_2 use. Add this information to the above graph.
35. On the following graph, mark the point describing distance traveled and hydrogen used for each trial.

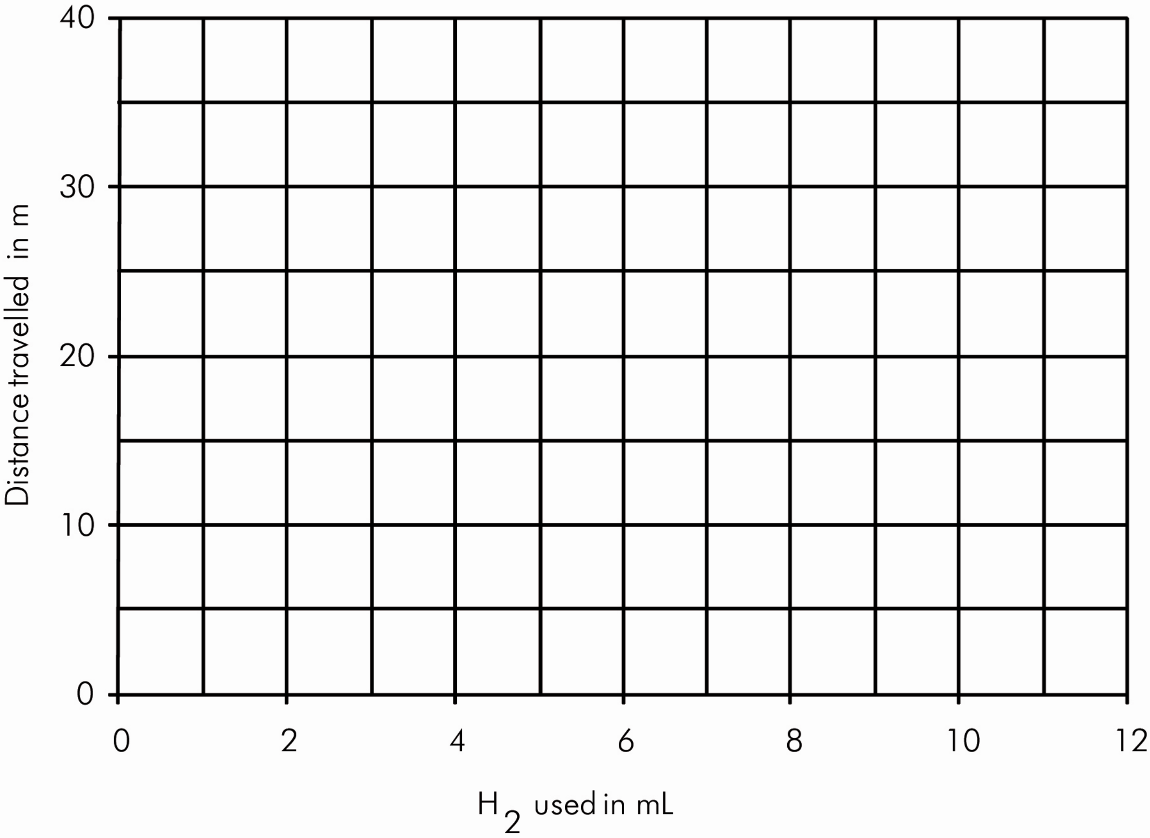


Fig. 9-14 Distance travelled as a function of hydrogen used

36. Disassemble the equipment, put it away and then take off your goggles and return them carefully.

9.3.2 Questions – Students

Use an extra sheet to answer the question.

Only when investigation Hydrogen Power! was performed before

1. What did you find when you compared the rate of hydrogen consumption in this investigation with investigation *HYDROGEN POWER*?

2. If you found a difference, what do you think caused this?

3. Can you think of any other examples of this from your personal experience?

4. How do you think this would affect cars in the future if they drove on flat or hilly roads? Is this effect similar to what happens to the cars we drive now?

5. Using your data on the distance your car travelled, how far did your car travel on 4 mL of hydrogen? How much hydrogen would you need to have your car travel exactly one kilometer? Show all your calculations.

10 Energy Efficiency

Electricity can be utilized to produce hydrogen and in turn hydrogen can be converted back to electricity. This offers a way to "store" electricity. But not all the electricity used to make the hydrogen may be recovered when the hydrogen is consumed in the fuel cell. Just how much is recovered and how much is lost is the subject of this investigation.

10.1 Teacher's Essentials

10.1.1 Objectives

Qualifications

In order to ensure maximum learning success, your students should already be familiar with:

- Power, work, energy
- Knowledge how to calculate volumes (L, mL, m^3, etc.)

Learning objectives

In this investigation your students will learn:

- Efficiency
- Transformation of energy

Outlook

This investigation may serve as a starting point for a variety of different topics, for example:

- Thermodynamics
- Gibbs Energy
- Ideal voltage
- Joule
- Ideal systems

10.1.2 Time Table

The amounts of time are rough estimates.

Task	**Time**
Preparation prior to class	20 min
Investigation	50 min
Time students will need to answer questions	35 min

Table 10-1: Schedule

10.1.3 Teaching Method

Method	Suitability
Group work	✓✓✓✓
Chalk and talk	✓
Silent work (student questions)	✓✓
Homework (student questions)	✓✓✓

Table 10-2: Teaching method (✓= poor … ✓✓✓✓=very good)

10.1.4 Background

In non-scientific writing the two words Power and Energy are often used interchangeably. In fact, they describe quite different concepts.

Power

When describing electrical events, the power (in watts) going into or out of a device can be determined by multiplying the current (in amperes) passing through the device by the voltage (in volts) that exists across that device. It can be written:

$I \times V = P$ (amperes × volts = watts)

Many examples will be familiar: a 1000 watt heater, a 200 watt amplifier, a 15 watt fluorescent lamp.

Power describes the strength of a process; it says nothing about the amount of work done.

Energy

Energy is a measure of power that continues over a certain time. A familiar example will be the use of kilowatt-hours in a household's electric utility bill. The energy used by various devices is not determined by their power only. A 15 watt fluorescent left on over a weekend will have consumed more energy than a 1000 watt heater used for a half-hour.

A common measure of energy is joule, the equivalent of a watt-second (one watt of power produced or consumed for one second). The amount of energy being used or supplied by a device can be determined by multiplying the power (in watts) by the time (in seconds) that power is used. We can write:

$P \times t = E$ (watts × seconds = joules = Ws)

Ws (joule)

As a measurement, Ws (joule) is used for more than electrical energy. For example, the exact composition of the gas that gas utilities deliver to their customers varies from month to month. Therefore gas utility companies often calculate customer bills according to the "joules" or heating value (see page 142) of the gas consumed. The utility company charges for the amount of energy that was consumed in gas that month. Whether or not actually that much energy (heat) was obtained, depends on your heating system and how you used the gas.

Efficiency

If all the energy in the gas is recovered, we would say the furnace is 100 % efficient. In reality, this does not happen. The types of furnaces being installed in houses typically have efficiency between 80 % and 96 %. That is, between 20 % and 4 % of the energy in the gas is wasted. In some older furnaces or furnaces that are poorly maintained the efficiency can drop below 50 %.

In this investigation, when we produce a known amount of hydrogen, we can measure the voltage and current that was applied to the electrolyzer and the duration of time it was applied. From this we can calculate the energy used to make that hydrogen.

Then in a fuel cell we can use that same amount of hydrogen to send current through a simulated electrical load, again noting the energy that was applied to the load.

Possibly not all the energy used to make the hydrogen will be recovered. Indeed, the question is important: what proportion is recovered?

We can calculate the fraction:

$$\eta = \frac{\text{Electrical energy produced from hydrogen in the fuel cell}}{\text{Electrical energy consumed to make hydrogen in the electrolyzer}}$$

We can then write this fraction as a percentage. This is the overall efficiency of the electrolyzer-fuel cell system.

Heating value

Overall efficiency calculates the ratio energy out / energy in. In order to determine, where most energy is lost, each step of the process has to be investigated.

It is helpful to know the amount of chemical energy that hydrogen gas contains. This is commonly called the energy density, or heating value. That is, the theoretically maximum amount of energy that could be obtained from a given amount of hydrogen in a perfect converter. The concept is similar to the gas utility billing its customers for the amount of heat that might be obtained in a perfect furnace.

The electrical efficiency of the electrolyzer, energy out / energy in, can be written as:

$$\eta = \frac{\text{Energy content of the hydrogen produced}}{\text{Electrical energy consumed in electrolyzer}}$$

Electrical efficiency

The electrical efficiency of the fuel cell, energy out / energy in, can be written as:

$$\eta = \frac{\text{Electrical energy produced in fuel cell}}{\text{Energy content of the hydrogen used}}$$

You obtain the overall efficiency of the two stages by simply multiplying the two efficiencies above. The two “energy content of the hydrogen” values cancel out, leaving as before:

$$\eta = \frac{\text{Electrical energy produced in fuel cell}}{\text{Electrical energy consumed in electrolyzer}}$$

Fuel cells do not convert all of the hydrogen’s energy to electricity.

