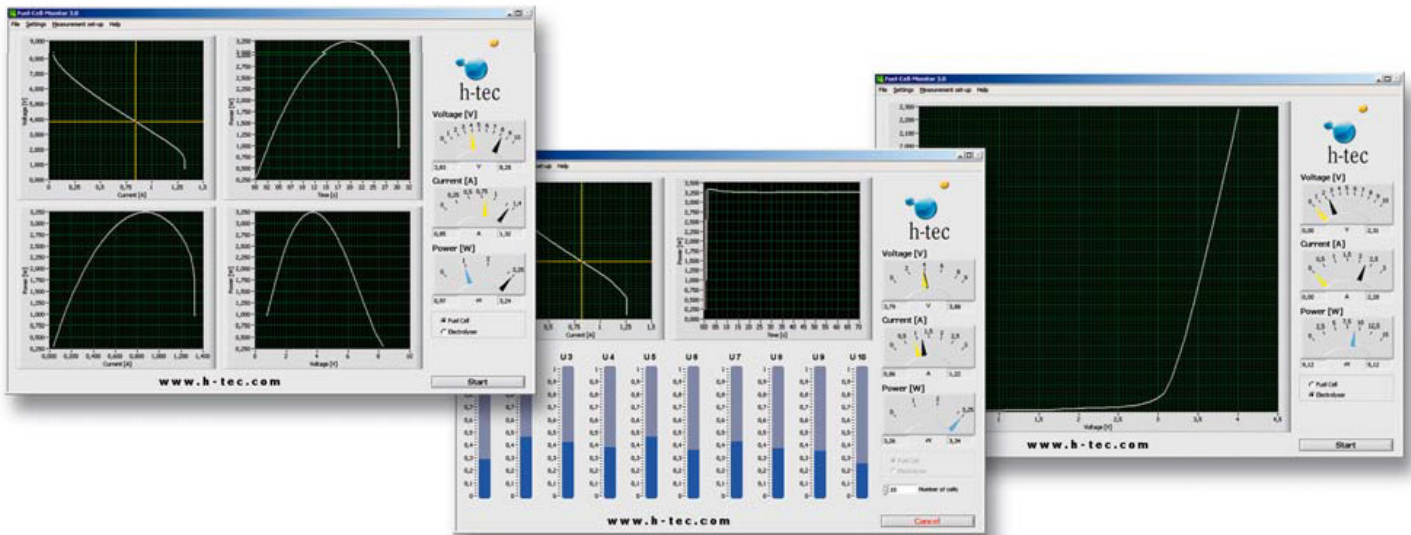
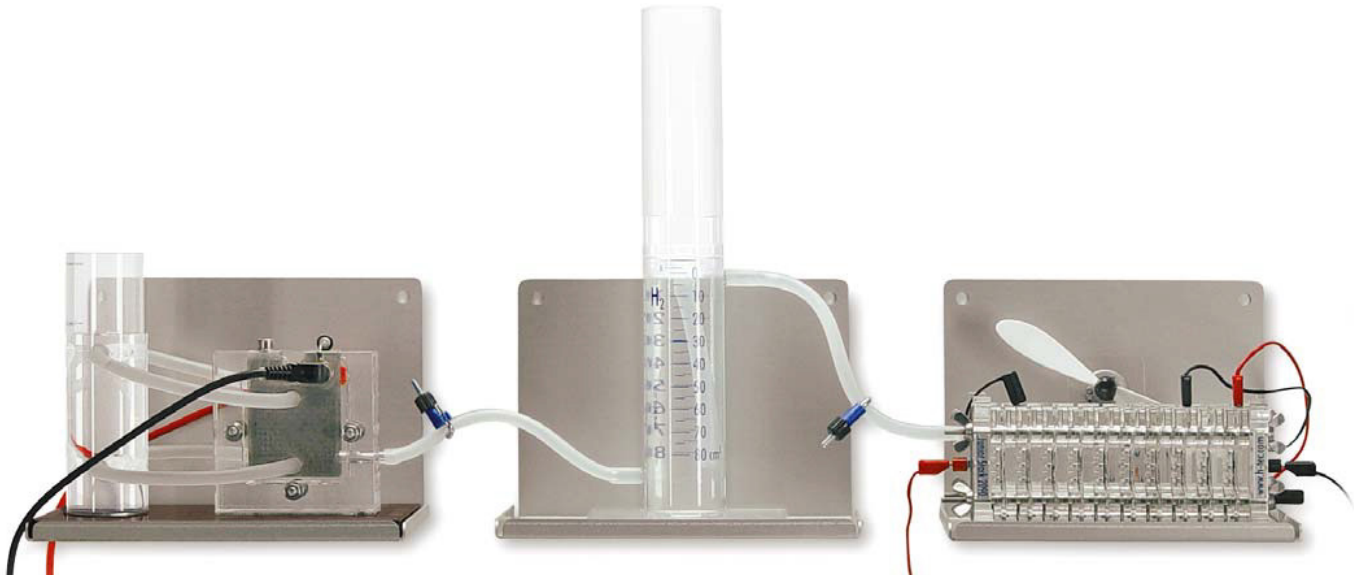


# Operating Instructions



U102 - Stack Experimentation Set Complete

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# Part 1 - Operating Instructions for the Stack Experimentation Set

## 1.1 Your Duty to Supervise

These Operating Instructions are intended for the responsible supervisor.

Read the Operating Instructions before using the equipment.

Observe the instructions and keep them on hand.

Pay particular attention to all Safety Instructions.

This product should be set up and operated only under the supervision of a responsible adult.

## 1.2 Introduction

Diminishing resources, more severe environmental impacts and the ever-increasing demand for energy, force us to re-evaluate the structure of our energy supply system. Automobile and oil companies increasingly invest in hydrogen technology because it offers solutions to some of these concerns. This fascinating technology combines a sound energy supply with minimal impact on our natural resources.

It is important to learn about this technology, especially for young people, who will most likely spend a large part of their lives with it.

In all steps of the energy process the devices avail of the most environmentally friendly solution, starting with the solar panels to provide the current for electrolysis and ending with the fuel cell for independent current production. As the devices represent the model of a complete energy supply system, each range of hydrogen technology can be described in an easy-to-grasp way.

The Stack Experimentation Set offers the possibility to show the mode of operation of hydrogen technology step by step and in an interesting way by means of experiments.

In the following all steps for start-up and operation in the different modes are described in detail.

H-TEC EDUCATION wishes you many enjoyable hours learning about this technology with the Stack Experimentation Set.

## 1.3 Intended Use

The Stack Experimentation Set allows demonstration and measurement of the way hydrogen technology works with the main components, the PEM electrolyzer, hydrogen storage tank and PEM fuel cell (PEM = Proton Exchange Membrane).

The system has been developed for teaching and demonstration purposes only.

Any other use is prohibited!

### **Caution!**

Distilled water is required to operate the Stack Experimentation Set. The water is split into hydrogen ( $H_2$ ) and oxygen ( $O_2$ ) in the electrolyzer. If not handled properly, these gases can be dangerous.

In order to avoid any risks you must follow the general safety instructions when working with the system.

## 1.4 Safety Instructions

- The units may only be set up and operated by a responsible supervisor.
  - **WARNING!** Not suitable for children under 12 years old.
  - Read the Operating Instructions before setting up the fuel cell. Follow them during use and keep them readily available for reference.
  - The equipment may only be used with the H-TEC Education Solar Modules, H-TEC Education battery box, or H-TEC Education plug-in power supply.
  - Wear protective goggles.
  - Equipment and gases must be used and stored out of the reach of small children.
  - Plug-in power supplies can be dangerous - they are not toys!
  - Disconnect the unit from the plugin power supply and the solar module before cleaning with liquids.
  - Unless instructed to the contrary by the manual, do not reverse or short-circuit the connecting terminals.
  - The units must not be operated when empty. Always ensure that they contain sufficient water. Pay attention to the water level marks.
  - Remove flammable gases, vapors or liquids from the area surrounding fuel cells and electrolyzers. The catalytic materials involved may cause spontaneous ignition.
  - Hydrogen and oxygen may escape from the units. Operate the units in well-ventilated rooms to ensure that the gases do not accumulate and form explosive mixtures.
  - The units may only be operated in display cases if adequate ventilation is guaranteed under all circumstances.
  - The operator is responsible for ensuring this.
  - Remove from the vicinity of the units anything that could ignite the hydrogen (e.g. open flame, materials that can become charged with static electricity, substances with a catalytic action).
  - Remove from the vicinity of the units all substances that could spontaneously ignite in increased oxygen concentration.
  - **Do not smoke!**
  - Hoses, plugs and gas tanks are used for pressure compensation. They must not be fixed or secured with clamps, adhesive, etc.
  - Only use the gas storage tanks associated with or supplied with the units. Never connect alternative gas storage tanks.
  - The units may only be operated at room temperature and ambient pressure.
  - Minimum separation distances must be observed when using solar modules and artificial lights. These are: 30 cm between H-TEC solar modules and the H-TEC Videolight, and 50 cm in the case of the H-TEC Spotlight. When using lights from other manufacturers, observe the minimum distance specified by them.
  - **WARNING!** The surface of solar modules can get very hot during extended operation.
  - **Tell your students about any potential dangers and carefully supervise experimentation.**
- H-TEC accepts no responsibility for injuries or damage sustained in the event that these Safety Precautions are not followed.

The components of this product feature freely accessible, live electric contact surfaces. Connecting to an impermissible operating voltage may result in a fire hazard, a risk of electric shock and damage to the components.

## 1.5 Contents of the Carrying Case



Double-cell PEM Electrolyzer Stack  
Electrolyzer 65



PEM Fuel Cell Stack  
Fuel Cell Stack 10



Fuel Cell Monitor Pro 4.0  
Includes power supply



Hydrogen Storage Tank  
Storage 80



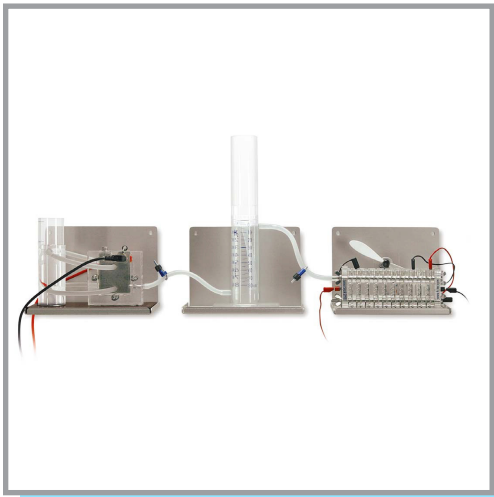
Fan Tutorial



Experimentation Lamp  
(Load)



Solar Module 13



Holder Set

Also Included:

- 1X Water Bottle
- 1X Carrying Case
- 1X USB Flash Drive containing
  - Fuel Cell Monitor Pro Software
  - *Fuel Cell Technology for Classroom Instruction* Textbook
  - Operating Instructions

## 1.6 Operating the Stack Experimentation Set

When a DC voltage is connected to the electrolyzer, e.g. solar module or power supply (not included), the electrolyzer splits distilled water into hydrogen and oxygen.

The water is fed to the electrolyzer from below, through tubes from the storage tank.

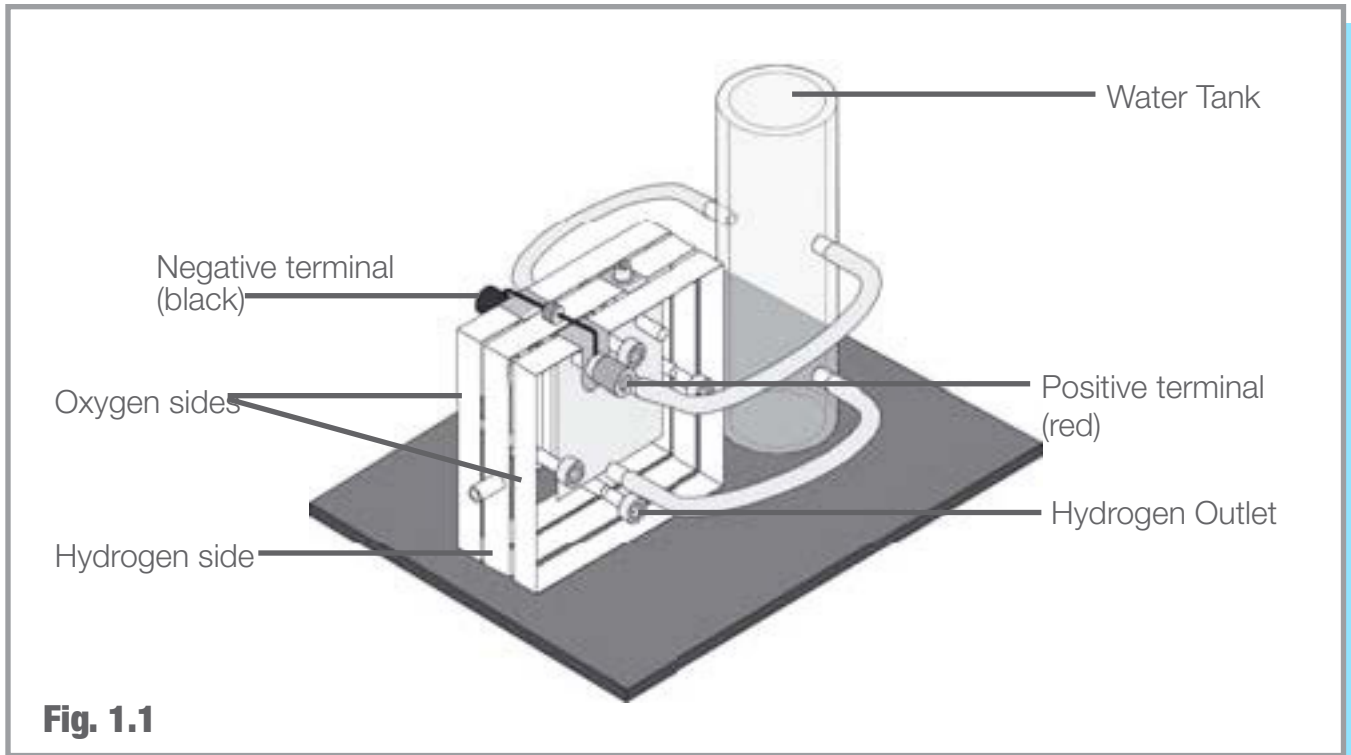
The oxygen produced dissipates into the atmosphere.

In order to store the hydrogen produced, the hydrogen outlet of the electrolyzer is connected to the lower hydrogen inlet of the 80 cm<sup>3</sup> gas storage tank. The top outlet of the gas storage tank is connected to the fuel cell stack. The hydrogen is collected in the hydrogen storage tank. The gases pass from the top end of the gas storage tank to the fuel cell, in which electricity, heat and water are produced. The amount of heat generated is small. Water that is produced condenses on the housing plates.

## 1.7 Equipment and Materials

### 1.7.1 PEM Electrolyzer Stack - Electrolyzer 65

The Electrolyzer 65 is a two-cell electrolysis stack with associated water supply. The center of the cell houses the hydrogen side of the two individual cells. The two outer sides of the cell have the function of supplying water and removing the oxygen produced. The two individual cells are connected electrically in series.