So what becomes of the remaining energy?

As it may be expected, a significant part is lost as heat. But what if we could put that heat to some practical use?

The customary way to produce electricity today is by first burning fuel to produce heat in a combustion engine or turbine, and then driving a generator to produce electricity.

However a fuel cell uses hydrogen fuel to produce electrical energy through a direct process. If the secondary heat in a fuel cell can be utilized, we can include it in a “total efficiency” calculation:

Total efficiency = Electrical efficiency + Thermal efficiency

$$\eta = \frac{\text{Electrical energy produced in fuel cell + heat produced in fuel cell}}{\text{Energy content of the hydrogen}}$$

Waste heat

Electrical generating systems that use the waste heat, whether they are fuel cells or conventional steam – or gas-turbines, are called Combined Heat and Power (CHP) systems. Most electrical generators convert only a third of the fuel's energy into electricity. Where heat is needed as well as electricity, a CHP system is 30–35 % more efficient than separate heat and power systems, converting as much as 85 % of the fuel into usable energy. CHP systems save energy, pollute less and are very reliable.

Fuel cell CHP systems can provide space heat, hot water, steam, process heating and cooling, depending on what kind of heat is generated and needed. Some fuel cell systems produce low temperature heat, and only warm air or water can be recovered. Other systems produce high temperature heat, so steam can be generated. High temperature heat is needed to produce a cooling effect, using absorption chillers and other specialized equipment.

Fuel cell CHP systems can reach overall efficiencies of 85 % with about 45 % electrical and 40 % thermal efficiency.

10.2 The Investigations – Teachers

10.2.1 Preparation

It is advisable that you try out this investigation before class.

10.2.2 In Class

Depending on your didactic approach and the number of Model Car kits at hand, you may either choose group work or chalk and talk teaching.

Safety

- ➔ Always make your students aware of investigating safely and make yourself familiar with the potential hazards.
- ➔ Make sure to provide the students with goggles and to wear goggles yourself.

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light with a reflector.

CAUTION

Overpressure in reversible fuel cell!

Injuries due to objects shooting out, when the top of the overflow compartments of the gas storage cylinders is obstructed.

- ➔ Do not block the top of the overflow compartments of the gas storage cylinders.
- ➔ Always wear eye protection.

⚠ **CAUTION**

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

- ➔ No open flames.
- ➔ No smoking.
- ➔ Well ventilated workspace.

⚠ **CAUTION**

Hot surface of solar panel and lamp!

Skin burns.

- ➔ Do not touch the hot surface of the solar panel or lamp.
- ➔ Allow solar panel / lamp to cool down before touching it.

10.2.2.2 Group Work

For group work several Model Car kits are required.

For this investigation it is recommended to have the students perform the investigation themselves.

10.2.2.3 Chalk and Talk

This investigation is highly recommended as group work. However, if you only have one Model Car kit at hand, we recommend that you have a small group of students assist you in doing the first part of the investigation and another group assisting you with the second part.

Investigation

In this investigation you need to perform two parts of an investigation:

- Determination of the electrical energy used while producing hydrogen
- Determination of the electrical energy produced while consuming hydrogen as a fuel

✓ Goggles or eye protection

✓ Solar panel or hand generator

TIP

As an alternative to the solar panel you may also use the hand generator as a source for electrical energy (see Instruction Manual).

- ✓ Reversible fuel cell
- ✓ Load measurement box
- ✓ 5 patch cords
- ✓ Distilled water
- ✓ 100–120 watts PAR lamp
- ✓ Watch with second hand or stopwatch function

Filling the reversibel fuel cell with distilled water

1. Put on your goggles.
2. Place the fuel cell upside down (numbers facing down) on the flat surface.
3. Remove the stoppers.

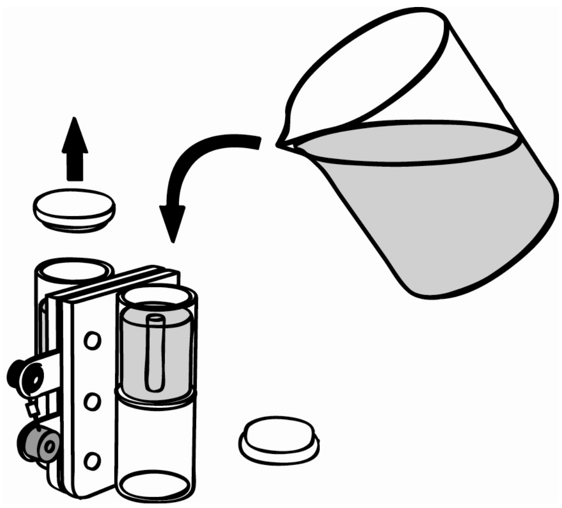


Fig. 10-1 Filling the reversible fuel cell with distilled water

NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the reversible fuel cell.

4. Pour distilled water into both storage cylinders until the water reaches the tops of the small tubes in the center of the cylinders.
5. Tap the fuel cell lightly to help water flow into the area surrounding the membrane and metal current-collecting plates.
6. Add more water until it starts to overflow into the tubes in the cylinders.
7. Place the stoppers back onto the cylinders. Make sure no air is trapped inside the cylinder.

TIP

A small air bubble in the order of 0.5 mL will not cause problems and can be ignored.

8. Turn the fuel cell right side up.

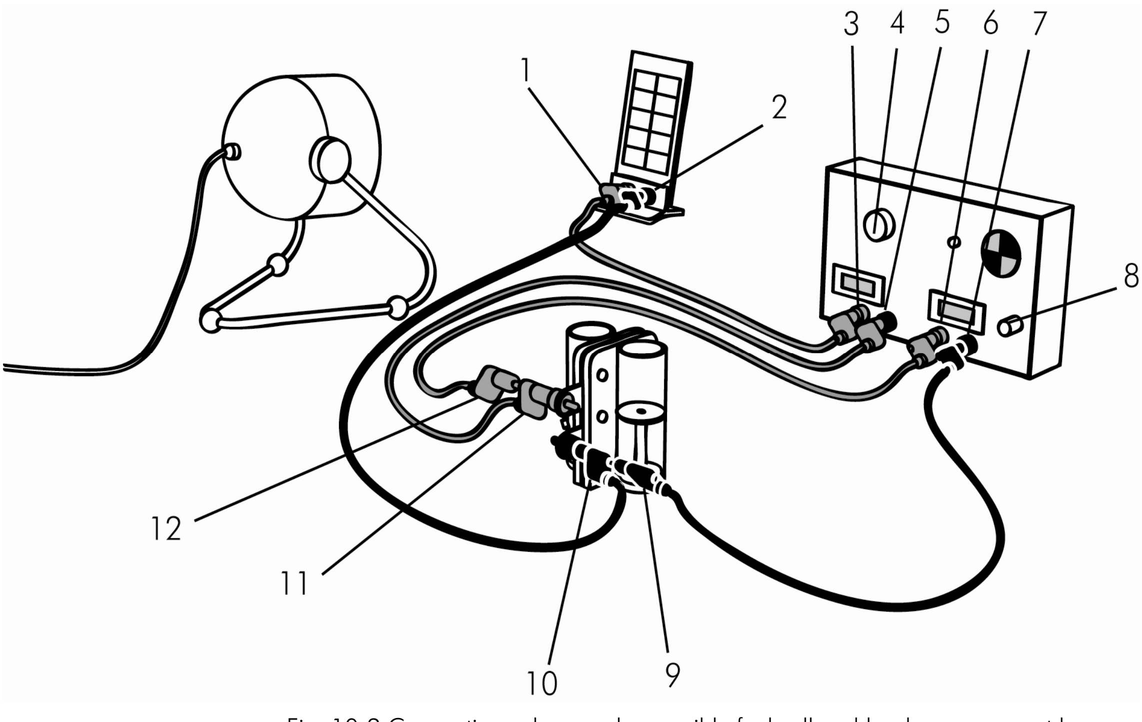


Fig. 10-2 Connecting solar panel, reversible fuel cell and load measurement box

9. Connect the red (positive) terminal of the solar panel (1) to the red (positive) terminal of the ammeter (3).
10. Connect the black (negative) terminal of the solar panel (2) to the black (negative) terminal of the reversible fuel cell (10).
11. Connect the red (positive) terminal of the reversible fuel cell (11) with the black (negative) terminal of the ammeter (5).

12. Connect the black (negative) terminal of the reversible fuel cell (9) with the black (negative) terminal (7) of the voltmeter.
13. Connect the red (positive) terminal of the reversible fuel cell (12) with the red (positive) terminal of the voltmeter (6).

The setup is now ready for the investigations.

PART 1: Determination of the energy used while producing hydrogen

In this part the reversible fuel cell will be used as an electrolyzer and the energy needed to produce hydrogen is specified.