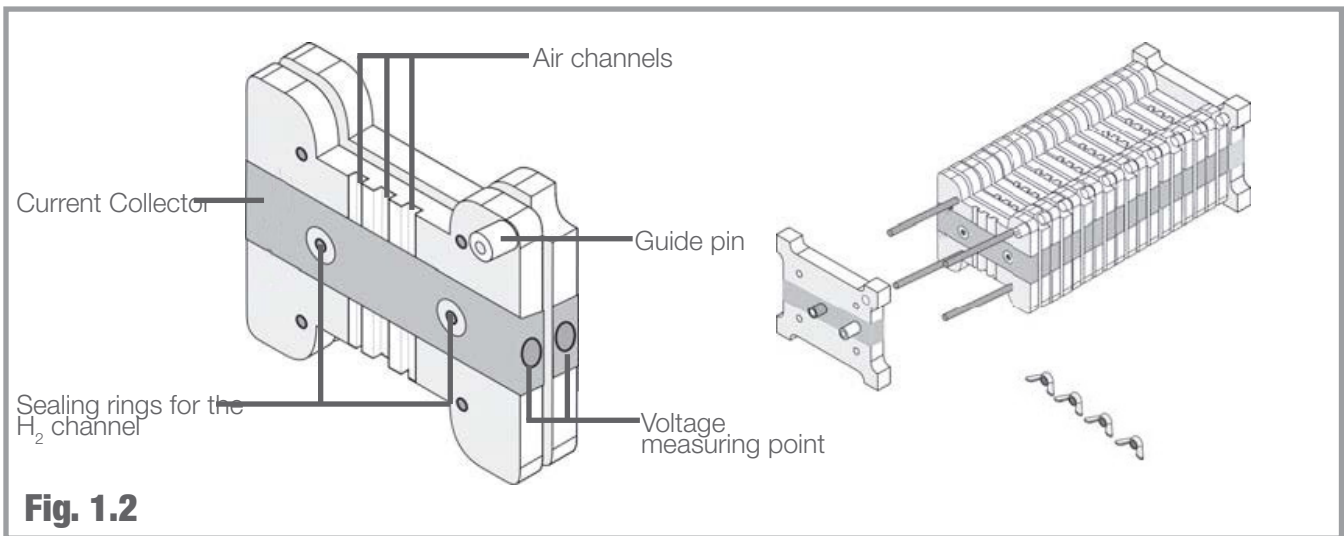


**Fig. 1.1**

### 1.7.2 PEM Fuel Cell Stack - Fuel Cell Stack 10

The Fuel Cell Stack 10 is a 10-cell PEM fuel cell stack, with individual cells being wired in series. The number of cells can be varied from a single cell to a maximum of 10 cells by sectioning. When the PEM fuel cell stack is supplied with hydrogen, it combines with oxygen in the air to produce current, heat and small quantities of water. Further information on assembly and disassembly can be found in Section 1.9: "Assembling the PEM Fuel Cell Stack".





**Fig. 1.2**

### 1.7.3 Fuel Cell Monitor Pro 4.0 (FCM)

The FCM is a measuring transformer card with the associated evaluation software “Fuel Cell Monitor 4”.

The FCM enables you to record, evaluate and store various measured values and characteristic curves from H-TEC EDUCATION mock-up fuel cells and electrolyzers using a PC. The external control board is connected to the PC using a USB cable. The supplied software “Fuel Cell Monitor 4” lets you record and display various diagrams for current, voltage and power values. Further information about handling can be found in Chapter 4.

## 1.8 Setting Up the Stack Experimentation Set

1. Read the Safety Instructions and this operation manual carefully before use.
2. Connect the hydrogen outlet of the Electrolyzer stack to the hydrogen inlet (bottom port) of the gas storage tank and open the hose clamp. (Fig. 1.3)
3. Fill the water tank on the Electrolyzer up to the -A- mark with distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ).

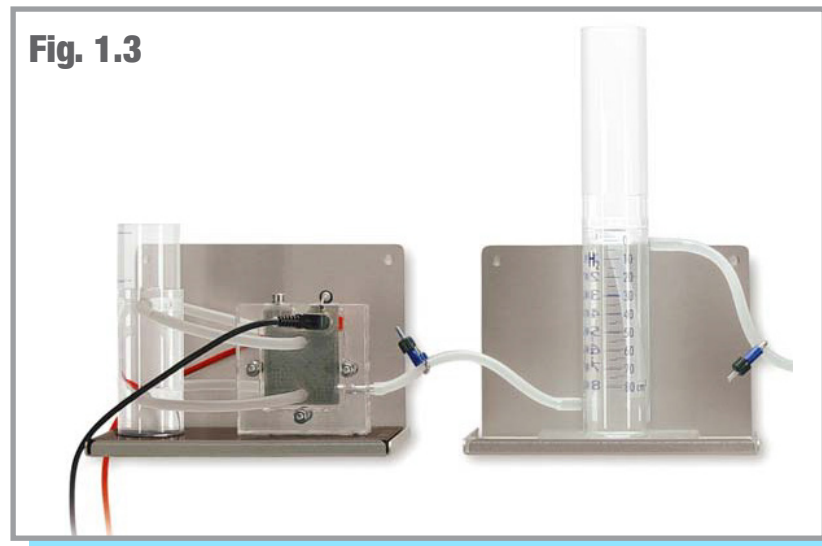
#### **Caution!**

When doing so, make absolutely sure that the hose clamp between the electrolyzer and the gas storage tank is open before starting the electrolyzer. Otherwise the electrolyzer could be damaged.

#### **Note:**

Various water fill heights are to be selected depending on the gas storage tank’s application. If you want to determine the chronological hydrogen production, fill the tank up to the zero mark. Then, screw the compensating reservoir onto the tank and close the hose clamp at the hydrogen output (top connection) of the gas storage tank. The gas produced now displaces the water in the tank and forces it into the compensating reservoir. You can read the amount of hydrogen produced on the scale.

In the event of prolonged operation, use of the tank as water separator is recommended. During the course of operation, water is pumped from the oxygen side of the electrolyzer to the hydrogen side. This, in turn, causes water from the tank to reach the fuel cell. Water in the fuel cell can result in a rapid power drop as the gas supply is blocked. In order to prevent this, it is recommended that the tank is filled with distilled water only up to the 80 cm<sup>3</sup> mark and the compensating reservoir is screwed onto the tank.



4. Connect a direct current power source (e.g. H-TEC EDUCATION Solar Module 13). Ensure the correct polarity (red = “+” and black = “-”) and to the maximum permitted voltage of 4 V.

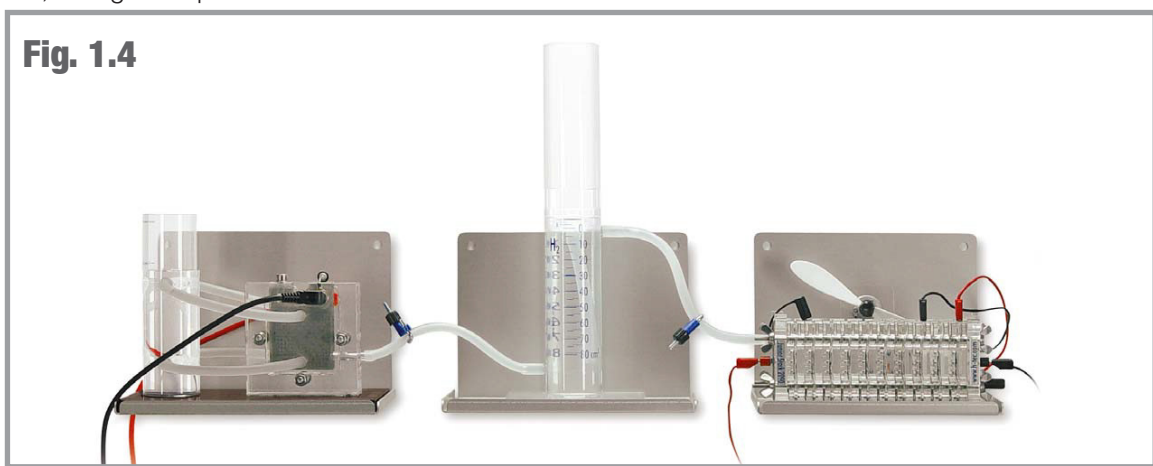
**Caution!**

Risk of fire due to electrical overload. Any operation beyond the electrical specifications will lead to excessive overheating of the electrolyzer. This may cause a fire. Never operate the electrolyzer beyond the electrical specifications stated in the technical data.

5. Connect the hydrogen outlet of the gas storage tank (top connection) to one of the hydrogen inputs of the fuel cell and seal the output of the fuel cell with the sealing cap. (Fig. 1.4) Ensure that the hose clamp between the gas storage tank and the fuel cell is open.

6. Wait a moment until some gas has accumulated in the tank. Then open the sealing cap of the fuel cell so that the gas can flow through the fuel cell. The residual air and residual moisture remaining in the hose and in the fuel cell escape. Then replace the sealing cap.

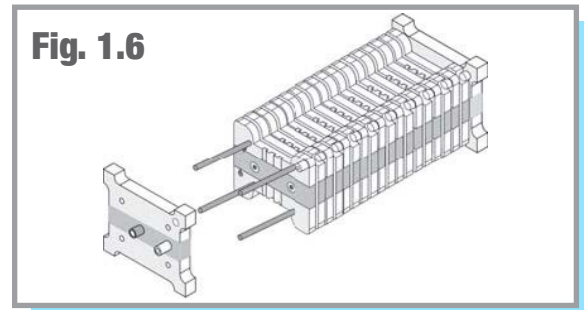
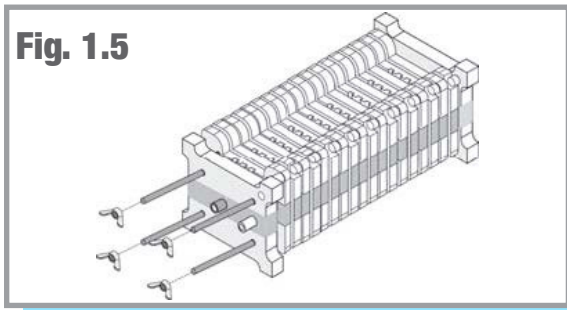
7. The device is now in demonstration mode. You can connect the lamp or the FCM as electrical consumers to record current, voltage and power values.



## 1.9 Assembling the PEM Fuel Cell Stack

The Fuel Cell Stack 10 is usually supplied ready-assembled. However, if you have purchased individual parts retrospectively, or have disassembled the Stack, please proceed as follows to carry out the assembly:

1. Remove the wing nuts on the “+” side (red socket) of the Fuel Cell Stack 10. To do this, it will be necessary to prevent the corresponding screws on the rear from turning. (Fig. 1.5)
2. Remove the free end plate. (Fig. 1.6)

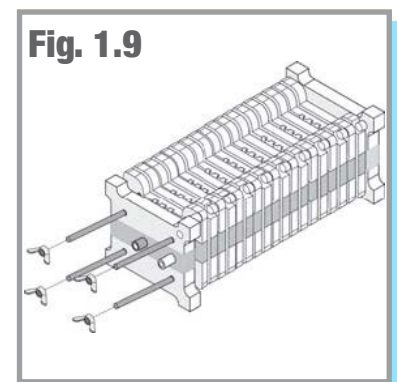
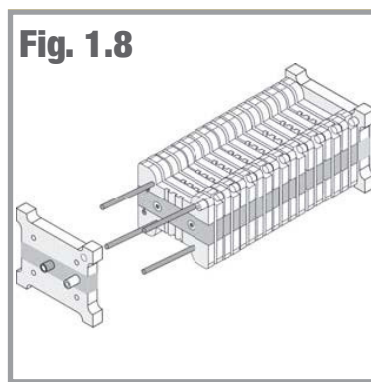
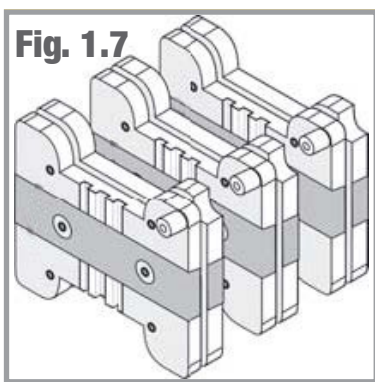


3. You can now remove cells from the Fuel Cell Stack 10 or fit additional cells. The maximum number of cells is limited to 10. (Fig. 1.7) To ensure good contact when fitting cells, it is essential to ensure the following:
  - the side with the air channels is always facing upwards.
  - the sealing rings are correctly seated in the slots provided for the purpose.
  - the locating peg of the end plate or the locating peg of the previous individual cell engages in the recess in the hydrogen side of the next cell. As a result of this, the wires of the protective diodes will be on the same side and cross over one another.

4. Replace the second end plate. Make sure that the locating peg of the last fuel cell engages in the opening in the end plate provided for the purpose. The two gas connections of the Fuel Cell Stack 10 must now lie on diagonally opposite sides. (Fig. 1.8)

5. Replace the wing nuts and tighten these alternately several times so that the cells sit uniformly. Tighten the wing nuts by hand. (Fig. 1.9)

6. Using a syringe and a piece of silicone tubing, pull a vacuum on the cell. The tubing should collapse. Leave the vacuum for several minutes, confirming the tubing does not reinflate. This will ensure there is no hydrogen loss when the stack is in use.



## 1.10 Technical Data

### Stack Experimentation Set

H x W x D:..... 510 x 420 x 210 mm

Weight:..... approx. 10.3 kg

### Fuel Cell Stack 10

H x W x D:..... 60 x 70 x 175 mm

Weight:..... 430 g

Power (10 cells):..... 2 W

Power (per cell):..... 200 mW

Electrode area:..... 4 cm<sup>2</sup>/cell

Generated voltage:..... 0.4-0.96 V/cell

### Electrolyzer 65

H x W x D:..... 140 x 180 x 120 mm

Weight:..... 460 g

Power:..... 15 W at 4 V DC

Permissible Current:..... 0 - 4.0 V DC

Electrode Area:..... 16 cm<sup>2</sup> each

H<sub>2</sub> production at rated output:..... approx. 65 mL/min.

### Storage 80

H x W x D:..... 265 x 100 x 100 mm

Weight:..... 190 g

Volume:..... 80 mL

### Experimentation Lamp

Power:..... 4.4 W

### Solar Module 13

H x W x D:..... 330 x 330 x 25 mm

Weight:..... 1.5 kg

Power:..... 13.2 W at 3.3 A

### Holder Set

H x W x D:..... 180 x 145 x 125 mm

Weight:..... 930 g

## 1.11 Troubleshooting

**The electrolyzer does not produce hydrogen when the solar cell is connected.**

Possible Cause:

- The light intensity is insufficient.

Solution:

- Check the power specifications of the light source. You must have sufficient sunlight or a halogen lamp with focused light. Energy saving lamps, fluorescent tubes, etc. are not suitable for the operation of solar modules.

**Despite correct assembly, the electrolyzer does not function.**

Possible Cause:

- You have not used distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ).

Solution:

- The cell is irreparably damaged.

**The fuel cell is only producing low power.**

Possible Cause:

- The cell was stored too long or too dry. A cell with a dry membrane loses power.

Solution:

- Continue operation. The membrane will moisten during operation, and will slowly return to full performance.