- ✓ Stop watch at hand

1. Push the *ON / OFF* button (8).
2. Set the *LOAD* knob (4) to *SHORT CIRCUIT*.

! NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light.

⚠ CAUTION

Hot surface of solar panel and lamp!

Skin burns.

- ➔ Do not touch the hot surface of the solar panel or lamp.
- ➔ Allow solar panel/ lamp to cool down before touching it.

3. Turn on the light.
4. Position the solar panel and light so that the current is in the range of 150 mA–200 mA, but they are not closer than 20 cm.

The reversible fuel cell (electrolyzer) starts producing hydrogen.

Student participation

5. When the level of gas in the hydrogen storage cylinder reaches 4 mL, have a student start the stopwatch.
6. Have students observe and write down the current and the voltage.

e. g. *Current: 0.150 A*

Voltage: 1.630 V

7. When the hydrogen gas level has reached 10 mL, have a student stop the stopwatch and let the class write down the elapsed time.

   e. g. Time elapsed: 300 s

8. Let the electrolyzer continue to run until the gas level has reached 12 mL.
9. Turn off the light and disconnect the patch cords.

Evaluating the data

10. Have students multiply the current and voltage to obtain the power (in watts) taken up by the electrolyzer.

    Power: 0.245 W

11. Have students multiply the power and elapsed time to obtain the energy used to produce 6 mL of hydrogen.

    Energy: 73.4 W s

Part 2: Determination of the energy produced while consuming hydrogen as a fuel

In this part the reversible fuel cell is used as a fuel cell and the energy output is measured.

TIP

In Part 2 it is expected that the values of current and voltage will vary from cell to cell.

It might also happen that current and voltage gradually decrease from the start of the measurement to the end. If students notice this decrease they might record in step 6 the current and voltage at the end (4 mL point), as well as at the beginning (10 mL point). Then in step 11 they can calculate the average power produced during the time the 6 mL of hydrogen was consumed.

If this decrease is excessive (more than 20 %) try purging the cell, as described in the Instruction Manual.

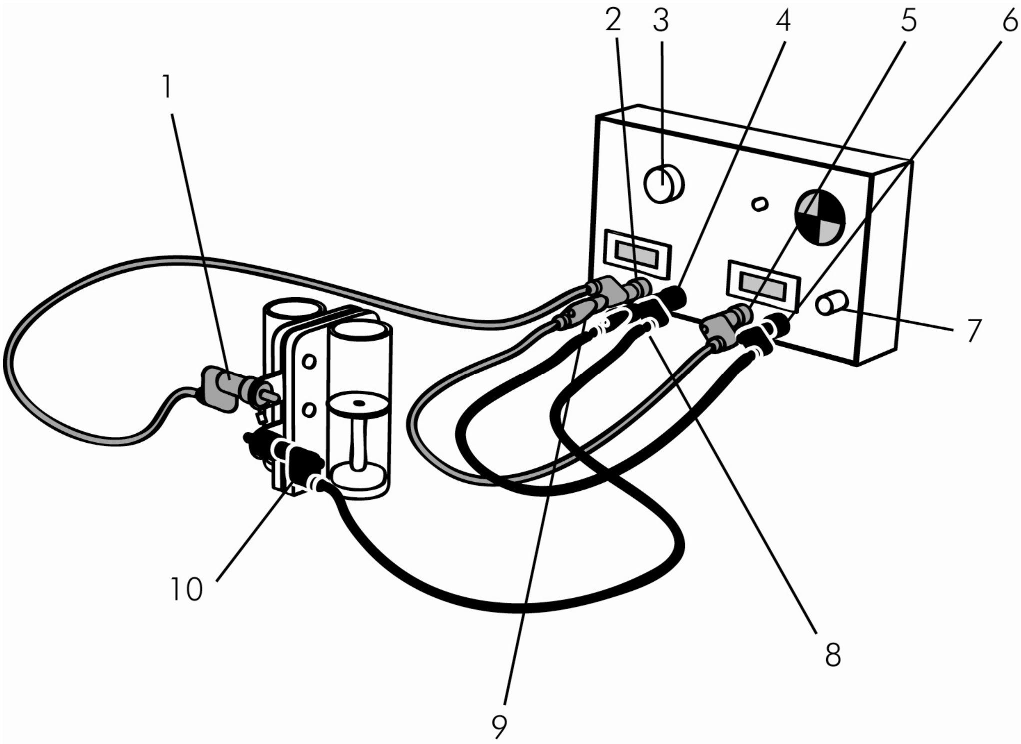


Fig. 10-3 Connecting the fuel cell with the load measurement box

To connect the fuel cell to the load measurement box:

> **NOTICE**
>
> **Short circuit of reversible fuel cell!**
>
> Hot spots on the membrane.
>
> ➔ Do **not** set the *LOAD* knob to *SHORT CIRCUIT*.
>
> ➔ Set the *LOAD* knob to *OPEN*.

1. Set the load measurement box *LOAD* knob (3) to *OPEN* and push the *ON / OFF* button (7).
2. Plug the red (positive) banana jack (1) into the red (positive) terminal of the reversible fuel cell and the other end into the red (positive) terminal (2) of the ammeter.
3. Repeat step 2 for the black (negative) terminals (10, 4).
4. Plug the red (positive) banana jack onto the red banana jack in the ammeter terminal (9) and plug it into the red (positive) terminal (5) in the voltmeter.
5. Do the same with the black cord and the black (negative) terminals (8, 6).

6. Set the *LOAD knob (3)* to 3 Ω.

The fuel cell starts consuming hydrogen and oxygen.

Student participation

7. When the level of gas in the hydrogen storage cylinder reaches exactly 10 mL, have student start the stopwatch.
8. Have students observe and write down the current and the voltage.

   Current: 0.213 A

   Voltage: 0.648 V

9. When the hydrogen gas level has decreased to 4 mL, have student stop the stopwatch and write down the elapsed time.

   Time elapsed: 180 s

10. Disassemble the equipment, put it away and then take off your goggles.

Evaluating the data

11. Have students multiply the current and voltage to obtain the power (in watts) the fuel cell is generating.

    Power: 0.138 W

12. Have students multiply the power and elapsed time to obtain the energy produced while consuming 6 mL hydrogen.

    Energy: 24.8 W s

13. With the results from Part 1, have students calculate the overall efficiency of the electrolyzer-fuel cell system.

    Overall efficiency: 33.8 %

10.2.3 Silent Work

The students can be encouraged to answer the questions in section *QUESTIONS* on page 161 in silent work or partner work. This depends on the students' abilities and the didactic approach.

10.2.4 Homework

The questions provided in section *QUESTIONS* on page 161 can be used for homework as well, if the students do not need the teacher's assistance to answer them.

10.2.5 Questions and Answers

The students may require a copy of the *BACKGROUND* section in order to answer the questions.

1. In this investigation we used a resistor as a simulated load. Why did we use this and not the car motor?

Using a resistor in the load box as a simulated load gives us more flexibility to choose different resistances and currents.

2. When making hydrogen, we measured the current through the electrolyzer, but isn't some of that current flowing through the voltmeter too? Should we consider this current?

   The current we measured while making hydrogen was the sum of current flowing through the electrolyzer and current through the voltmeter. But the voltmeter has such a high resistance that the current flow is very small and can be ignored.

3. Our calculations of energy-in and energy-out were described in terms of making and using hydrogen. What about the oxygen? Does it matter?

   Both hydrogen and oxygen are produced and both are used. Because we compared the total energy input and total energy output, any contribution from the oxygen was included in the final comparison.

4. Do you suppose the fuel cell might be more or less efficient if we run it at a different current? Increasing the resistance of the simulated load will result in a lower current and therefore the fuel cell will take longer to consume the same amount of hydrogen. But will the total energy obtained from the hydrogen be about the same? If you have time, repeat the investigation using a load of 5 or 10 Ω. In order to get through the steps quickly, you might make and use a smaller volume of hydrogen, less than 6 mL.

   When the fuel cell operates at a higher resistance (lower current), its efficiency is slightly better (higher).

   The volume of hydrogen produced and consumed will not change the efficiency, although doing the investigation with a smaller volume does increase the effect of experimental error when reading the gas levels.

5. So, what do you think: Where did the energy go?

   More electricity was used to make hydrogen than was recovered with the fuel cell. Probably some of the missing energy was lost as heat.

6. Are the individual efficiencies of the electrolyzer and the fuel cell about the same? A table of physical constants will tell us that the energy density of hydrogen is 33.3 kW hr/kg. Can you determine the efficiency of each stage of the electrolyzer–fuel cell process?

   Here's a start. Knowing that the density of hydrogen gas at room temperature is 12 m^3/kg, we can use unit-cancellation to convert "kW hr/kg" to a more convenient term for our investigation:

$$\frac{33.3\text{ kW hr}}{\text{kg}} \times \frac{\text{kg}}{12\text{m}^3} \times \frac{1000\text{ W}}{1\text{ kW}} \times \frac{1\text{ m}^3}{1000000\text{ cm}^3} \times \frac{1\text{cm}^3}{1\text{ mL}} \times \frac{3600\text{ s}}{1\text{ hr}} = \frac{9.99(\text{Ws})}{\text{mL}}$$

Efficiency is the ratio energy out / energy in – thus a dimensionless ratio.

Electrolyzer efficiency is:

$$\eta_{El} = \frac{\text{Energy content of 6 mL hydrogen produced}}{\text{Energy used by the electrolyzer making 6 mL hydrogen}}$$

$$\frac{6\ mL \times 10\ Ws/mL}{73.4\ Ws} \times 100\ \% = 81.7\ \%$$

Fuel cell efficiency is:

$$\eta_{FC} = \frac{\text{Energy produced by fuel cell consuming 6 mL hydrogen}}{\text{Energy content of 6 mL hydrogen}}$$

$$= \frac{24.8\ Ws}{6\ mL\ 10\ Ws/mL} \times 100\ \% = 41.3\ \%$$

So the efficiencies of the electrolyzer and the fuel cell are not the same; the electrolyzer is approximately twice as efficient as the fuel cell. The overall efficiency of the electrolyzer-fuel cell system is the product of the individual efficiencies:

$$\eta_{total} = \eta_{El} \times \eta_{FC}$$

$$(81.7\ \%) \times (41.3\ \%) = 33.7\ \%$$

7. One way to calculate the amount of "lost" power in a fuel cell is to consider the theoretical cell voltage of a hydrogen-oxygen cell. This value, 1.23 volts, represents the ideal voltage of a perfect (but unrealizable) fuel cell. The difference between this ideal voltage and the actual voltage, which you measured in step 8, provides a way to calculate the lost power.
   Recall that current × voltage = power.
   Using the theoretical cell voltage, and the voltage and current measurements from step 8, calculate the power loss inside the fuel cell. What happens to this power?

   From the observed values of 0.213 A and 0.648 V:

   current × voltage loss = power loss

   0.213 A × (1.23 – 0.648) V = 0.124 W = power loss inside the fuel cell

   This power loss is related to energy in the fuel cell that cannot be used to produce electricity. Some of the lost power appears as heat.

8. With practical technology, some but not all the lost power can be recovered as heat. Perhaps 70 % can be recovered and used. In your fuel cell, this is a small amount of power, and it may be hard to get a sense of its magnitude. Again using your observations from step 8, calculate the ratio of "recoverable heat" to electrical power produced.

   We can't recover 0.124 W, but we might recover 70 % of that, or 0.087 W.

Electrical power that the fuel cell is generating: 0.138 W

ratio of "recoverable heat" to electrical power produced

= 0.087 W / 0.138 W = 0.63

9. In a larger fuel cell power unit, say 50 kW (typical for a fuel cell car) how much secondary heat could be utilized? Assume this power unit has the same efficiency characteristics as the fuel cell in your investigation.

   At the calculated ratio, a 50 kW fuel cell automobile power unit might at peak output provide an additional 50 kW $\times$ 0.63 = 32 kW in heat.

10.3 Student's Section

10.3.1 The Investigation

Safety

➔ Wear goggles when experimenting.

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

➔ Only use light sources with a maximum power of 120 W.

➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.

➔ Do not concentrate light with a reflector.

CAUTION

Overpressure in reversible fuel cell!

Injuries due to objects shooting out, when the top of the overflow compartments of the gas storage cylinders is obstructed.

➔ Do not block the top of the overflow compartments of the gas storage cylinders.

➔ Always wear eye protection.

CAUTION

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

➔ No open flames.

➔ No smoking.

➔ Well ventilated workspace.

Student's Section

CAUTION

Hot surface of solar panel and lamp!

Skin burns.

- ➔ Do not touch the hot surface of the solar panel or lamp.
- ➔ Allow solar panel / lamp to cool down before touching it.

In this investigation you need to perform two parts of an investigation:

- Determination of the energy used while producing hydrogen
- Determination of the energy produced while consuming hydrogen as a fuel

- ✓ Goggles or eye protection
- ✓ Solar panel or hand generator
- ✓ Reversible fuel cell
- ✓ Load measurement box
- ✓ 5 patch cords
- ✓ Distilled water
- ✓ 100–120 watts PAR lamp, or equivalent light source
- ✓ Watch with second hand or stopwatch function

Filling the reversibel fuel cell with distilled water

1. Put on your goggles.
2. Place the fuel cell upside down (numbers facing down) on the flat surface.
3. Remove the stoppers.

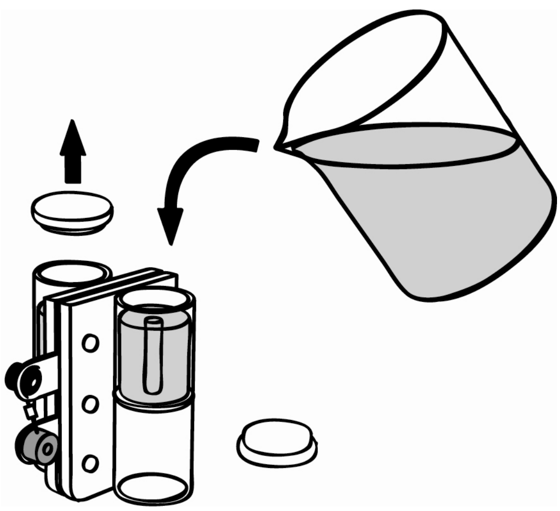


Fig. 10-4 Filling the reversible fuel cell with distilled water

NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the reversible fuel cell.

4. Pour distilled water into both storage cylinders until the water reaches the tops of the small tubes in the center of the cylinders.
5. Tap the fuel cell lightly to help water flow into the area surrounding the membrane and metal current-collecting plates.
6. Add more water until it starts to overflow into the tubes in the cylinders.
7. Place the stoppers back onto the cylinders. Make sure no air is trapped inside the cylinder.

TIP

A small air bubble in the order of 0.5 mL will not cause problems and can be ignored.

8. Turn the fuel cell right side up.

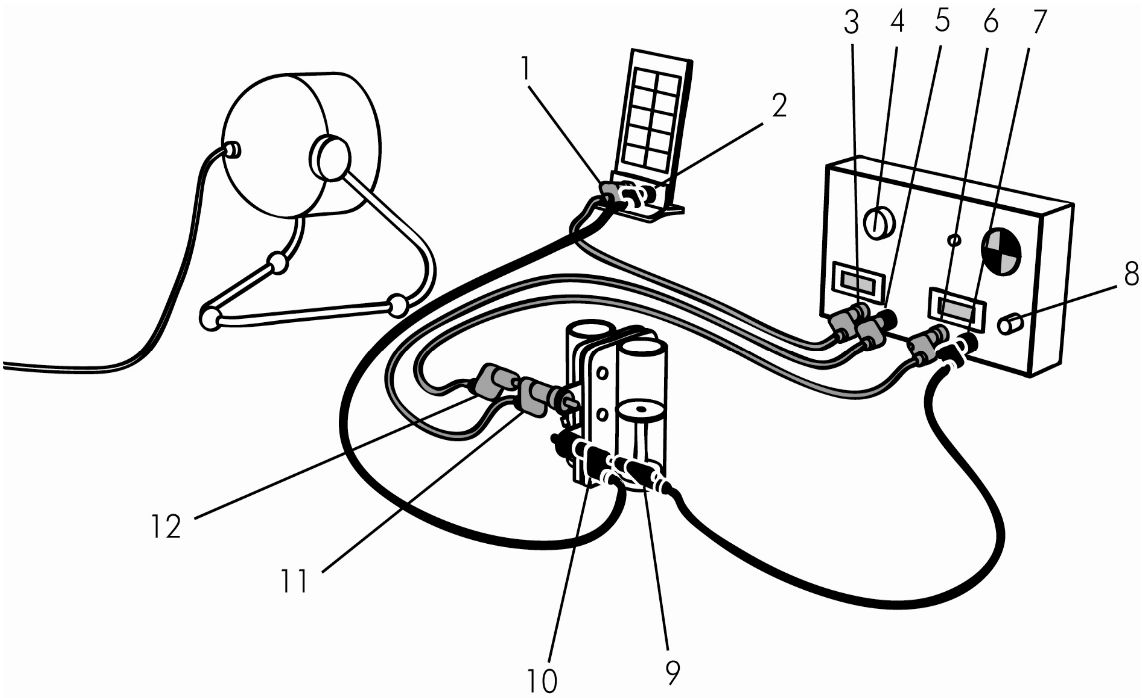


Fig. 10-5 Connecting solar panel, reversible fuel cell and load measurement box

9. Connect the red (positive) terminal of the solar panel (1) to the red (positive) terminal of the ammeter (3).
10. Connect the black (negative) terminal of the solar panel (2) to the black (negative) terminal of the reversible fuel cell (10).
11. Connect the red (positive) terminal of the reversible fuel cell (11) with the black (negative) terminal of the ammeter (5).
12. Connect the black (negative) terminal of the reversible fuel cell (9) with the black (negative) terminal (7) of the voltmeter.
13. Connect the red (positive) terminal of the reversible fuel cell (12) with the red (positive) terminal of the voltmeter (6).