**Despite hydrogen being present, the load connected to the fuel cell does not function.**

Possible Cause:

- Water has penetrated the fuel cell during operation. This is preventing electrons from moving across the membrane.

Solution:

- Open both caps on the fuel cell, and blow through the connections to dry the cell.

## 1.12 Maintenance

The components do not require maintenance. However, the following points should be observed:

- Use fresh, distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ) with each use.
- After operation, remove the water from the water reservoir and the hydrogen storage tank.

Before storing the cells:

- Continue to operate the fuel cell until the load stops. This will keep some water in the cell, so the membrane will stay moist..
- Close the caps to ensure the water in the cell does not evaporate.
- Wipe the baseplate dry to avoid water traces.

## 1.13 Disposal

Do not dispose of fuel cells and electrolyzers as general household waste.

 **WARNING**

Fire hazard from catalytic substances  
The catalysts for the electrodes of fuel cells and electrolyzers promote burning when they come into contact with flammable substances.  
Avoid contact with hydrogen, alcohol fumes or other organic fumes. Ensure correct disposal.

According to European regulations, used electric and electronic devices may no longer be disposed of as unsorted household waste. The symbol of the crossed-out wheellie bin indicates the requirement for separate disposal.

Your local waste management company can provide you with additional information about disposal options.

## Part 2 - Experiments

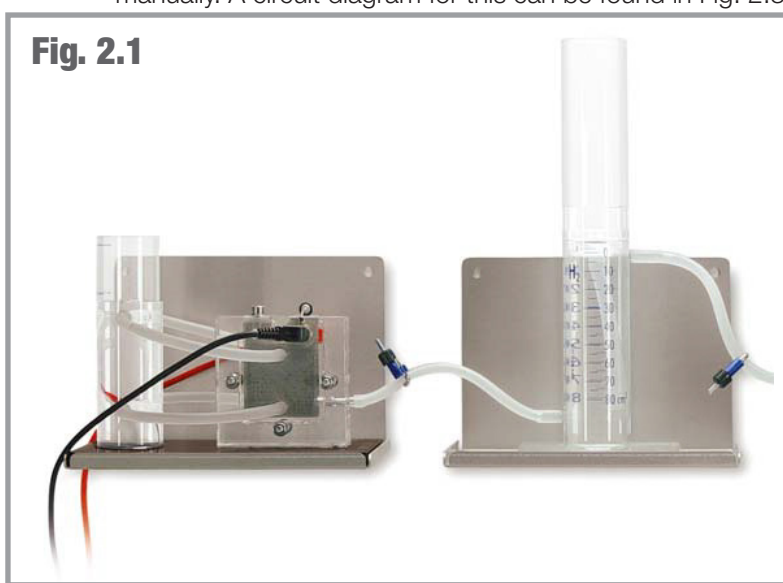
### Caution!

#### Risk of fire due to electrical overload

Any operation beyond the electrical specifications will lead to excessive overheating of the electrolyzer. This may cause a fire. Never operate the electrolyzer beyond the electrical specifications stated in the technical data.

## 2.1 Recording of the Current/Voltage Characteristic Curve of the PEM Fuel Cell Stack

It is recommended to use the Fuel Cell Monitor Pro 4.0 (FCM) included in the set for the recording of the current/voltage characteristic curve of the PEM fuel cell stack. It is also possible for you to determine the characteristic curve manually. A circuit diagram for this can be found in Fig. 2.3.



### Materials needed:

- Electrolyzer 65
- Storage 80
- Fuel Cell Stack 10
- Power Source
- Fuel Cell Monitor Pro 4.0

In order to record the characteristic curve manually, you need:

- Various resistors or potentiometers and measuring equipment for current and voltage

1. Connect the hydrogen outlet of the Electrolyzer to the bottom inlet of the Storage 80 and open the hose clamp (Fig. 2.3).

2. Fill the water tank of the Electrolyzer stack up to the marking with distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ).

### Caution!

Always ensure that the hose clamp between the hydrogen output of the electrolyzer and the hydrogen input (bottom connection) of the gas storage is open before starting up the electrolyzer. Otherwise the electrolyzer could be damaged.

### Note:

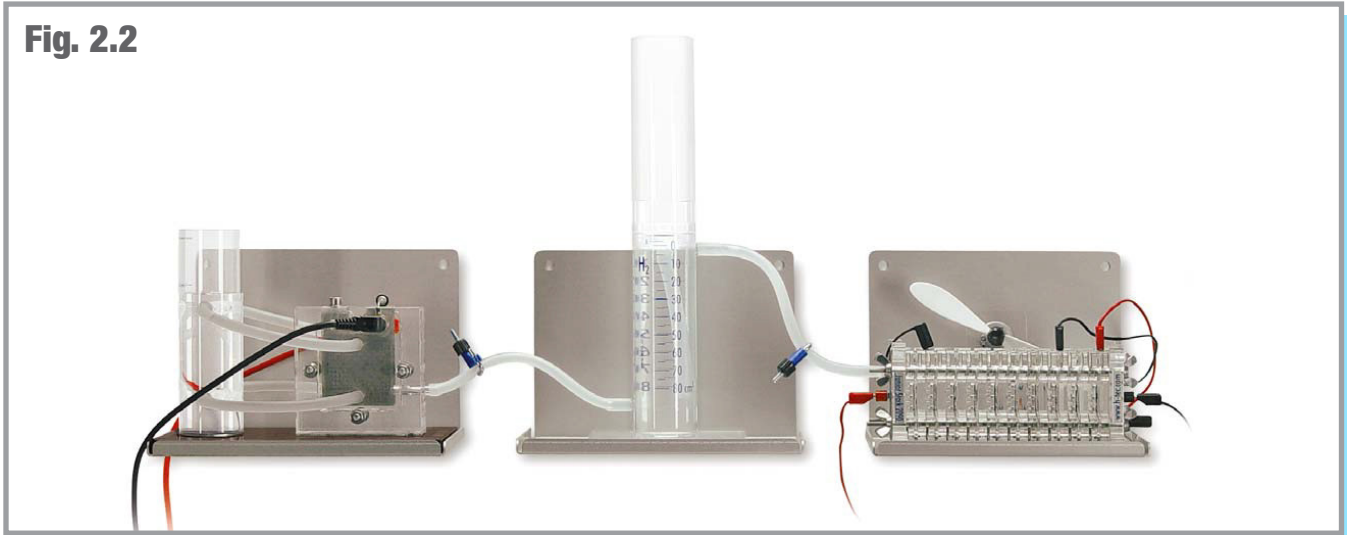
Depending on the use of the gas storage, it is recommended to select different water filling levels.

If you want to determine the chronological hydrogen production, fill the tank up to the zero mark. Then screw the compensating reservoir onto the tank and close the hose clamp at the hydrogen output (top connection) of the gas storage. The gas produced now displaces the water in the tank and presses it into the compensating reservoir. You can read the amount of hydrogen produced on the scale.

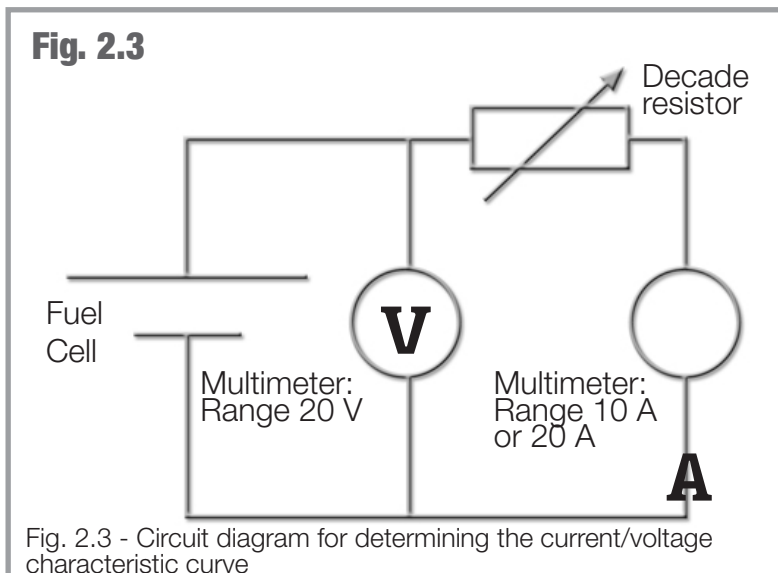
In the case of longer operation, it is recommended to use the tank as water separator. In the course of the operation, water is pumped from the oxygen side of the electrolyzer to the hydrogen side. In turn, this results in water from the tank reaching the fuel cell. Water in the fuel cell can result in a rapid power drop as the gas supply is blocked. In order to prevent this, it is recommended to only fill the tank with distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ) up to the 80 cm<sup>3</sup> mark. Screw the compensating reservoir onto the tank afterwards

3. Connect a direct current power source (e.g. H-TEC EDUCATION Solar Module 13). **Pay attention here to the correct polarity (red="+" and black="-") and to the maximum permitted voltage of 4 V.**

4. Connect the hydrogen output of the tank (top connection) to one of the hydrogen inputs of the fuel cell and seal the output of the fuel cell with a sealing cap (Fig. 2.2). Ensure that the hose clamp between the gas storage and the fuel cell is open.

**Fig. 2.2**


5. Wait a moment until some gas has accumulated in the tank. Then open the sealing cap of the fuel cell so that the gas can flow through the fuel cell. The residual air and residual moisture remaining in the hose and in the fuel cell escape. Afterwards, replace the sealing cap.
6. The device is now in demonstration mode. Connect the FCM (see Section 3), in order to record current, voltage and power values.
7. In order to determine the characteristic curve manually, use the circuit diagram below (Fig 2.3). Start the measurement with the no-load voltage and continue the series of measurements of large to small resistors. Ensure that there is sufficient gas available for the PEM fuel cell stack. In the case of very small resistance values, the values for current intensity and voltage may not be stable if not enough gas is supplied.

**Fig. 2.3**


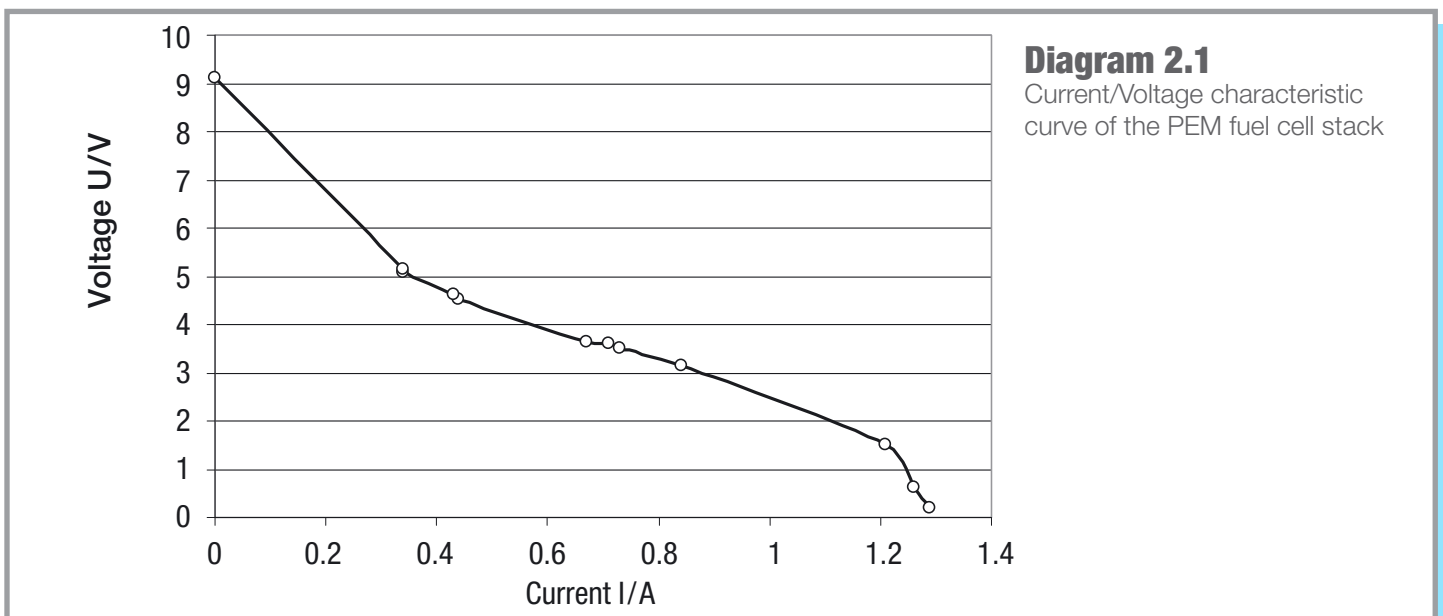
**Measurement results of the manual measurement**

Example (performed with the H-TEC EDUCATION hydrogen experimentation system Stack Experimentation Set Complete)

Resistance R/Ohm	Current I/A	Voltage U/V	Power P/W
0.22	1.29	0.19	0.25
0.33	1.26	0.62	0.78
0.55	1.21	1.51	1.83
3.20	0.84	3.16	2.65
4.70	0.73	3.52	2.57
4.92	0.71	3.62	2.57
5.25	0.67	3.63	2.43
10.00	0.44	4.51	1.98
10.55	0.43	4.62	1.99
14.70	0.34	5.09	1.73
15.25	0.34	5.15	1.75
infinite	0.00	9.10	0.0

Table 2.1 Measurement of the current and voltage values of the 10-cell PEM fuel cell stack for different load resistances

**Current/Voltage characteristic curve of the 10-cell PEM fuel cell stack**





The performance of the fuel cell stack depends on, the gas flow rate, the moistness of the membrane and the temperature.

The measured values from Table 3.1.1 are shown in the diagram 3.1.1. The no-load voltage of this 10-cell fuel cell stack is  $U_0=9.10$  V. The no-load voltage of each individual cell is thus approximately  $U_0=0.91$  V.

As voltage measuring points are present on each individual cell, the individual voltages can also be measured. The total voltage of the fuel cell stack corresponds to the sum of the individual cell voltages.

## Evaluation

If a hydrogen and an oxygen electrode are located in a fuel cell, there is a potential difference  $\Delta E$  between the two electrodes. This depends on the temperature; the theoretical value can be calculated from the free reaction enthalpy  $\Delta G$  and for 25 °C is  $\Delta E=1.23$  V. Therefore, the 10-cell PEM fuel cell stack has a potential difference of  $\Delta E=12.3$  V.

The terminal voltage for the fuel cell or the PEM fuel cell stack can have a maximum value as large as this theoretical value. However, other potential jumps also occur at the electrodes.

Phase potentials between electrode and membrane still occur at the electrodes in the electrochemical equilibrium. Thereby, a constant load exchange between both takes place, however the gross reaction is zero. If a current is also flowing through the fuel cell, the electrochemical equilibrium at the electrodes is disturbed. The electrode potential adopts a value dependent on the current density due to different reactions at the electrode. The difference from the equilibrium value is called "Electrical Polarization"; the electrode is polarized.

The typical characteristic curve of a fuel cell therefore does not show an approaching linear course until the transition to larger current intensities; in this range, the migration of the ions through the membrane is decisive. In our example, we have insufficient measured values in the range of lower current intensities to be able to consider the nonlinear range more precisely. It can be concluded from the fall in the characteristic curve for higher current intensities that sufficient hydrogen is no longer reaching the electrodes.