The setup is now ready for the investigations.

PART 1: Determination of the energy used while producing hydrogen

In this part the reversible fuel cell will be used as an electrolyzer and the energy needed to produce hydrogen is specified.

✓ Stop watch at hand

1. Push the *ON* / OFF button (8).
2. Set the *LOAD* knob (4) to *SHORT CIRCUIT*.

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

➔ Only use light sources with a maximum power of 120 W.

➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.

➔ Do not concentrate light with a reflector.

CAUTION

Hot surface of solar panel and lamp!

Skin burns.

➔ Do not touch the hot surface of the solar panel or lamp.

➔ Allow solar panel/ lamp to cool down before touching it.

3. Turn on the light.
4. Position the solar panel and light so that the current is in the range of 150 mA–200 mA, but they are not closer than 20 cm.

The reversible fuel cell (electrolyzer) starts producing hydrogen.

5. When the level of gas in the hydrogen storage cylinder reaches 4 mL, start the stopwatch.

Get results!

6. Observe the current and the voltage and write them down.
7. When the hydrogen gas level has reached 10 mL, stop the stopwatch and write down the elapsed time.
8. Let the electrolyzer continue to run until the gas level has reached 12 mL.
9. Turn off the light and disconnect the patch cords.

Evaluating the data

10. Multiply the current and voltage to obtain the power (in watts) taken up by the electrolyzer.
11. Multiply the power and elapsed time to obtain the energy used to produce 6 mL of hydrogen.

Part 2: Determination of the energy produced while consuming hydrogen as a fuel

In this part the reversible fuel cell is used as a fuel cell and the energy output is measured.

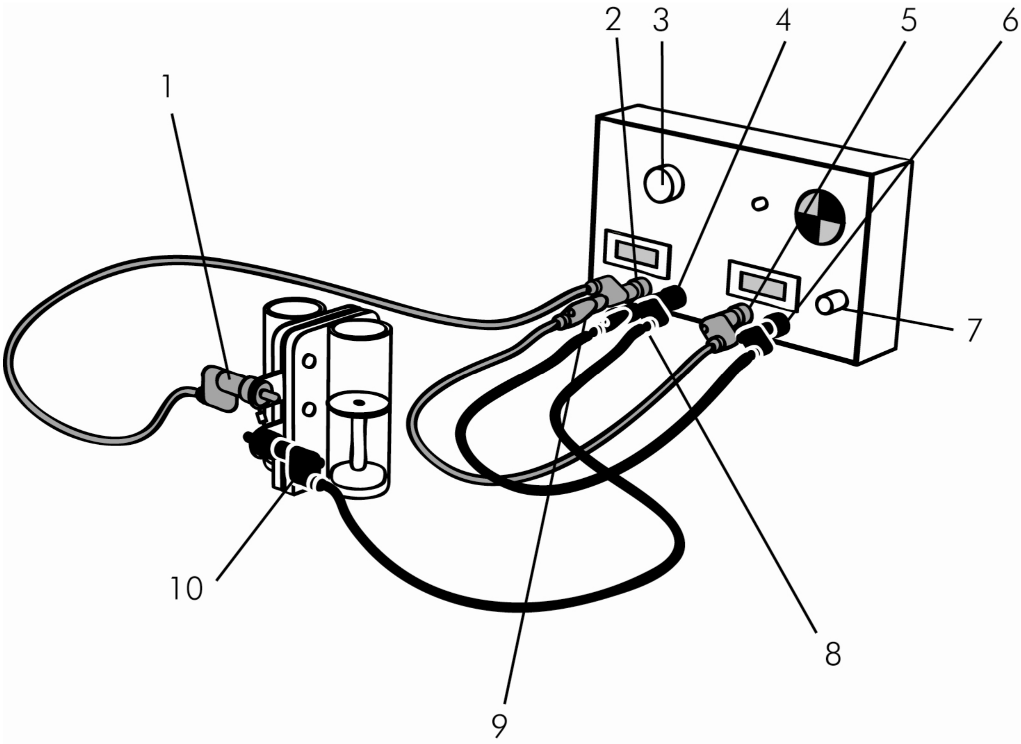


Fig. 10-6 Connecting reversible fuel cell and load measurement box

To connect the fuel cell to the measurement load box:

NOTICE

Short circuit of the reversible fuel cell!

Hot spots on the membrane.

➔ Do **not** set the *LOAD* knob to *SHORT CIRCUIT*.

➔ Set the *LOAD* knob to *OPEN*.

1. Set the measurement load box *LOAD* knob (3) to *OPEN* and push the *ON / OFF* button (7).
2. Plug the red (positive) banana jack (1) into the red (positive) terminal of the reversible fuel cell and the other end into the red (positive) terminal (2) of the ammeter.
3. Repeat step 2 for the black (negative) terminals (10, 4).
4. Plug the red (positive) banana jack onto the red banana jack in the ammeter terminal (9) and plug it into the red (positive) terminal in the voltmeter (5).
5. Do the same with the black cord and the black (negative) terminals (8, 6).

6. Set the *LOAD* knob to 3 Ω.

The fuel cell starts consuming hydrogen and oxygen.

7. When the level of gas in the hydrogen storage cylinder reaches exactly 10 mL, start the stopwatch.

Get results!

8. Observe the current, and the voltage and write them down.
9. When the hydrogen gas level has decreased to 4 mL, stop the stopwatch and write down the elapsed time.
10. Disassemble the equipment, put it away and then take off your goggles and return them carefully.

Evaluating the data

11. Multiply the current and voltage to obtain the power (in watts) the fuel cell is generating.
12. Multiply the power and elapsed time to obtain the energy produced while consuming 6 mL hydrogen.
13. With the results from Part 1, calculate the overall efficiency of the electrolyzer-fuel cell system.

10.3.2 Questions – Students

Use an extra sheet to answer the question.

1. In this investigation we used a resistor as a simulated load. Why did we use this and not the car motor?

2. When making hydrogen, we measured the current through the electrolyzer, but isn't some of that current flowing through the voltmeter too? Should we consider this current?

3. Our calculations of energy-in and energy-out were described in terms of making and using hydrogen. What about the oxygen? Does it matter?

4. Do you suppose the fuel cell might be more or less efficient if we run it at a different current? Increasing the resistance of the simulated load will result in a lower current, and therefore the fuel cell will take longer to consume the same amount of hydrogen. But will the total energy obtained from the hydrogen be about the same? If you have time, repeat the investigation using a load of 5 or 10 Ω. In order to get through the steps quickly, you might make and use a smaller volume of hydrogen, less than 6 mL.

5. So, what do you think: Where did the energy go?

6. Are the individual efficiencies of the electrolyzer and the fuel cell about the same? A table of physical constants will tell us that the energy density of hydrogen is 33.3 kW hr/kg. Can you determine the efficiency of each stage of the electrolyzer–fuel cell process?

Here's a start. Knowing that the density of hydrogen gas at room temperature is 12 m^3/kg, we can use unit-cancellation to convert "kW hr/kg" to a more convenient term for our investigation:

$$\frac{33.3\ \text{kW hr}}{\text{kg}} \times \frac{\text{kg}}{12\text{m}^3} \times \frac{1000\ \text{W}}{1\ \text{kW}} \times \frac{1\ \text{m}^3}{1000000\ \text{cm}^3} \times \frac{1\text{cm}^3}{1\ \text{mL}} \times \frac{3600\ \text{s}}{1\ \text{hr}} = \frac{9.99(\text{W s})}{\text{mL}}$$

7. One way to calculate the amount of "lost" power in a fuel cell is to consider the theoretical cell voltage of a hydrogen-oxygen cell. This value, 1.23 volts, represents the ideal voltage of a perfect (but unrealizable) fuel cell. The difference between this ideal voltage and the actual voltage, which you measured in step 6, provides a way to calculate the lost power.
   Using the theoretical cell voltage, and the voltage and current measurements from step 6, calculate the power loss inside the fuel cell. What happens to this power?
   Recall that current × voltage = power

8. With practical technology, some but not all the lost power can be recovered as heat. Perhaps 70 % can be recovered and used. In your fuel cell, this is a small amount of power, and it may be hard to get a sense of its magnitude. Again using your observations from step 6, calculate the ratio of "recoverable heat" to electrical power produced.

9. In a larger fuel cell power unit, say 50 kW (typical for a fuel cell car) how much secondary heat could be utilized? Assume this power unit has the same efficiency characteristics as the fuel cell in your investigation.

11 What Is a Hybrid?

The major goal of this investigation is that each team of students produces a report, which shows they understand why fuel continues to be necessary for powered transportation. An additional goal is that students will design and perform investigations using the Model Car to explore hybrid vehicles, in particular using solar energy to assist the fuel cell.