## 2.2 Determination of the Efficiency of the PEM Fuel Cell Stack

It is recommended to use the Fuel Cell Monitor Pro 4.0 (FCM) included in the set for the recording of the current/voltage characteristic curve of the PEM fuel cell stack. It is also possible for you to determine the characteristic curve manually. A circuit diagram for this can be found in Fig. 2.3.

### Materials needed:

- Electrolyzer 65
- Storage 80
- Fuel Cell Stack 10
- Power Source
- Fuel Cell Monitor Pro 4.0

In order to record the characteristic curve manually, you need:

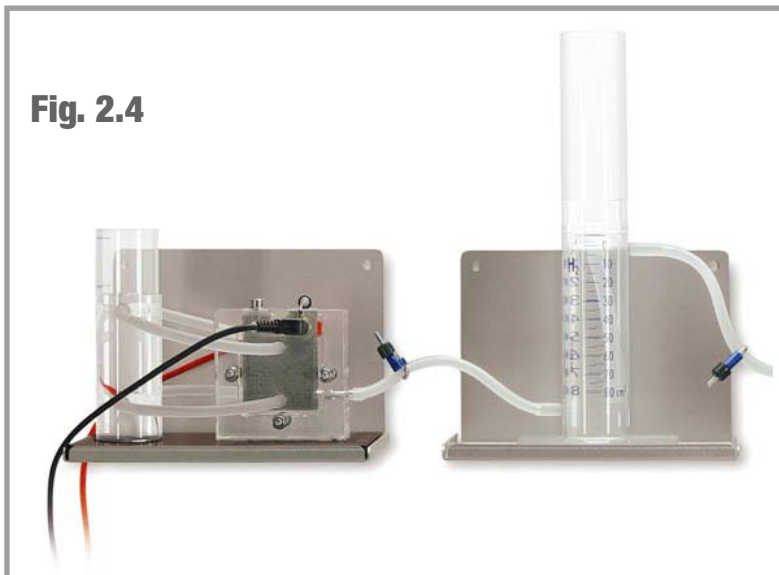
- Various resistors or potentiometers and measuring equipment for current and voltage
- stopwatch

1. Connect the hydrogen outlet of the Electrolyzer to the bottom inlet of the Storage 80 and open the hose clamp (Fig. 2.4).

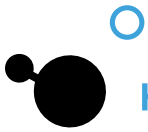
2. Fill the water tank of the Electrolyzer stack up to the marking with distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ).

### Caution!

Always ensure that the hose clamp between the hydrogen output of the electrolyzer and the hydrogen input (bottom connection) of the gas storage is open before starting up the electrolyzer. Otherwise the electrolyzer could be damaged.



**Fig. 2.4**



3. Fill the tank up to the zero mark with distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ). Then screw the compensating reservoir onto the tank and close the hose clamp at the hydrogen outlet (top connection) of the gas storage. The gas produced now displaces the water in the tank and presses it into the compensating reservoir. You can read the amount of hydrogen produced on the scale.

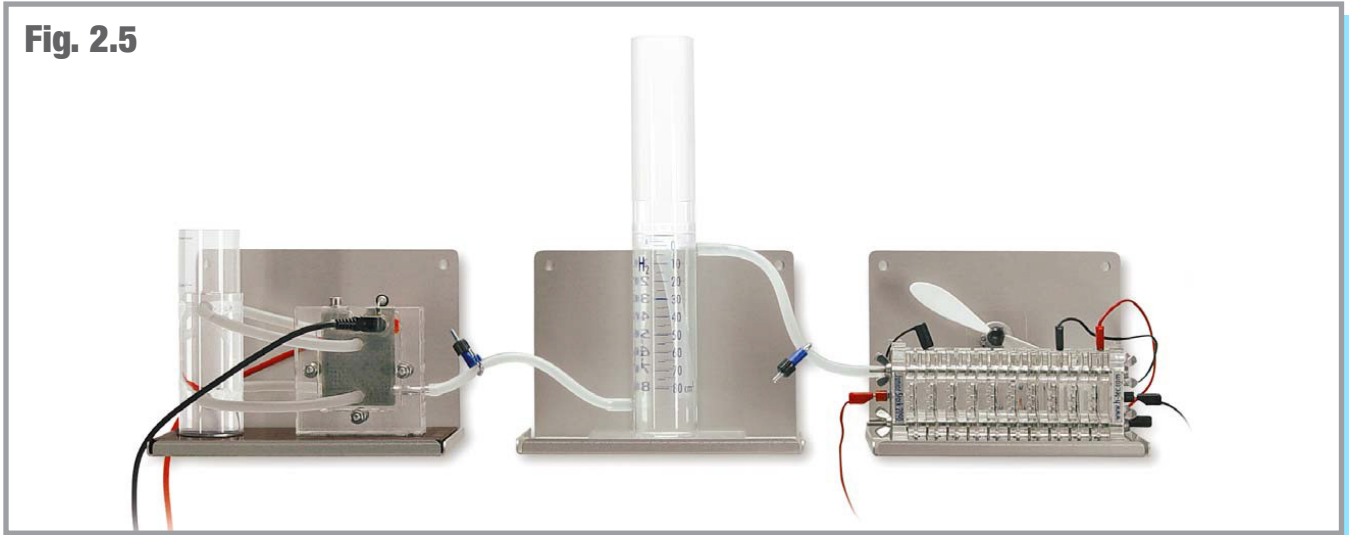


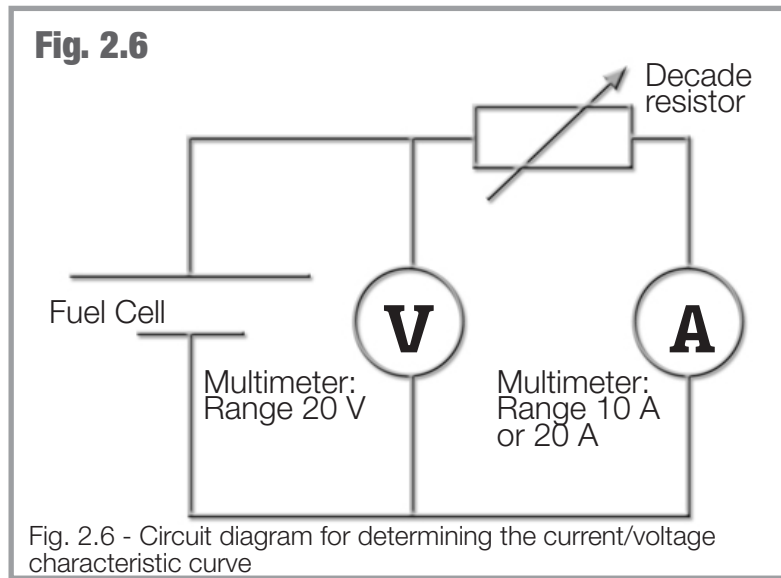
Fig. 2.5

4. Connect a direct current power source (e.g. H-TEC EDUCATION Solar Module 13). Pay attention here to the correct polarity (red="+" and black="-") and to the maximum permitted voltage of 4 V.
5. Connect the hydrogen output of the tank (top connection) to one of the hydrogen inputs of the fuel cell and seal the output of the fuel cell with a sealing cap (Fig. 2.5). Ensure that the hose clamp between the gas storage and the fuel cell is open.
6. Wait a moment until some gas has accumulated in the tank. Then open the sealing cap of the fuel cell so that the gas can flow through the fuel cell. The residual air and residual moisture remaining in the hose and in the fuel cell escape. Afterwards, replace the sealing cap.
7. The device is now in demonstration mode. Connect the FCM (see Section 3), in order to record efficiency and follow the instructions in Section 3.3.7 and follow the instructions for recording efficiency.

**Note:**

The measurement of the efficiency with the FCM is based on a simplified formula for the benefit of good usability. It refers exclusively to hydrogen powered fuel cells from the company H-TEC EDUCATION. The displayed efficiencies correspond to the energetic efficiencies. An efficiency calculated on the basis of the heating value and one based on the combustion value are displayed.

8. In order to determine the efficiency manually, produce 80 cm<sup>3</sup> of hydrogen. Disconnect the power source to the PEM electrolyzer stack and every electrical connection to the fuel cell stack. Do not connect an electrical load to the fuel cell stack again until you start the measurements. Use the circuit diagram on the next page for this (Fig. 2.6).



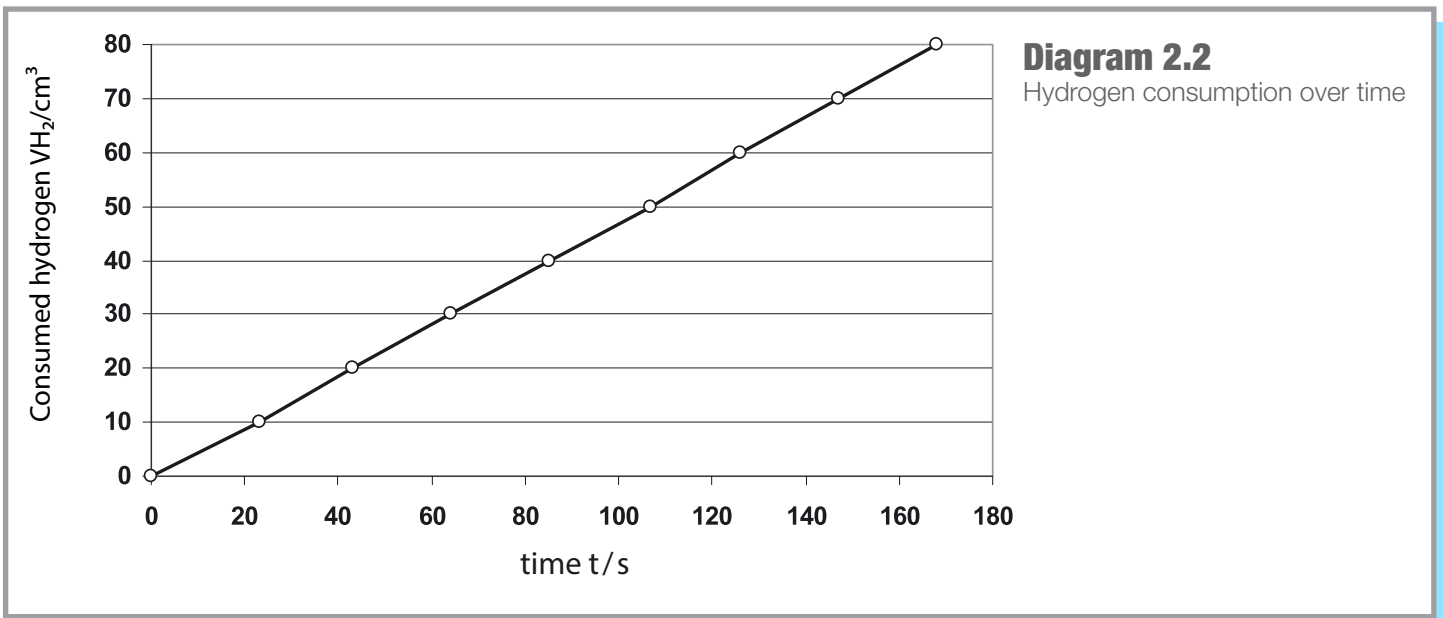
Note the measured values for time, voltage and current in accordance with constant volume stages (e.g. 10 cm<sup>3</sup>). Ensure that the current values do not fluctuate too strongly. If the current reduces significantly in the course of the measurement, the cause can be that residual gases still present in the tank adversely affect the function of the fuel cell. This problem can also occur if too little hydrogen is present in the tank (e.g. only still 5 cm<sup>3</sup>).

### **Measurement results of the manual measurement**

Example (performed with the H-TEC EDUCATION hydrogen experimentation system Stack Experimentation Set Complete)

Consumed hydrogen $V_{H_2}/cm^3$	Time t/s	Voltage U/V	Current I/A	Power P/W
0	0	5.80	0.44	2.55
10	23	5.76	0.43	2.48
20	43	5.75	0.43	2.47
30	64	5.75	0.43	2.47
40	85	5.75	0.43	2.47
50	107	5.75	0.43	2.47
60	126	5.75	0.43	2.47
70	147	5.74	0.43	2.47
80	168	5.73	0.42	2.41

Table 2.2 If hydrogen gas is supplied to a fuel cell, it is continuously converted into electrical energy. The time, voltage and current values for specified, consumed hydrogen gas volumes have been recorded in this table.



### Determining “Energy Efficiency”

The energy efficiency  $\eta_{\text{energetic}}$  shows how much of the supplied energy  $E_{\text{input}}$  leaves the system, in this case the fuel cell as actually usable energy  $E_{\text{usable}}$ . The greater the efficiency the better is the energy usage.

$$\eta_{\text{energetic}} = \frac{E_{\text{usable}}}{E_{\text{input}}} = \frac{E_{\text{electric}}}{E_{\text{hydrogen}}}$$

The energetic efficiency can be calculated using the following formula:

$$\eta_{\text{energetic}} = \frac{E_{\text{electric}}}{E_{\text{hydrogen}}} = \frac{U \cdot I \cdot t}{V_{\text{H}_2} \cdot H_l}$$

$$\eta_{\text{energetic}} = \frac{5.75 \text{ V} \cdot 0.43 \text{ A} \cdot 168 \text{ s}}{80 \cdot 10^{-6} \text{ m}^3 \cdot 10.8 \cdot 10^6 \frac{\text{J}}{\text{m}^3}} = 0.48 = \underline{48\%}$$

$H_l$  = Heating value of the hydrogen (also called lower heating value) =  $10.8 \cdot 10^6 \text{ J/m}^3$

$V_{\text{H}_2}$  = Amount of hydrogen produced in  $\text{m}^3$

$U$  = Average voltage (measured in V)

$I$  = Average current (measured in A)

$t$  = Time (measured in s)

In our example, the energy efficiency of the fuel cell is 48%. This means that 48% of the energy stored in the hydrogen which we operate the fuel cell with is output as electrical energy.

The fuel cell also outputs heat. If this heat is not used, it must be considered as lost energy. In this way, the energetic efficiency is limited from the start. An ideal efficiency  $\eta_{\text{id}}$  is defined for this, the quotient from the free reaction enthalpy  $\Delta G$  (the work released during the reaction, e.g. in the form of electrical energy) and the reaction enthalpy  $\Delta H$  (the total energy released during the reaction).

$$\eta_{\text{id}} = \frac{\Delta G}{\Delta H}$$

The difference between free reaction enthalpy  $\Delta G$  and the reaction enthalpy  $\Delta H$  is the released heat  $Q$ . The heat can be described as a product from the temperature  $T$  and the reaction entropy  $\Delta S$ .

$$Q = T \cdot \Delta S$$

The reaction enthalpy can be determined using the following equation:

$$\Delta H = \Delta G + T \cdot \Delta S$$

The ideal efficiency  $\eta_{id}$  is calculated according to the following formula:

$$\eta_{id} = \frac{\Delta G}{\Delta H} = \frac{\Delta H - T \cdot \Delta S}{\Delta H} = 1 - \frac{T \cdot \Delta S}{\Delta H} = 1 - \frac{298 \text{ K} \cdot \left(-162.985 \frac{\text{J}}{\text{mol} \cdot \text{K}}\right)}{-28,5840 \frac{\text{J}}{\text{mol} \cdot \text{K}}}$$

$$\eta_{id} = 0.83 = \underline{83\%}$$

$$T = 298 \text{ K}$$

$$\Delta S = -162.985 \frac{\text{J}}{\text{mol} \cdot \text{K}} \quad \text{for standard pressure and temperature}$$

$$\Delta H = -28,5840 \frac{\text{J}}{\text{mol} \cdot \text{K}} \quad \text{for standard pressure and temperature}$$

The energy efficiency of 83% is further limited due to voltage losses, for example heat development. The ideal cell voltage of 1.23 Volts is not achieved due to the electrode-specific over-voltages, the internal resistance of the fuel cell and diffusion losses within the fuel cell.

Similarly to the PEM electrolyzer stack, the efficiency of the fuel cell is strongly dependent on output. If the consumer has a large electrical resistance, the efficiency of the fuel cell is in fact high; however the fuel cell is then only operated in the partial load range. Thus less output than it can produce is taken from it. In order to establish at which load resistance the energetic efficiency of the fuel cell is the greatest, this experiment can be repeated with different resistances.

### Determining "Faraday Efficiency"

With the second Faraday law and the amount of substance related condition equation for gases, a relationship between the flowing current and the theoretically consumed amount of gas of the fuel cell can be established. The Faraday Efficiency of the fuel cell is obtained from the ratio of theoretically calculated gas quantity to actually consumed gas quantity.

The Second Faraday Law is:

$$Q = I \cdot t = n \cdot z \cdot F$$

The amount of substance related condition equation for gases is:

$$p \cdot V = n \cdot R \cdot T$$

If both formulas are combined, the gas volume can be calculated as follows:

$$V = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z}$$

$V$  = theoretically produced gas volume in  $\text{m}^3$

$R$  = universal gas constant =  $8.314 \frac{\text{J}}{\text{mol} \cdot \text{K}}$

$p$  = ambient pressure in Pa

$F$  = Faraday's Constant =  $96,485 \frac{\text{C}}{\text{mol}}$  ( $1\text{C} = 1\text{As}$ )

$T$  = ambient temperature measured in K

$I$  = current measured in A

$t$  = time measured in s

$Q$  = electrical load measured in C

$n$  = substance quantity measured in mol

$z$  = number of electrons to separate a molecule

$z(\text{H}_2) = 2$ , i.e. two mol electrons are needed to release one mol hydrogen

$z(\text{O}_2) = 4$ , i.e. four mol electrons are needed to release one mol oxygen

As a PEM fuel cell stack is used for this experiment, it must be taken into account that the current flows through each individual cell, i.e. the gas volume is consumed in each individual cell, thus the result here must be multiplied by the factor of ten.

The Faraday Efficiency is obtained from the following formula:

$$\eta_{\text{Faraday}} = \frac{V_{\text{H}_2}(\text{calculated})}{V_{\text{H}_2}(\text{consumed})}$$

$$V_{\text{H}_2}(\text{consumed}) = 80 \text{ cm}^3 = 80 \text{ mL}$$

$$V_{\text{H}_2}(\text{calculated}) = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z} = \frac{8,314 \frac{\text{J}}{\text{mol} \cdot \text{K}} \cdot 0,36 \text{ A} \cdot 298 \text{ K} \cdot 168 \text{ s}}{96,485 \frac{\text{C}}{\text{mol}} \cdot 1,013 \cdot 10^5 \text{ Pa} \cdot 2} \cdot 10$$

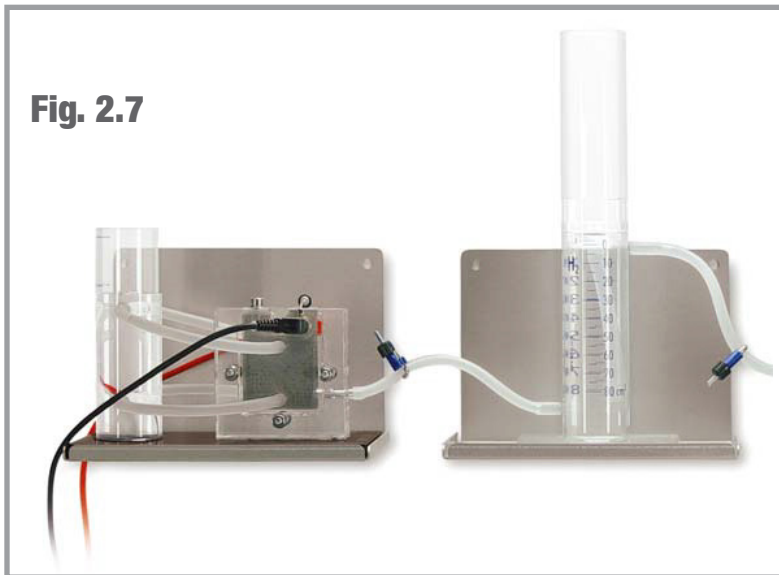
$$V_{\text{H}_2}(\text{calculated}) = 76,65 \cdot 10^{-6} \text{ m}^3 = 76,65 \text{ cm}^3 = \underline{76,65 \text{ mL}}$$

$$\eta_{\text{Faraday}} = \frac{76,65 \text{ mL}}{80 \text{ mL}} = 0,958 \approx 96\%$$

The amount of gas actually consumed is somewhat larger than the calculated amount. The reason for this is diffusion losses in the fuel cell.

## 2.3 Influence of Heat and Air Flow on the PEM Fuel Cell Stack

It is recommended to use the Fuel Cell Monitor Pro 4.0 (FCM) included in the set for the examination of the influences of heat and air flow on the PEM fuel cell stack. It is also possible for you to determine the influences manually.



**Fig. 2.7**

### Materials needed:

- Electrolyzer 65
- Storage 80
- Fuel Cell Stack 10
- Power Source
- Fuel Cell Monitor Pro 4.0
- Thermometer

In order to record the characteristic curve manually, you need:

- Various resistors or potentiometers and measuring equipment for current and voltage

1. Connect the hydrogen outlet of the Electrolyzer to the bottom inlet of the Storage 80 and open the hose clamp (Fig. 2.4).

2. Fill the water tank of the Electrolyzer stack up to the marking with distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ).

### Caution!

Always ensure that the hose clamp between the hydrogen output of the electrolyzer and the hydrogen

input (bottom connection) of the gas storage is open before starting up the electrolyzer. Otherwise the electrolyzer could be damaged.

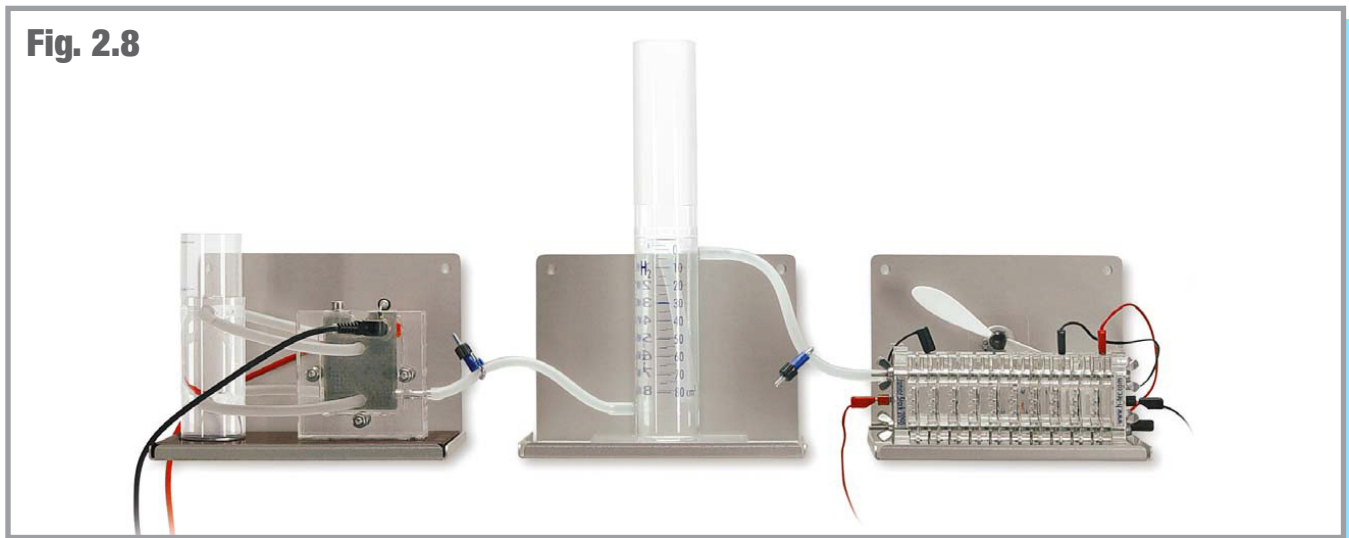
### Note:

If you want to determine the chronological hydrogen production, fill the tank up to the zero mark. Then screw the compensating reservoir onto the tank and close the hose clamp at the hydrogen outlet (top connection) of the gas storage. The gas produced now displaces the water in the tank and presses it into the compensating reservoir. You can read the amount of hydrogen produced on the scale. In the case of longer operation, it is recommended to use the tank as water separator. In the course of the operation, water is pumped from the oxygen side of the electrolyzer to the hydrogen side. In turn, this results in water from the tank reaching the fuel cell.

Water in the fuel cell can result in a rapid power drop as the gas supply is blocked. In order to prevent this, it is recommended to only fill the tank with distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ) up to the 80 cm<sup>3</sup> mark. Screw the compensating reservoir onto the tank afterwards.

3. Connect a direct current power source (e.g. H-TEC EDUCATION Solar Module 13). **Pay attention here to the correct polarity (red= “+” and black= “-”) and to the maximum permitted voltage of 4 V.**

4. Connect the hydrogen outlet of the tank (top connection) to one of the hydrogen inlet of the fuel cell and seal the outlet of the fuel cell with a sealing cap (Fig. 2.7). Ensure that the hose clamp between the gas storage and the fuel cell is open.



5. Wait a moment until some gas has accumulated in the tank. Then open the sealing cap of the fuel cell so that the gas can flow through the fuel cell. The residual air and residual moisture remaining in the hose and in the fuel cell escape. Afterwards, replace the sealing cap.

**Note:**

The PEM fuel cell stack heats up in operation and the air flows due to convection vertically through the air ducts. However, the cell can dry out if the flow rate is too high. Depending on the connected electrical load, ambient temperature and humidity as well as air movement in the surrounding area, you can achieve a higher output by rotating the cell onto its side (the air ducts are then horizontal).

Among other things, the electrical data of the fuel cell stack are dependent on the gas flow rate and the moistness of the membrane. In order to establish a stable condition of the fuel cell stack, it should operate with high electrical load for a short time. The PEM fuel cell stack thus reaches operating temperature and the possibly dried out membrane in the fuel cell moistens itself. This can require several minutes.

Examine the behavior of the fuel cell stack for the following influences:

- A. Operation with high ambient temperature
- B. Optimization of the air supply
- C. Modification of the stack installation, air slots in horizontal or vertical direction

In each case, record the current, voltage and output values (e.g. with the FCM, see Section 2.1). Attempt to justify the behavior of the fuel cell.

**Note:**

The FCM provides various measurement options such as a voltage or current regulated measurement which are particularly suitable for performing examinations over a longer time period. Another measurement option provided by FCM is the monitoring of the stack individual voltages. The influences on the individual cells of the stack can be particularly well displayed with this measurement option. Please refer to Section 3.3 of the operating manual for information about the individual measurement options.

**Results for Exercise A: “Operation at higher ambient temperatures”**

A clear effect can hardly be measured here. Nevertheless, consideration about the influence of the temperature should be made as the heat plays a strong role for higher output fuel cells. The following explanations can be made here:

- Heated ambient air can result in an improvement of the output of the stack during starting or during operation with small load (no large power output and therefore only low operating temperature). However, this can also have negative effects. If the heat is too great and the air too dry, the “moisture balance” of the fuel cells can be disrupted.
- Slight drops of the voltage can occur when opening the hydrogen output on the PEM fuel cell stack. The cause for this is the flowing, cold hydrogen.

**Note:**

The temperature inside the stack can be measured with a suitable temperature sensor. Insert the temperature sensor centrally in one of the air slots of the PEM fuel cell stack for this.

**Results for Exercise B: “Optimization of the Air Supply”**

Due to the optimization of the air supply, e.g. using the supplied fan, the individual cells of the stack are better supplied with oxygen (from the air).

If the fan is operated via the PEM fuel cell stack, it also, of course, consumes some energy. However, there is an optimization possibility where the fan is connected via 2 individual cells and, despite this larger electrical load, more power is output from the stack (see Table 2.3 measured with 10-cell tack for a load resistance of 4.7 Ohm).

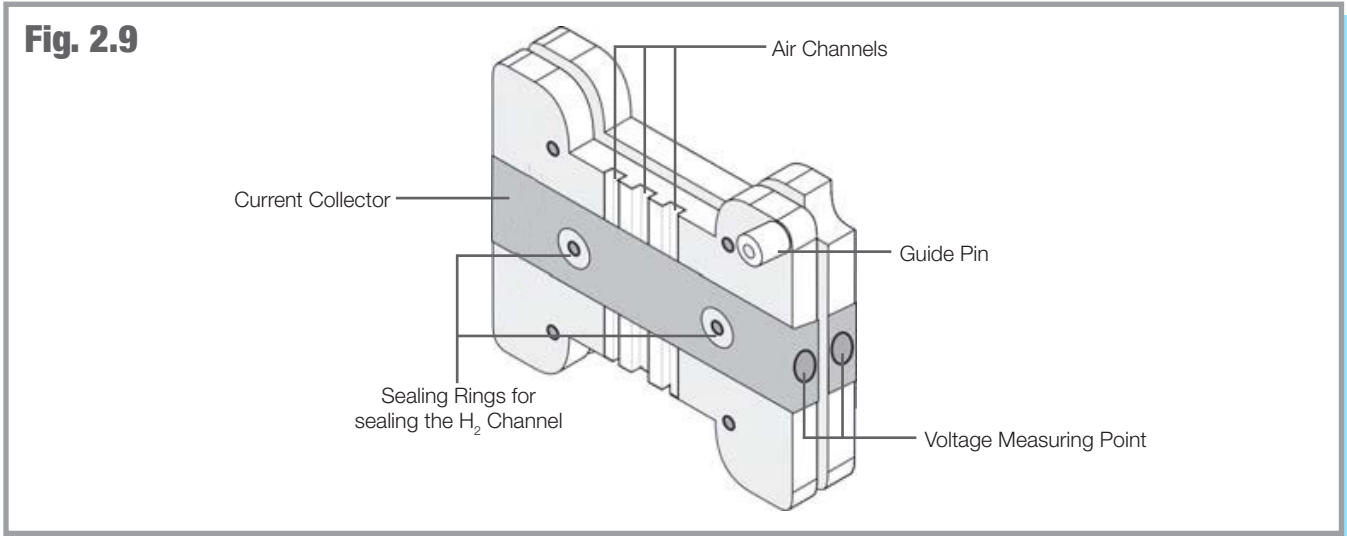
Number of cells the fan is connected to	Voltage U/V	Current I/A	Power P/W
0	3.25	0.69	2.24
1	3.6	0.77	2.77
2	3.7	0.79	2.92
3	3.6	0.78	2.81
4	3.5	0.76	2.66
5	3.4	0.74	2.52
6	3.3	0.72	2.38
7	3.1	0.68	2.11
8	2.9	0.63	1.83
9	2.7	0.59	1.60
10	2.5	0.53	1.33

Table 2.3 Current, voltage and power values of the stack with fan connected to a different number of individual cells



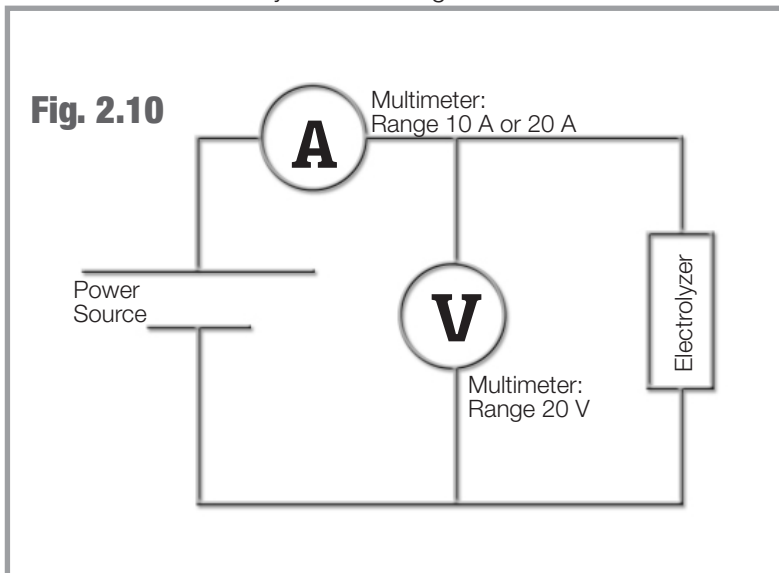
### Results for Exercise C: “Modification of the stack installation (air channels in horizontal or vertical direction)”

If the stack is arranged so that the air channels run vertically, this results in good convection (heat flow) into the gas channels, i.e. the air in the gas channels is heated and in this way rises upwards (“chimney principle”). Due to this flow, fresh air reaches the stack continuously and the heat is distributed evenly. This results in the output rising somewhat and adjusting itself to a constant value.