11.1 Teacher's Essentials

This investigation differs from the didactical approaches of the prior investigations as it aims solely at group work.

Placing students in a simulated adult situation can result in more sophisticated behavior as they begin to think as maturely as they can.

11.1.1 Objectives

Qualifications

In order to ensure maximum learning success, your students should already be familiar with:

- Electrical circuits
- Ability to write reports
- Solar cells
- Fuel cells
- Electrolysis

Learning objectives

All students should reach this expected outcome:

1. Solar energy has advantages, but is not suitable to run a car directly, on its own. If the sun is not shining, no energy is produced. Through researching the literature, students may also learn that with present solar array technology, the amount of power produced per unit area (the power density) is not enough to power a passenger car which typically has a 50 kW engine.
2. One way around this problem is to use solar energy to produce a fuel. A large stationary solar array can power an electrolyzer, generating hydrogen. The hydrogen is later used in a fuel cell-powered vehicle. This is solar power, but with an intermediary. A car needs a fuel, because the driver wants to be independent of sunlight.
3. Various hybrid vehicles both in development and in production, combine different methods of propulsion. Examples include the Toyota Prius, and cars having a photovoltaic panel for air conditioning and accessories.

Outlook

This investigation may serve as a starting point for a variety of different topics, for example:

- Constructing fuel cell powered cars
- Hybrid cars and their advantages
- Alternative propulsion technologies

11.1.2 Time Table

The amounts of time are rough estimates.

Task	Time
Preparation prior to class	10 min
Investigation	2 × 50 min
Time students will need to research at home	25 min

Table 11-1: Schedule

11.1.3 Teaching Method

Method	Suitability
Group work	✓✓✓✓
Chalk and talk	–
Silent work (student questions)	✓✓✓
Homework (student questions)	✓✓✓

Table 11-2: Teaching method (✓= poor … ✓✓✓✓=very good)

11.2 The Investigation – Teachers

11.2.1 Preparation

It is advisable that you try out this investigation before class – it is designed for group work only. In order to prepare yourself, refer to the *STUDENT'S SECTION* on page 176.

11.2.2 In Class

This investigation is presented as an open-ended simulation exercise. It invites teams of students to put themselves in a fact-finding mindset where they will combine information they obtain from the Internet and their own investigation.

In the simulation the president of a company asks for a report on the feasibility of solar powered motive transport. The head of New Product Research instructs his engineers (the students) to investigate while he goes on vacation.

This approach can be done in several ways, such as:

- The class organizes a comprehensive investigation
- A small group of motivated students performs the investigation and presents its report to the class
- One team gathers information from literature and the Internet, another team performs trials with the Model Car components. They write a joint report

11.2.2.1 Chalk and Talk

For this investigation only a short introduction – depending on the level your class starts from, is required. It is designed to encourage students to come up with their own approaches in solving problems by stating hypotheses, and by proving or disapproving them. Chalk and talk teaching is not appropriate for this investigation.

11.2.2.2 Silent Work

Parts of this investigation can be performed as silent work, i.e. handing out additional information on hybrid cars and related topics, or in having the students search on the internet.

11.2.2.3 Homework

The same as in section silent work is applicable.

11.2.3 Possible Approaches

As much as possible, you should let students devise their own set-ups. However, for your convenience the following table describes many of the possible combinations the students might choose to investigate.

Safety

➔ Make your students aware of investigating in a safety conscious manner.

NOTICE

Overheating of the solar panel!

Malfunctioning of or permanent damage to the solar cells.

- ➔ Only use light sources with a maximum power of 120 W.
- ➔ Keep a minimum distance of 20 cm (8 inches) between light source and solar panel.
- ➔ Do not concentrate light with a reflector.

CAUTION

Overpressure in reversible fuel cell!

Injuries due to objects shooting out, when the top of the overflow compartments of the gas storage cylinders is obstructed.

- ➔ Do not block the top of the overflow compartments of the gas storage cylinders.
- ➔ Always wear eye protection.

CAUTION

Ignition of hydrogen!

Skin burns and damage to the fuel cell.

- ➔ No open flames.
- ➔ No smoking.
- ➔ Well ventilated workspace.

CAUTION

Hot surface of solar panel and lamp!

Skin burns.

- ➔ Do not touch the hot surface of the solar panel or lamp.
- ➔ Allow solar panel / lamp to cool down before touching it.

! NOTICE

Only use distilled water!

Tap water and other liquids will permanently damage the membrane of the reversible fuel cell.

! NOTICE

Short circuit of reversible fuel cell!

Hot spots in the membrane, leading to deterioration of the membrane.

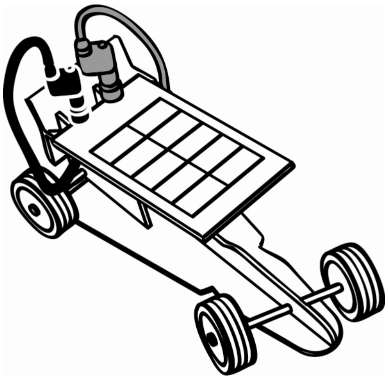
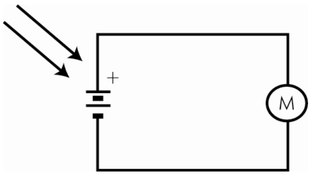
➔ Do not short circuit the reversible fuel cell.

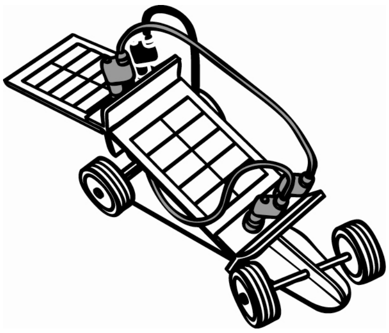
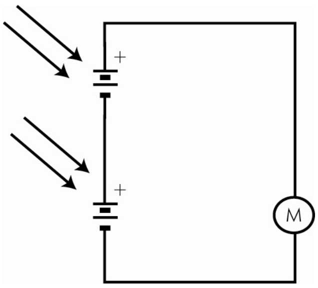
Indeed, some of the set-ups (S2, F2, H2) work poorly, or not at all. If your class has two kits available the students could use tape to try mounting two solar panels or two fuel cells to the car chassis. (See illustrations following.) Take care to use tape that does not leave a residue on the components.

If your class has only one Model Car kit, S2, S3, F2 and F3 are not possible.

The table describes various combinations of items in the Model Car kit, with cautions where appropriate. If you choose to add other things, such as a laboratory power supply, or a different solar panel, do not exceed the maximum input ratings of the electrolyzer (1.8 volts, 0.5 amperes) or the car motor (3 volts).

The most useful and informative set-ups in this investigation are those labeled S1, F1 and especially H1.

<table>
<tr>
<td>S1</td>
<td>Solar panel and motor

</td>
<td>Observation
It works, but only in bright light.

Conclusion
Such a vehicle needs the sun shining brightly. Students will realize why this is not a satisfactory power source for a vehicle.</td>
</tr>
<tr>
<td>S2</td>
<td>Two solar panels in series with motor

</td>
<td>Observation
It works better than a single solar panel, but only when both panels are evenly illuminated. Because the panels are not at the same angle to the light source, it is difficult to choose the best illumination. If only one panel is illuminated, the car does not move.

Conclusion
Higher voltage without higher current does not improve motor performance. The problems are the same as S1.</td>
</tr>
</table>

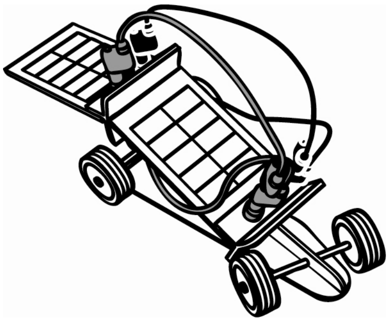
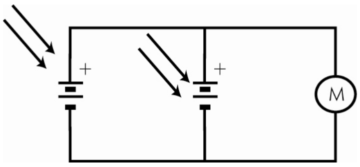
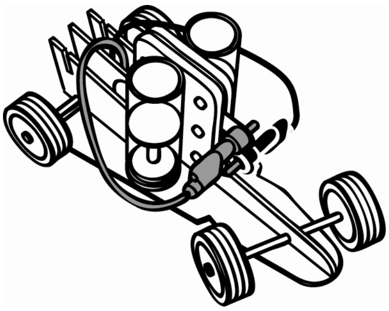
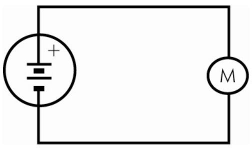
S3	Two solar panels in parallel with motor  	**Observation** The current is the sum of both panels. Car moves, if only one panel is illuminated. **Conclusion** The series / parallel connection does matter. Larger arrays can yield higher current at the same voltage (therefore greater power), but the problems are the same as S1.

Table11-3 Possible set ups solar panel

F1	Fuel cell and motor  	**Observation** It runs for a measurable time, but then needs more hydrogen fuel. **Conclusion** This behavior is like conventional cars. The car runs as long as there is fuel, independent of illumination level.

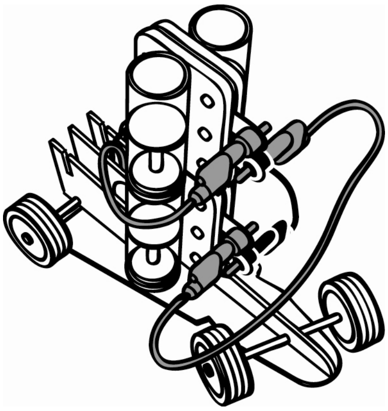
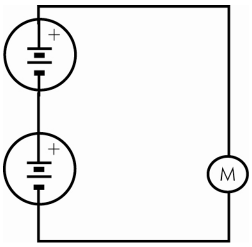
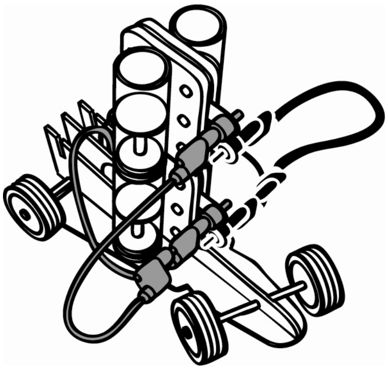
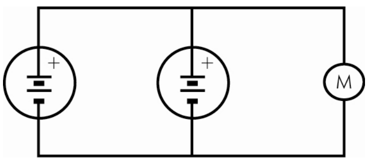
F2	Two fuel cells in series with motor   	**Observation** It runs about twice as fast. This will not damage the motor, which can tolerate up to 3 volts. **Conclusion** Series connection of two fuel cells yields higher operating voltage and therefore greater current giving a better fit with the motor's characteristics. If the polarity of one cell is reversed, the motor will not run, but no damage will occur.
F3	Two fuel cells in parallel with motor   	**Observation** No better than a single fuel cell, but runs twice as long. **Conclusion** Although the available current is doubled, the motor at this point on its characteristic curve does not perform any better. If the polarity of one cell is reversed, the cells are effectively short-circuited and may be damaged. In addition, the motor will not run.

Table 11-4 Possible set ups fuel cell

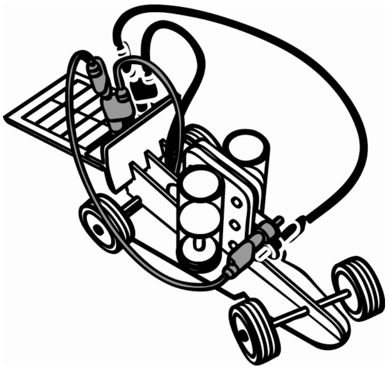
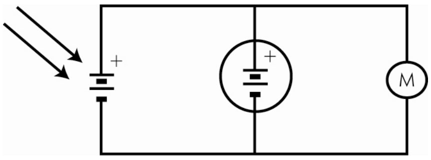
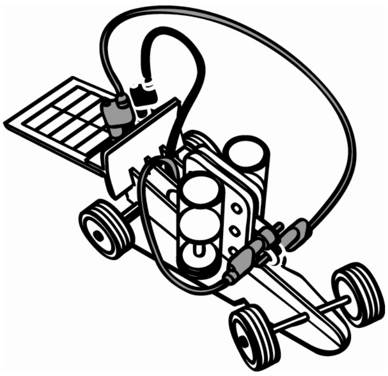
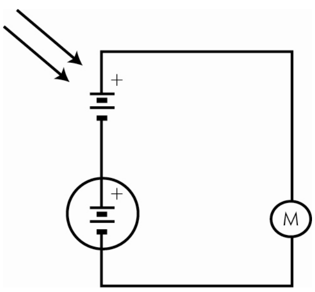
H1	Solar panel, fuel cell, motor in parallel   	**Observation** Students could measure the rate of hydrogen consumption with and without the solar panel connected. Even in low light, the solar panel will help the motor run longer. If you disconnect the motor (simulates parking the car) the solar panel charges the cell with hydrogen. Polarity of the interconnections is significant, but not dangerous. If the polarity of the motor is reversed, it merely runs backward. If the solar panel is connected with the wrong polarity, it will do nothing, and the protective diode on the fuel cell will prevent any damage to the fuel cell. **Conclusion** Such a hybrid solar-assisted fuel cell car can run longer because the motor takes part of its energy from the sun, saving hydrogen. When the car is parked the solar panel charges the cell with hydrogen. A solar panel could provide such a vehicle with auxiliary power for air conditioning or battery charging.
H2	Solar panel, fuel cell, motor in series   	**Observation** In darkness, the solar panel behaves like an open circuit. Nothing happens. In light, it does not work either. **Conclusion** Not a useful way to connect the components.
Students may come up with other set-ups...		

Table 11-5 Possible set ups hybrid

11.2.3.2 Questions and Answers

1. I think you should first try using solar power only. See what the advantages and problems are. Can you propose solutions?

Set-ups that use solar power only are described in S1, S2, and S3, see Table 11-5.

Advantages of using exclusively solar power	Problems of using exclusively solar power	Remedy of problems
• Source of energy (the sun) is free • Sustainable, non-polluting	• The sun is not always shining • The power density (power per unit surface area) of photovoltaic arrays is low. Compared to the amount of power required to run a general purpose vehicle, the amount of solar energy falling on a car-sized solar panel is very small. Also, the efficiency of typical solar cells is 15 % or less	• Store energy in an intermediate battery, as used today in lightweight solar vehicles • Very light vehicles. The Internet will provide examples • Very large solar panels. Students can calculate the maximum power density of the solar panel. See • *ADDITIONAL QUESTION AND ANSWER* on page 175 • Improved solar technology. Higher efficiency, meaning better conversion of solar energy into

Table 11-6 Possible solutions to question 1

2. Then try running the car with fuel cell power. What are the differences?

Set-ups that use fuel cell power only are described in F1, F2, F3.

A fuel cell power source behaves more like a normal car:

- *The amount of fuel determines the range.*

- *The number of cells – the engine size – determines speed.*

3. Could solar energy collected in a stationary plant be an energy source for transportation?

   Yes. Using large electrolyzers, solar energy can be converted to hydrogen. Then the hydrogen can be used as fuel in a fuel cell vehicle.

4. An idea often heard combines solar power and fuel cell technology into some type of hybrid. For example, if the car is parked some of the sunlight energy falling on it might be stored as hydrogen for use when you then drive in the dark? Perhaps you could look into that as well.

   Set-up H1 in the table effectively demonstrates a solar + fuel cell hybrid.

   - *When the Model Car moves in low light, the fuel cell uses hydrogen to power the motor.*
   - *When the car moves in bright light, the solar panel functions as a supplementary power source helping the fuel cell power the motor.*
   - *When the car is parked (motor disconnected from the other two components) in bright light, the solar panel and reversible fuel cell produce hydrogen which is stored for later use.*

   In practice, fuel cells used as transportation power sources do not have the ability to act as both electrolyzer and fuel cell. The need for high efficiency makes such low-efficiency reversible devices impractical.

5. Try to find information from the Internet. Are there any examples of combined energy sources (hybrid energy supplies)?

   - *Storage batteries can store energy from other sources such as: dynamic energy from braking; solar energy on the surfaces of the car; gravitational energy while moving downhill – even wind energy while the car is stationary.*
   - *Solar power could be used to operate some accessories (air conditioning, instruments, audio-visual, storage battery) thereby reducing the fuel demands of a fuel cell or conventional engine.*

   There is a large market for hybrid. The combination of gasoline engine + motor/generator + storage battery is a common one.

6. Does solar power have a future for powering vehicles or will vehicles continue to use a fuel? Would the addition of a storage battery make a difference? More generally, what is the future of fuels with regard to transportation and mobility?

The solar power gathered on the surface of a vehicle is not sufficient to power a conventionally-sized passenger car. Even if a storage battery is used to accumulate energy when the car is stationary, because photovoltaic power densities are low, solar is sufficient for only special lightweight cars.

Batteries are used in many prototype vehicles to gather energy from auxiliary sources (solar panels, dynamic braking) and assist the principal power system, which could be a fuel cell and electric motor.

In the future fuels will still be needed for passenger vehicles because they will need to be heavy enough to be safe and large enough to carry more than one person. Fuel has a high power density.

However the fuel we use in cars can be produced in a stationary setting from renewable energy sources such as solar – and wind, water, geothermal, biomass… In this way we will not consume the reserves of our fossil fuels. We simply produce the fuel and consume the fuel in a sustainable process.

Converting solar power into hydrogen and using it as a car fuel is an important concept because it is sustainable.