## 2.4 Current/Voltage Characteristic Curve of the PEM Electrolyzer Stack

It is recommended to use the Fuel Cell Monitor Pro 4.0 (FCM) included in the set for the recording of the current/voltage characteristic curve of the PEM electrolyzer stack. It is also possible for you to determine the characteristic curve manually. A circuit diagram for this can be seen in Fig 2.10



### Materials needed:

- Electrolyzer 65
- Power Source
- Fuel Cell Monitor Pro 4.0

In order to record the characteristic curve manually, you need:

- measuring equipment for current and voltage
- variable direct current power supply (e.g. lab power supply)

1. Fill the water tank of the Electrolyzer stack up to the marking with distilled water ( $\sigma < 2 \mu\text{S}/\text{cm}$ ).
2. Connect the PEM electrolyzer stack and the main adapter power supply as described in Part 3. For more information about recording the characteristic curve of electrolyzers, please refer to the corresponding Section 3.3.8 of this operation manual.
3. For the manual characteristic curve recording, use the circuit diagram in Fig. 2.10.

### Caution!

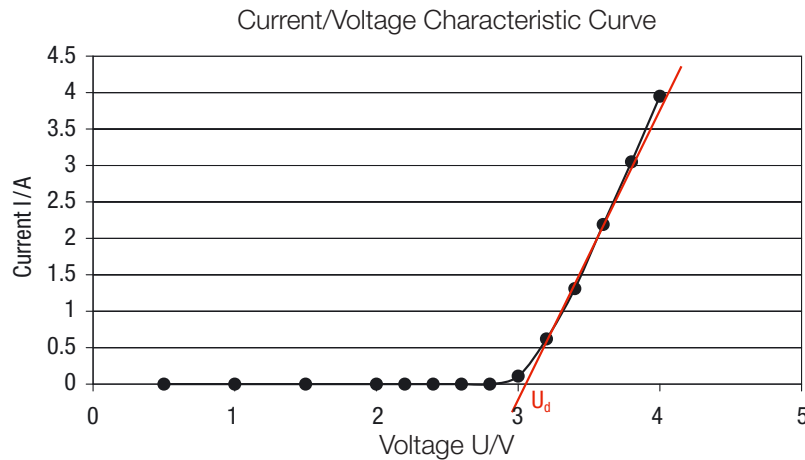
Ensure the maximum permitted voltage of 4 Volts is not exceeded. Applying a higher voltage can damage the electrolyzer!

**Note:**

The power supply should be set to 0 Volts at the start of the measurement.

5. Set the voltage at the power supply in 0.5 Volt steps up to 2.0 Volts and afterwards in 0.2 Volt steps continuously from 2 Volts to maximum 4 Volts. Make a note of the respective voltage and the corresponding current intensity in a table. Between the measurements, wait until the values have stabilized in order to obtain representative values. Pay attention to the gas production and note the associated voltage in the table.

**Diagram 2.3**



Voltage U/V	Current I/A	Power P/W
0.5	0	0
1.0	0	0
1.5	0	0
2.0	0	0
2.2	0	0
2.4	0	0
2.6	0	0
2.8	0	0
3.0	0.11	0.33
3.2	0.62	1.98
3.4	1.31	4.45
3.6	2.19	7.88
3.8	3.05	11.59
4.0	3.95	15.80

Table 2.4 Measurement of the current values of the PEM electrolyzer stack for different voltages

The PEM electrolyzer stack does not produce hydrogen and oxygen gas until a certain direct current value is exceeded. The current values start to increase from this point. The table shows the respective current values for the different voltages applied.

The output of the PEM electrolyzer stack is strongly dependent on the operating time frame. If the PEM electrolyzer stack is used only for a short time, the current at 4 V can be smaller than shown in the table. If the electrolyzer is run for a long period of time, the current can be much higher than the table shows.

### Evaluation

Show the recorded value pairs in a graph. The resulting curve is the current/voltage characteristic curve of the PEM electrolyzer stack.

If a hydrogen and an oxygen electrode are in an electrolysis cell, there is a potential difference  $\Delta E$  between the two electrodes. This depends on the temperature; the theoretical value can be calculated from the free reaction enthalpy  $\Delta G$  and is  $\Delta E = 1.23 \text{ V}$  at  $25 \text{ }^\circ\text{C}$ . No decomposition of water takes place at less than this voltage. Therefore this voltage is also called the ideal decomposition voltage.

The applied voltage for the electrolysis must therefore be at least as large as this voltage so that a current can flow. However, other potential jumps also occur at the electrodes.

Phase limit potentials between electrode and membrane still occur at the electrodes in the electrochemical equilibrium. Thereby, a constant load exchange between both takes place, however the gross reaction is zero.

If a current is also flowing through the electrolyzer, the electrochemical equilibrium at the electrodes is disturbed. The electrode potential adopts a value dependent on the current density due to different reactions at the electrode. The difference from the equilibrium value is called "Electrical Polarization"; the electrode is polarized.

The characteristic curve of the PEM electrolyzer stack therefore does not show an approaching linear course until the transition to larger currents; in this range, the migration of the ions through the membrane is decisive.

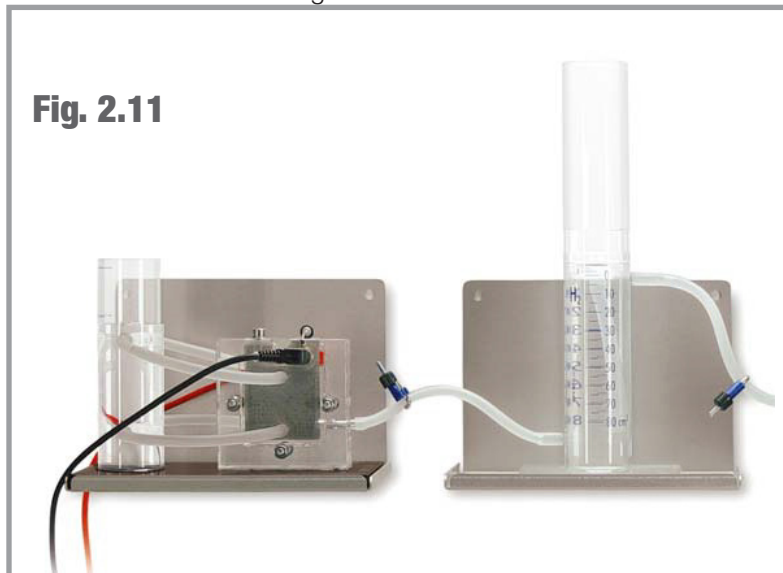
Draw the straight line (linear progression of the characteristic curve) and mark the intersection point of the straight lines with the U-axis. The intersection point gives the real decomposition voltage  $U_d$ .

In our experiment, this decomposition voltage is approx. 3.0 V. As this is a 2-cell stack where the two individual cells are wired in series, it must be taken into account that the voltage is doubled. Thus, the decomposition voltage per individual cell is approx. 1.5 V.

As already mentioned, the decomposition voltage in practice is somewhat higher than the ideal decomposition voltage due to losses in the electrolyzer. The difference between the theoretical and the practical voltage value depends on several parameters, e.g. on the type and quality of the electrode material, the electrolyte and the temperature.

## 2.5 Determining the Efficiency of the PEM Electrolyzer Stack

It is recommended to use the Fuel Cell Monitor Pro 4.0 (FCM) included in the set for the recording of the efficiency of the PEM electrolyzer stack. It is also possible for you to determine the efficiency manually. A circuit diagram for this can be seen in Fig 2.12



**Fig. 2.11**

### Materials needed:

- Electrolyzer 65
- Power Source
- Storage 80
- Fuel Cell Monitor Pro 4.0

In order to record the characteristic curve manually, you need:

- measuring equipment for current and voltage
- stopwatch
- power source (e.g. Solar Module 13, or lab power supply)

1. Connect the hydrogen outlet of the Electrolyzer to the bottom inlet of the Storage 80 and open the hose clamp (Fig. 2.11).
2. Fill the water tank of the Electrolyzer stack up to the marking with distilled water ( $\sigma < 2 \mu\text{S/cm}$ ).
3. Fill the bottom tank of the Storage 80 up to the zero mark with distilled water ( $\sigma < 2 \mu\text{S/cm}$ ). Then screw the compensating reservoir onto the tank and close the hose clamp at the hydrogen outlet (top connection).

### Caution!

Always ensure that the hose clamp between the hydrogen output of the electrolyzer and the hydrogen input (bottom connection) of the gas storage is open before starting up the electrolyzer. Otherwise the electrolyzer could be damaged.

4. In order to record the efficiency using the FCM, connect the electrolyzer and the main adapter power supply as described in Section 3 and follow the instructions for recording efficiency characteristic curves of an electrolyzer in Part 3.3.9 of the operating manual.

### Note:

The measurement of the efficiency with the FCM is based on a simplified formula for the benefit of good usability. It refers exclusively to electrolyzers from the company H-TEC EDUCATION. The efficiency shown refers to the fuel value of hydrogen.

5. In order to determine the efficiency manually, use the circuit diagram on the next page (Fig 2.12). Start the time measurement at the moment when you connect the PEM electrolyzer stack to the power supply. Note the time, the voltage present at the electrolyzer and the current for specified gas volumes (e.g. 10 mL , 20 mL , 30 mL , etc.).

### Caution!

Ensure the maximum permitted voltage of 4 Volts is not exceeded. Applying a higher voltage can damage the electrolyzer!

Tank contents V /mL	Time t/s	Voltage U/V	Current I/A	Power P/W
0	0	3.9	3.8	14.82
10	10	3.9	3.8	14.82
20	22	3.9	3.8	14.82
30	31	3.9	3.8	14.82
40	42	3.9	3.8	14.82
50	51	3.9	3.8	14.82
60	62	3.9	3.8	14.82
70	73	3.9	3.8	14.82
80	84	3.9	3.8	14.82

Table 2.5 Measurement results of the manual measurement

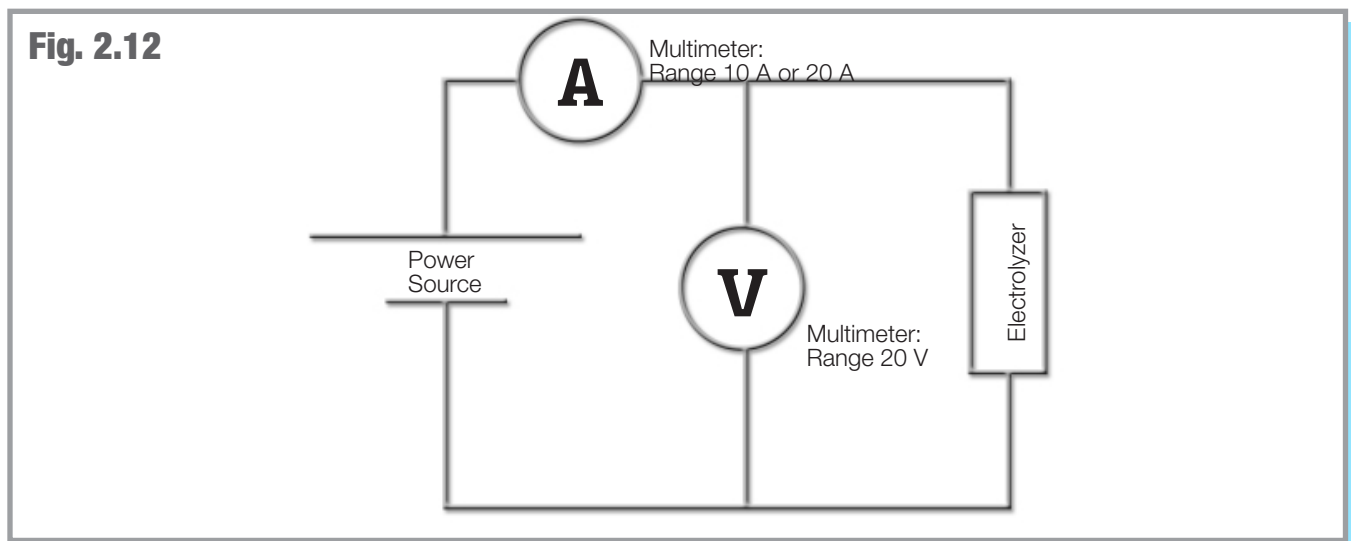
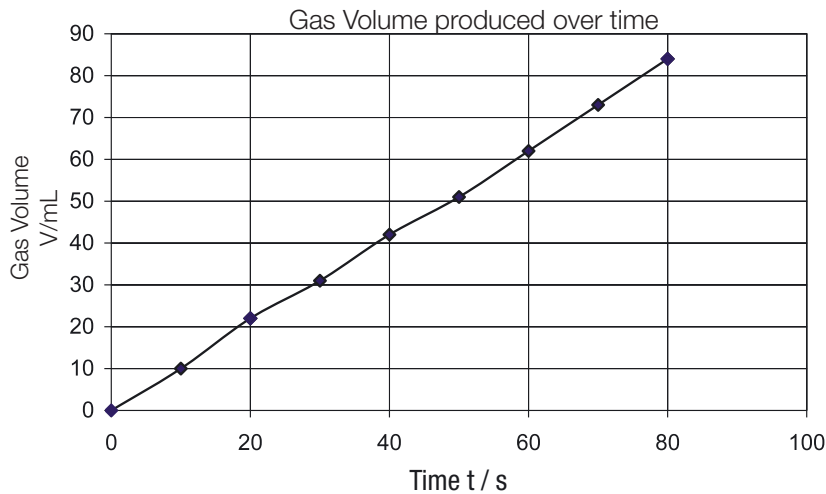


Fig. 2.12 circuit diagram for determining the efficiency of the PEM Electrolyzer Stack

**Diagram 2.4**



If the applied direct current on a PEM electrolyzer stack exceeds a specified value, it produces hydrogen gas and oxygen gas continuously. The time, voltage and current values for specified hydrogen gas volumes produced (in 10 mL stages) have been recorded in this table.

### Determining “Energy Efficiency”

The energy efficiency  $\eta_{\text{energetic}}$  shows how much of the supplied energy  $E_{\text{input}}$  leaves the system, in this case the PEM electrolyzer stack, as actually usable energy  $E_{\text{usable}}$ . The greater the efficiency the better the energy usage.

$$\eta_{\text{energetic}} = \frac{E_{\text{usable}}}{E_{\text{input}}} = \frac{E_{\text{hydrogen}}}{E_{\text{electric}}}$$

Plot the gas volume produced depending on time in a graph.

$$\eta_{\text{energetic}} = \frac{E_{\text{hydrogen}}}{E_{\text{electric}}} = \frac{V_{\text{H}_2} \cdot H_h}{U \cdot I \cdot t}$$

$$\eta_{\text{energetic}} = \frac{8 \cdot 10^{-5} \text{ m}^3 \cdot 12.745 \cdot 10^6 \frac{\text{J}}{\text{m}^3}}{3.9 \text{ V} \cdot 3.8 \text{ A} \cdot 84 \text{ s}} = 0.819 \approx \underline{82\%}$$

$H_h$  = Caloric value of hydrogen\* =  $12.745 \cdot 10^6 \frac{\text{J}}{\text{m}^3}$

$V_{\text{H}_2}$  = Amount of hydrogen produced in  $\text{m}^3$

$U$  = Average voltage (measured in V)

$I$  = Average current (measured in A)

$t$  = Time (measured in s)

\* The energy that is released during the combustion of a substance (oxidation) is defined as the calorific value  $H_h$  (also called higher heating value). It also includes the energy contained by the water vapor from combustion as condensation heat. This energy cannot be used in conventional combustion systems. Therefore, a value is also formulated that does not include the condensation heat. This variable is called a heating value  $H_i$  and is used to calculate the efficiency for heating systems, motors and fuel cells.

### Determining “Faraday Efficiency”

With the second Faraday law and the amount of substance related condition equation for gases, a relationship between the flowing current and the theoretically produced amount of gas of the PEM electrolyzer stack can be established. The Faraday Efficiency of the PEM electrolyzer stack is obtained from the ratio of the actually produced gas quantity to the theoretically calculated gas quantity.

The Second Faraday Law is:

$$Q = I \cdot t = n \cdot z \cdot F$$

The amount of substance related condition equation for gases is:

$$p \cdot V = n \cdot R \cdot T$$

If both formulas are combined, the gas volume can be calculated as follows:

$$V = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z}$$

$V$  = theoretically produced gas volume in  $\text{m}^3$

$R$  = universal gas constant =  $8.314 \frac{\text{J}}{\text{mol} \cdot \text{K}}$

$p$  = ambient pressure in Pa

$F$  = Faraday’s Constant =  $96,485 \frac{\text{C}}{\text{mol}}$  ( $1\text{C} = 1\text{As}$ )

$T$  = ambient temperature measured in K

$I$  = current measured in A

$t$  = time measured in s

$Q$  = electrical load measured in C

$n$  = substance quantity measured in mol

$z$  = number of electrons to separate a molecule

$z(\text{H}_2) = 2$ , i.e. two mol electrons are needed to release one mol hydrogen

$z(\text{O}_2) = 4$ , i.e. four mol electrons are needed to release one mol oxygen

As two electrolysis cells are wired in series for the PEM electrolyzer stack used, it must be taken into account for the calculation of the volume that the current flows through each individual cell, i.e. the calculated gas volume is produced in each cell, thus the result here must be multiplied by two.

$$V \text{ (calculated)} = \frac{R \cdot I \cdot T \cdot t}{F \cdot p \cdot z} \cdot 2 = \frac{8.314 \frac{\text{J}}{\text{mol} \cdot \text{K}} \cdot 3.8 \text{ A} \cdot 298 \text{ K} \cdot 84 \text{ s}}{96,485 \frac{\text{C}}{\text{mol}} \cdot 1.013 \cdot 10^5 \text{ Pa} \cdot 2} \cdot 2$$

$$V_{\text{H}_2} \text{ (calculated)} = 8.091 \cdot 10^{-5} \text{ m}^3 = 80.91 \text{ cm}^3 = \underline{80.91 \text{ mL}}$$

The Faraday Efficiency is obtained using the following formula:

$$\eta_{\text{Faraday}} = \frac{V_{\text{H}_2} \text{ (produced)}}{V_{\text{H}_2} \text{ (calculated)}}$$

The experimentally produced hydrogen volume is:

$$V_{\text{H}_2} \text{ (produced)} = 80 \text{ mL}$$

Accordingly, the Faraday Efficiency is:

$$\eta_{\text{Faraday}} = \frac{80 \text{ mL}}{80.91 \text{ mL}} = 0.989 \approx 98.9\%$$

The difference between the theoretical and actually produced gas quantity is very small, i.e. the electric current is almost exclusively converted for the intended reaction (decomposition of the water into hydrogen and oxygen).

No other secondary reactions take place. Quite small diffusion losses of the gases inside the cell can occur.

The diffusion losses are produced by a very small part of the gases diffusing through the membrane of the PEM electrolyzer stack and reacting to water at the catalyzer. A small amount of the gas produced is directly converted again without it being able to discharge from the cell.

## Part 3 - Fuel Cell Monitor Pro 4.0 (FCM)

### 3.1 General

#### 3.1.1 Product Description

The Fuel Cell Monitor Pro 4.0 (FCM) is a didactic product consisting of a measurement board and evaluation software "Fuel Cell Monitor 4.0". It is tailored to the requirements for the measurement of H-TEC EDUCATION products and must only be used for this. The FCM provides you with the possibility of measuring, storing and evaluating various measured values and characteristic curves of H-TEC EDUCATION fuel cell education models. The measurement board is connected to the PC using a USB cable. The supplied software gives you the possibility to record and display the following graphs:

- Voltage against current
- Power over time
- Power against current
- Power against voltage

The measurement board also provides the possibility of four conductor measurement for the compensation of measurement errors. The measured value recording can be performed automatically, voltage-regulated, current-regulated or manually. The efficiency of H-TEC EDUCATION educational fuel cells can also be measured with the FCM. The FCM can also display up to ten individual voltages of a fuel cell stack in real-time and record and display characteristic curves and efficiency of H-TEC EDUCATION educational electrolyzers.

#### 3.1.2 Menu Languages

The FCM can be operated in the following languages:

- English
- German
- French
- Spanish

#### 3.1.3 System Requirements

Minimum computer requirements: Pentium 200 MHz or comparable processor. The FCM needs at least 80 MB free disc space (for the installation of the standard drivers, however at least 580 MB is recommended). Operating system: Windows XP, Windows 7, or Windows 10, RAM: minimum 128 MB (recommended 256 MB), USB connection.

The software for the FCM is designed for operation with Windows XP, Windows 7, and Windows 10. We therefore accept guarantee for functionality only if the FCM is operated with one of these systems.

The screen resolution should be set to at least 1024 x 768. A spreadsheet program (such as, e.g. MS Excel or Open Office) is also recommended for the further processing of the stored measured data.

#### 3.1.4 Standard Delivery

Measurement Board, USB cable, software, individual voltage measurement cable, cable set, power supply for the FCM and detailed operation manual.



### 3.1.5 Appropriate Use

Measurements of H-TEC EDUCATION products in the following areas can be performed and evaluated using the external measurement board of the FCM and the associated software:

- Fuel Cell Mode
  - Voltage: 0 - 10 V DC
  - Current: 0 - 5 A
  - Power: 0 - 10 W
- Electrolyzer Mode
  - Voltage: 0 - 4 V DC
  - Current: 0 - 3 A
  - Power: 0 - 10 W

The hardware and software have been exclusively developed for educational and demonstration purposes. The output measured values and graphs must be assessed qualitatively.

Any other use is not permitted.

In order to prevent dangers, strictly observe the general safety instructions for your measurements with the FCM and fuel cells.

### 3.1.6 Usage Conditions

Read through the following paragraphs carefully before you use this software. If you do not agree with the following, do not use the software and delete it from your data carriers.

You are not entitled to reverse engineer, decompile or disassemble the software product whether in whole or in part.

### 3.1.7 Liability

It is not possible with today's technology to rule out every error in a software application. Accordingly, the software "Fuel Cell Monitor 4.0" can contain errors. For this reason, the manufacturer makes no guarantee of any kind for this software and is not liable for any kind of damage which has been caused directly or indirectly by the software. The exception to this is gross negligence.

### 3.1.8 Support

The software has been carefully tested by H-TEC EDUCATION in order to provide you with as reliable a product as possible. Nevertheless, should you notice undiscovered error sources, please contact us. Please state the version of your "Fuel Cell Monitor 4.0" in the case of questions or suggestions. You can display this using "Help" > "about FCM".

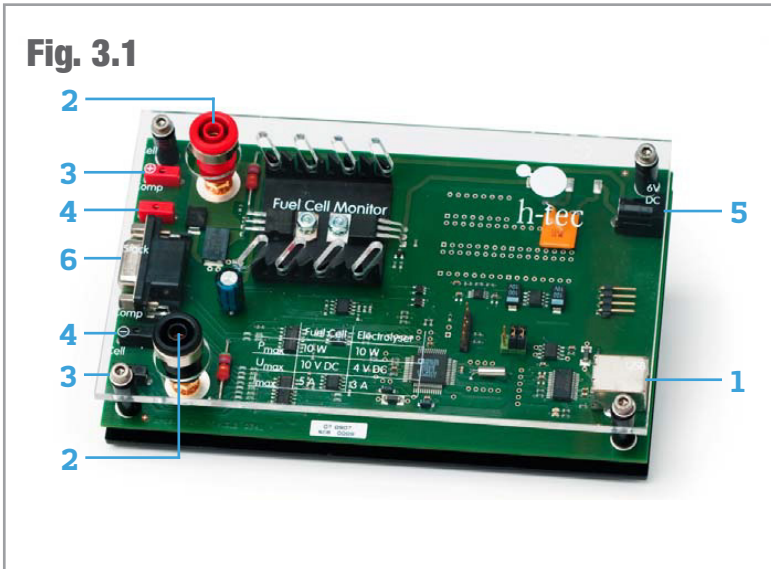
### 3.1.9 Manufacturer

H-TEC EDUCATION  
1902 Pinon Dr. Ste. B  
College Station, TX 77845  
USA

Phone: +1 979-703-1925  
Fax: +1 979-314-1122  
Email: sales@myhtec.com  
Website: www.myhtec.com

## 3.2 Measurement Board and Software

### 3.2.1 Connections



**1.** USB connection: for connecting the measuring transformer card to the PC. The connection cable is included in the standard delivery.

**2.** Fuel cell and electrolyzer 4 mm connection sockets: connections for the cell to be measured (fuel cell or electrolyzer). Also suitable for 4 mm safety measuring cables. 4 mm red and black cables are included in the standard delivery.

**3.** Fuel cell and electrolyzer 2 mm connection sockets: connections for the cell to be measured (fuel cell or electrolyzer). 2 mm red and black cables are included in the standard delivery.

**4.** Connection sockets for four-wire measurement: 2 mm connections for the compensation of measurement errors during the fuel cell and electrolyzer measurement. 2 mm red and black cables and adapter for the use of 4 mm cables are included in the standard delivery.

**5.** Power supply connection: Connection of the power supply for electrolyzer measurements. The power supply is included in the standard delivery.

**6.** Connection for stack individual voltage measurements: for connecting the individual voltage measurement cable to a fuel cell stack for the measurement of the individual cell voltages. The individual voltage measurement cable is included in the standard delivery.

It is recommended to setup the hardware and software in the following order in order to ensure smooth progress of the installation.

1. Connect the measurement board
2. Install the drivers
3. Install the FCM software

#### Important information before the installation:

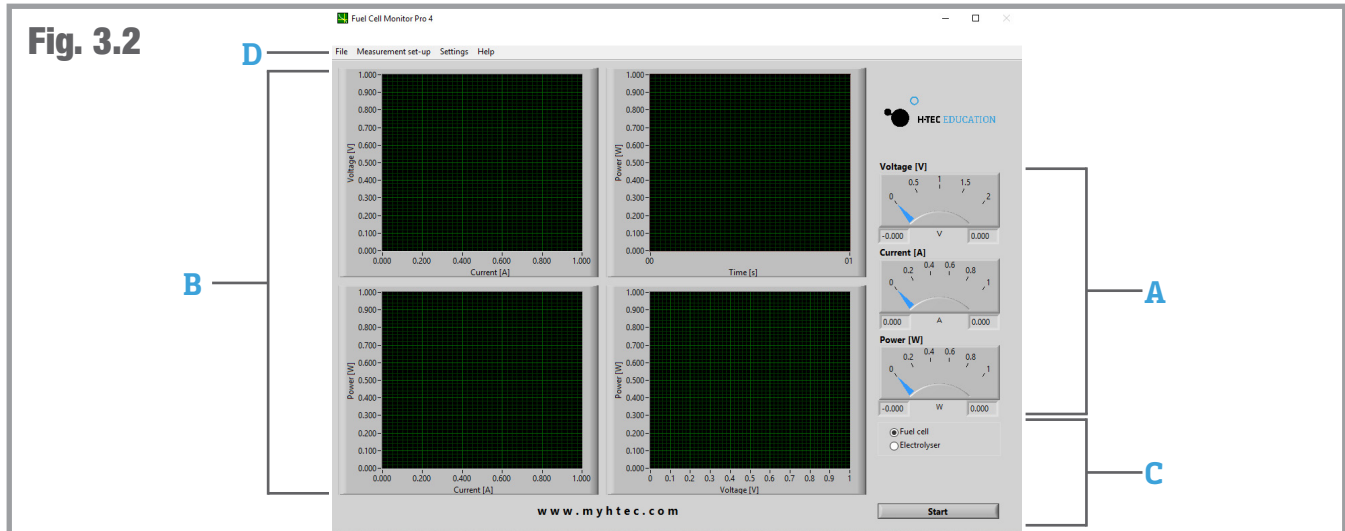
1. You need at least local administrator rights for the installation of the drivers and the FCM software for Windows Vista / Windows 7 / Windows 10.
2. You need at least local power user rights to use the FCM software for Windows Vista / Windows 7 / Windows 10.

### 3.2.2 Installation of the FCM Software

After unzipping the “Fuel Cell Monitor Pro Installer” Folder from the H-TEC EDUCATION Flash Drive you received, navigate through the folders to find the “Setup” Application File. Run the application to install the FCM Software on your computer.