11.2.3.3 Problems Illuminating the Solar Panel Mounted onto the Car

If working indoors, the students might

- Set car to move in a circle, and then follow it around holding a bright light. Apart from the obvious hazards of tripping on the electrical cord, dropping the lamp, being burned by the hot lamp, and overheating the solar panel, this approach may not yield similar results from one trial to the next.
- Set car on a block so it doesn't move under a stationary light.

If working in sunlight, the students might

- Set the car to move in a circle. Because of the constantly changing angle of incidence, this works well only if the sun is high in the sky.
- Set the car to move in a straight line with the solar panel optimally positioned.

11.2.3.4 Additional Question and Answer

Question

How large an array of solar cells of the type in the Model Car kit would be required to deliver the 50 kW needed for peak loads of a typical electric vehicle?

Approach

Using the solar panel and load measurement box, students could calculate the power delivered per unit area of the panel, or power density. (The load box is necessary because attempts to measure voltage and current at the motor will not be successful.)

Answer

Under bright sun, the 45 cm^2 (=0.0045 m^2) surface of your solar panel might deliver 250 mA into 10 ohms.

The power density is therefore:

$$\text{Power density} = \frac{\text{power}}{\text{area}} = \frac{I^2 \times R}{\text{area}} = \frac{(0.25\ \text{A})^2 \times 10\ \Omega}{0.0045\text{m}^2} = 139\ {}^{\text{W}}/_{\text{m}^2}$$

The size of an array needed to produce 50 kW would be:

$$\frac{\text{Power needed}}{\text{Power density}} = \frac{50000\ \text{W}}{139\ {}^{\text{W}}/_{\text{m}^2}} = 360\ \text{m}^2$$

11.3 Student's Section

Imagine that you work as a member of a research team for a company that makes automotive components.
Yesterday, your boss received the following directive:

From: Office of the President

To: All Department Heads

At a recent meeting, the Board of Directors discussed the issue of solar-powered vehicles for general use. Some felt that a completely solar-powered vehicle was not possible, and that some other (or added) power source and fuel were needed.

For strategic planning over the next year, the Board needs to know just what is possible. There is currently a lot of talk about "hybrid" systems, although we are unsure what that means.

Please gather from your respective departments whatever information you can about this important issue, and deliver your reports by the end of this month.

BR

Ian Smith

Today, your team received the following note:

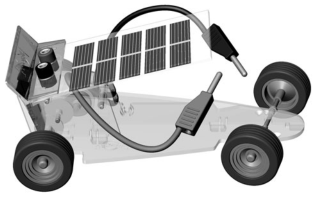
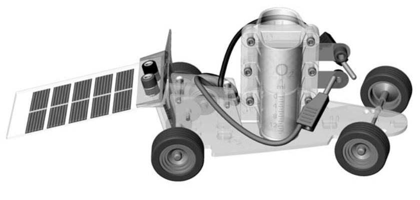
From: Head of New Product Research
To: All R & D staff

Dear all,

yesterday I received the attached directive. The Board seems to want a lot in a hurry. I need you to plan an investigation, do it, and write a report.

As some of you know, tomorrow I am heading for Australia for two weeks. I feel bad about leaving you on your own with this task. But I have been thinking for a while and will write some ideas and questions to get you started.

In your lab you have the Dr FuelCell™ Model Car. You can use it in ways you may not realize. See these images; the solar panel can be attached to the car in at least two ways:

Using tape, you can even attach two solar panels or two fuel cells to the car chassis. I don't know if parallel or series connection is better.

If you're working inside, you may need to follow the car as it moves, holding the light above the solar panel. Or you could set the car on a block so it doesn't move. Please refer to the Instruction Manual before commencing with your work.

There are many ways to connect the fuel cells, solar panels and car motor to run the car. In your report, draw diagrams of the connections you are describing, and note how the different arrangements affect how the car runs.

Project tasks

1. I think you should first try using solar power only. See what the advantages and problems are. Can you propose solutions?
2. Then try running the car with fuel cell power. What are the differences?
3. Could solar energy collected in a stationary plant be an energy source for transportation?
4. An idea often heard combines solar power and fuel cell technology into some type of hybrid. For example, if the car is parked some of the sunlight energy falling on it might be stored as hydrogen for use when driven in the dark. Perhaps you could look into that as well.
5. Try to find information from the Internet. Are there any examples of combined (hybrid) energy sources?
6. Does solar power have a future for powering vehicles or will vehicles continue to use a fuel? Would the addition of a storage battery make a difference? More generally, what is the future of fuels with regard to transportation and mobility?

Well, that's about it; my flight leaves tonight. I'll be back in two weeks. I know the Board is eager to read your report. Actually, so am I. The transportation industry could use a shake-up!

I'm off.

BR

John

What will you do?

There are many ways to connect the fuel cells, solar panels and car motor to run the car. In your report, draw diagrams of the connections you are describing, and note how the different arrangements affect how the car runs.

Student's Section

- ➔ Whichever approach you may take – adhere to the safety instructions in the Instruction Manual.

11.3.1.2 Additional Question

How large an array of solar cells of the type in the Model Car kit would be required to deliver the 50 kW needed for peak loads of a typical electric vehicle?

12 Glossary

Term	Explanation
Ammeter	A device that measures current flowing in a circuit.
Ampere (amp)	The unit of electric current, having the symbol A.
Angle of incidence	That number of degrees by which a line deviates from the perpendicular to a designated plane.
Anion	An atom or group of atoms that has a negative electric charge.
Anode	The electrode where the oxidation reaction takes place; that is, a reaction where there is a loss of electrons.
Catalyst	Any substance that reduces the activation energy of a reaction but does not take part in the net reaction and so remains unchanged.
Cathode	The electrode where the reduction reaction takes place; that is, a reaction where there is a gain of electrons.
Cation	An atom or group of atoms that has a positive electric charge.
Circuit, electrical	Any closed path followed or capable of being followed by an electrical current.
Circumference	The distance around a path or object. The circumference of a circle is determined by multiplying the diameter (or twice the radius) of the circle by π.
Compound, chemical	A substance composed of two or more different types of atoms.
Current, electrical	A flow of electrons usually measured in amperes and designated by the symbol I.

Term	Explanation
Distilled water	Water which has been made into vapor and then condensed back as pure water leaving behind any dissolved or suspended substances.
Efficiency	A measure of the energy-effectiveness of a system with unity or 1 being a perfect result. Efficiencies are usually expressed as percentages where the output is divided by the input.
Electrical generator	A device that produces a flow of electrons.
Electrolysis	Chemical change, especially decomposition, produced in an electrolyte by an electric current.
Electrolyte	A substance that when dissolved breaks into ions, allowing the resulting solution to conduct electricity.
Electrolyzer	A device that uses a flow of electrons to break a compound into its constituent elements. The electrolyzer in this kit breaks water into hydrogen gas and oxygen gas.
Electron	A subatomic negatively charged particle.
Energy, electrical	The energy (in joules) generated or used by a device can be calculated as the product of its power (in watts) and the time over which that power occurs (in seconds). Often designated by the symbol E.
Formula (chemical)	A symbolic expression that describes the number and kind of atoms within one molecule of a substance or ionic compound.
Hypothesis	A possible explanation, subject to verification or proof, used as a basis for investigation or further investigation.
Input	The amount of whatever is being measured entering a system.

Term	Explanation
Joule	The unit of electric energy, having the symbol J. One joule is equivalent to one watt-second. (The joule is also used as the unit of work and of heat.)
Milliampere	One thousandth of an ampere, having the symbol mA.
Observation	The use of any and all senses to notice something. Observations could include smells, heat changes, light emissions, movements or sounds.
Output	The amount of whatever is being measured leaving a system.
PAR lamp	Parabolic Aluminized Reflector lamp.
Patch cord	An electrical conductor made of a flexible insulated cable with plugs or clamps at each end designed to temporarily connect components.
Photon	A quantum of electromagnetic energy usually associated with light. Photons exhibit qualities of both waves and particles.
Power, electrical	The power (in watts) generated or used by a device can be calculated by multiplying its current (in amperes) times the voltage across its terminals (in volts). Often designated by the symbol P.
Prediction	The act of making known in advance what is liable to occur.
Questioning	An inquiry that invites or calls for a reply or response.
Reaction (chemical)	A chemical change or transformation in which a substance decomposes, combines with other substances or interchanges constituents with other substances.
Short circuit	A situation in which a circuit is complete but has little or no resistance or load.

Term	Explanation
Solar cell	A device that changes light into an electric current. Solar cells are usually mounted together to produce a solar panel.
Volt	The unit of electric potential difference, having the symbol V.
Voltage	A measure of the electrical potential between two points, usually measured in volts and designated by the symbol V.
Voltmeter	A device that measures voltage difference between two points in a circuit.
Watt	The unit of electric power, having the symbol W.

Table 12-1 Glossary

Heliocentris

Heliocentris Energiesysteme GmbH
Rudower Chaussee 29
12489 Berlin
Germany

http://www.heliocentris.com