When the application is installed, a shortcut should be created on your desktop. Connect the Measurement Board to your computer using the provided USB cable and open the FCM software. You will then need to select the correct COM port in the System Settings dialogue box. Using the process of elimination, choose the first option in the “FCM circuit board interface” and select Okay. The setting is now saved. If the dialogue window is displayed again, select a different COM port and/or check the USB connection. If the dialogue window is not displayed again, the FCM has a connection to the measuring transformer card.

Now you will be requested to disconnect any possibly connected fuel cells or electrolyzers from the measurement board. The program performs a zero compensation. The FCM is ready for operation afterwards. This is indicated by green and red flashing diodes on the measuring transformer card. The program interface is now displayed on your screen (see Figure 3.2) which consists of the following components:



**A. Dial Instruments** - The three dial instruments clearly show the current and maximum measured values. The pointers can have three colors: The maximum value for voltage, current and power is displayed using a black pointer. A blue pointer displays the current value. This pointer is yellow after completion of the measurement. The yellow pointer displays the so-called MPP (“Maximum Power Point”) - the point of the characteristic curve at which the cell has its maximum power output. The values are also displayed again in the form of numeric values under the dial instruments whereby the current value (blue - or in MPP yellow - pointer) is displayed on the left and the maximum value on the right.

**B. Graphs** - The recorded measured values and their course are displayed in the four graphs in the form of function graphs. A yellow cursor is displayed in the voltage/current graph after completion of the measurement. This shows the MPP of your cell. By clicking on the cursor and keeping the mouse button pressed, you can drag it along the characteristic curve and thus let different measured values on the characteristic curve be displayed.

**C. Control** - The type of the cell to be measured is specified here and measurements are started or stopped. Furthermore, you also have the possibility for certain measurements to input values (further information in Section 3.3) and a progress bar is displayed for measurements where a measurement duration can be specified.

**D. Menu Bar** - Among other things, the various measurement options and system settings are made and data are saved using the menu of the FCM (further information in the next section).

### 3.2.3 Menu Items

This section briefly shows the menu items of the FCM. Please refer to the corresponding sub-items in Section 3.3 for details about the individual measurement options.

#### File

Here, you can save the recorded measured data, display the screen as an HTML document or print it under “Report” and end the program. The “Exit” option using the cross on the top right in the program window is deactivated in order to ensure the proper shutdown of the software otherwise problems with the port recognition can occur when the software is restarted.

**Measurement Set-Up**

In the Measurement Set-Up menu, you can choose Fuel Cell or Electrolyzer, and choose your measurement options, such as: Automatic, Voltage Controlled, Current Controlled, Efficiency, etc.

**Settings**

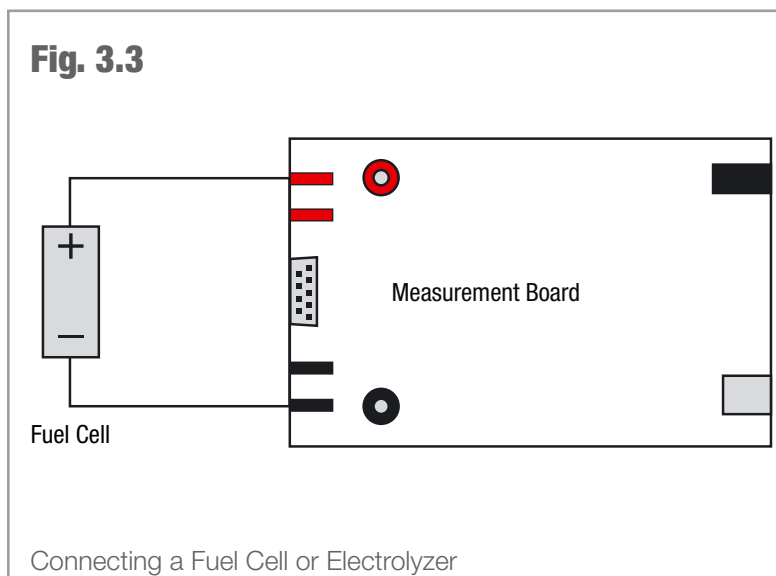
Here you can select between the menu languages, set the port for the measurement board, specify the file path and the file format for the measured data to be saved, and select the axis assignment for current and voltage for the electrolysis measurement.

**Help**

You will find the version number and the producer of the software.

### 3.3 Measured Value Recording

#### 3.3.1 General



When the program is started, a window is displayed with the instruction to disconnect any possibly connected fuel cells or electrolyzers from the measurement board. This is used for the zero compensation of the FCM. Confirm the by pressing "OK". The FCM is now ready for operation.

The FCM has automatic scaling during he characteristic curve recording. This means the axes of the graphs are automatically optimally adapted to the measured values. After the measurement has ended, you can also change the minimum and maximum values on the axes of the graphs manually in order, for example, to display specified areas of the characteristic curve magnified. Click on any scale value on the respective axis with the left mouse button and then input the desired value using the keyboard. Confirm your input afterwards by pressing Enter. The scaling changes in accordance with your input.

The menu is disabled after starting measurements. If you want to make changes in the menu after starting measurements, you must cancel the measurement or wait until the measurement is completed.

Before starting measurements, ensure that the fuel cell or the electrolyzer is connected to the measurement board as shown in Figure 3.3.

#### 3.3.2 Recording the Automatic Characteristic Curve of a Fuel Cell

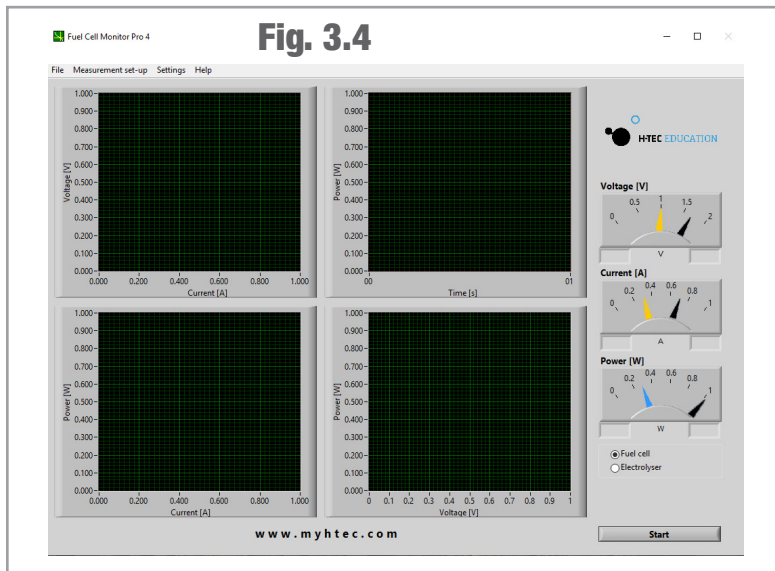
The measured values are recorded at system-controlled intervals for the automatic characteristic curve recording. A resistance is automatically changed from large to small values for this. The typical characteristic curve for fuel cells is thus produced.

**Note:**

The automatic characteristic curve recording is particularly suitable for a fast and simple display.

**Procedure:**

- Connect a fuel cell to the connection sockets of the measurement board (see Figure 3.3). Pay attention here to the correct polarity (red="+" and black="-").
- The value of the no-load voltage is now displayed in black by the top dial instrument and as a numeric value on the right under the dial instruments. The FCM is now in standby mode.
- Click on the Start button.
- The FCM now automatically records the characteristic curve of the fuel cell from the no-load voltage to the short-circuit current, graphically displays the values and is again in standby mode afterward (see Figure 3.4). The measurement can be canceled at any time using the "Cancel" button.



**Note:**

When you start the FCM, it is automatically in the "automatic characteristic curve recording of a fuel cell" mode. If you have performed a different measurement in the meantime, you can find the automatic measurement again under the menu item "Measurement Set-Up" > "Fuel Cell" > "Automatic".

**Note:**

After the measurement is completed, you can move the cursor in the voltage/current graph by clicking on the working point with the left mouse button and keeping the button pressed. The values are taken over by the dial instruments and can be read there.

**Black pointer:** maximum value

**Blue pointer:** value at the cursor position

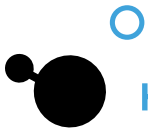
**Yellow pointer:** value at the cursor position in the Maximum Power Point (MPP).

### 3.3.3 Recording the Voltage-regulated Characteristic Curve of a Fuel Cell

In the case of voltage-regulated characteristic curve recording, the FCM regulates the measurement so that a previously specified voltage value is started and maintained. In the ideal case, the power output of the fuel cell remains constant; a characteristic curve running in parallel to the time axis is produced in the power/time graph. However, in practice non-constant operating parameters (temperature, humidity etc.) result in the fact that the power can change in the course of a measurement.

**Procedure:**

- Connect a fuel cell to the connection sockets of the measuring transformer card (see Figure 3.3). Pay attention here to the correct polarity (red="+" and black="-").
- Select the "Measurement Set-Up" menu item. Then select "Fuel Cell" > "Voltage-regulated" and input the desired voltage in Volts and measurement duration and sampling rate in seconds. The sampling rate specifies at which time interval (minimum 0.5 s) measured values are recorded by the FCM.
- For example, a sampling rate of 0.5 s means that a measured value is recorded every half a second. You can enter the desired values manually in the corresponding fields or adjust them using the arrow keys. Confirm your input afterward by pressing "OK".
- The value of the no-load voltage is now displayed in black by the top dial instrument and as a numeric value on the right under the dial instruments. The FCM is now in standby mode.



- It is also possible to input the voltage value directly using the control.
- Click on the Start button.
- The FCM now starts the specified voltage value, keeps it as constant as possible for the specified measurement duration and is again in standby mode after the measurement.
- The measurement can be stopped at any time using the “Cancel” button.

**Note:**

After the measurement is completed, you can move the cursor in the voltage/current graph by clicking on the working point with the left mouse button and keeping the button pressed. The values are taken over by the dial instruments and can be read there.

**Black pointer:** maximum value

**Blue pointer:** value at the cursor position

**Yellow pointer:** value at the cursor position in the Maximum Power Point (MPP).

**Note:**

The voltage-regulated characteristic curve recording is particularly suitable for long-term measurements. When setting a long measurement duration, the sampling rate can be set lower to reduce the measured data.

### 3.3.4 Recording the Current-regulated Characteristic Curve of a Fuel Cell

In the case of current-regulated characteristic curve recording, the FCM regulates the measurement so that a previously specified current value is started and maintained. In the ideal case, the power output of the fuel cell remains constant; a characteristic curve running in parallel to the time axis is produced in the power/time graph. However, in practice non-constant operating parameters (temperature, humidity etc.) result in the fact that the power can change in the course of a measurement.

**Procedure:**

- Connect a fuel cell to the connection sockets of the measuring transformer card (see Figure 3.3). Pay attention here to the correct polarity (red= “+” and black= “-”).
- Select the “Measurement Set-Up” menu item. Then select “Fuel Cell” R “Current-regulated” and input the desired current value in amperes and measurement duration and sampling rate in seconds. The sampling rate specifies at which time interval (minimum 0.5 s) measured values are recorded by the FCM.
- For example, a sampling rate of 0.5 s means that a measured value is recorded every half a second. You can enter the desired values manually in the corresponding fields or adjust them using the arrow keys. Confirm your input afterward by pressing “OK”.
- The value of the no-load voltage is now displayed in black by the top dial instrument and as a numeric value on the right under the dial instruments. The FCM is now in standby mode.
- It is also possible to input the current value directly using the control.
- Click on the Start button.
- The FCM now starts the specified current value, keeps it as constant as possible for the specified measurement duration and is again in standby mode after the measurement.
- The measurement can be canceled at any time using the “Cancel” button.

**Note:**

After the measurement is completed, you can move the cursor in the voltage/current graph by clicking on the working point with the left mouse button and keeping the button pressed. The values are taken over by the dial instruments and can be read there.

**Black pointer:** maximum value

**Blue pointer:** value at the cursor position

**Yellow pointer:** value at the cursor position in the Maximum Power Point (MPP).

**Note:**

The voltage-regulated characteristic curve recording is particularly suitable for long-term measurements. When setting a long measurement duration, the sampling rate can be set lower to reduce the measured data.

### 3.3.5 Recording the Manual Characteristic Curve of a Fuel Cell

You can select a point on the characteristic curve of the fuel cell for the manual characteristic curve recording. It adapts to the associated voltage and current value; the load resistance belonging to this point is also displayed.

**Procedure:**

- Connect a fuel cell to the connection sockets of the measuring transformer card (see Figure 4.3). Pay attention here to the correct polarity (red= “+” and black= “-”).
- Select the “Measurement Set-Up” menu item. Then select “Fuel Cell” > “Manual”. Then select “OK”.
- The value of the no-load voltage is now displayed in black by the top dial instrument and as a numeric value on the right under the dial instruments. The FCM is now in standby mode.
- Now click on the Start button. The characteristic curve of the fuel cell is first determined automatically; a dialogue window is displayed afterwards. Click “OK” if the characteristic curve meets your expectations. If not, select “Cancel”. You can then restart the automatic characteristic curve recording.

**Note:**

The menu is disabled as the FCM is performing the measurement.

Now select a working point on the characteristic curve in the voltage/current graph at which you would like to measure the fuel cell (default MPP - yellow cursor). Click on the working point with the left mouse button and keep it pressed to move the point. Click on Start again. The FCM now starts this point of the characteristic curve and maintains it.

You also have the possibility to move the cursor on the characteristic curve during the running measurement by clicking on the working point with the left mouse button and keeping it pressed. The FCM then starts the new point whereby the new current and voltage values are adjusted. In doing so, the resistance value is displayed as the quotient of voltage and current.

The measurement can be canceled at any time using the “Cancel” button.

**Note:**

During a longer measurement, it can happen that the power of the cell increases if the cursor is moved from the MPP. This initially seems illogical, however can be explained as follows: As this is a case of a current-regulated measurement in the background, the FCM takes over the current value of the characteristic curve and multiplies this by the current voltage value. However, as the parameters (temperature, humidity etc.) of the fuel cell change over longer operation, its power also changes, i.e. current and voltage and thus also the characteristic curve. The voltage value of the characteristic curve therefore no longer matches the current voltage.

**Remedy:** Restart the measurement and let the fuel cell operate under load for a few minutes until it has reached its operating temperature before you start measurements. The power output is then more constant.

**Note:**

After the measurement is completed, you can move the cursor in the voltage/current graph by clicking on the working point with the left mouse button and keeping the button pressed. The values are taken over by the dial instruments and can be read there.

**Black pointer:** maximum value

**Blue pointer:** value at the cursor position

**Yellow pointer:** value at the cursor position in the Maximum Power Point (MPP).

### 3.3.6 Recording the Manual Characteristic Curve of a Fuel Cell

**Procedure:**

- Select “Measurement Set-Up” > “Single Stack Voltages” from the menu and input how many cells your stack has (2 to 10).
- Connect the individual voltage measurement cable to the “COM” connection of the measurement board and connect the measurement cables to the positive and negative poles of the stack. Afterwards, connect the connectors of the individual voltage measurement cable to the individual stack cells. Start at “U1” on the negative side of the stack (see Figure 3.5).

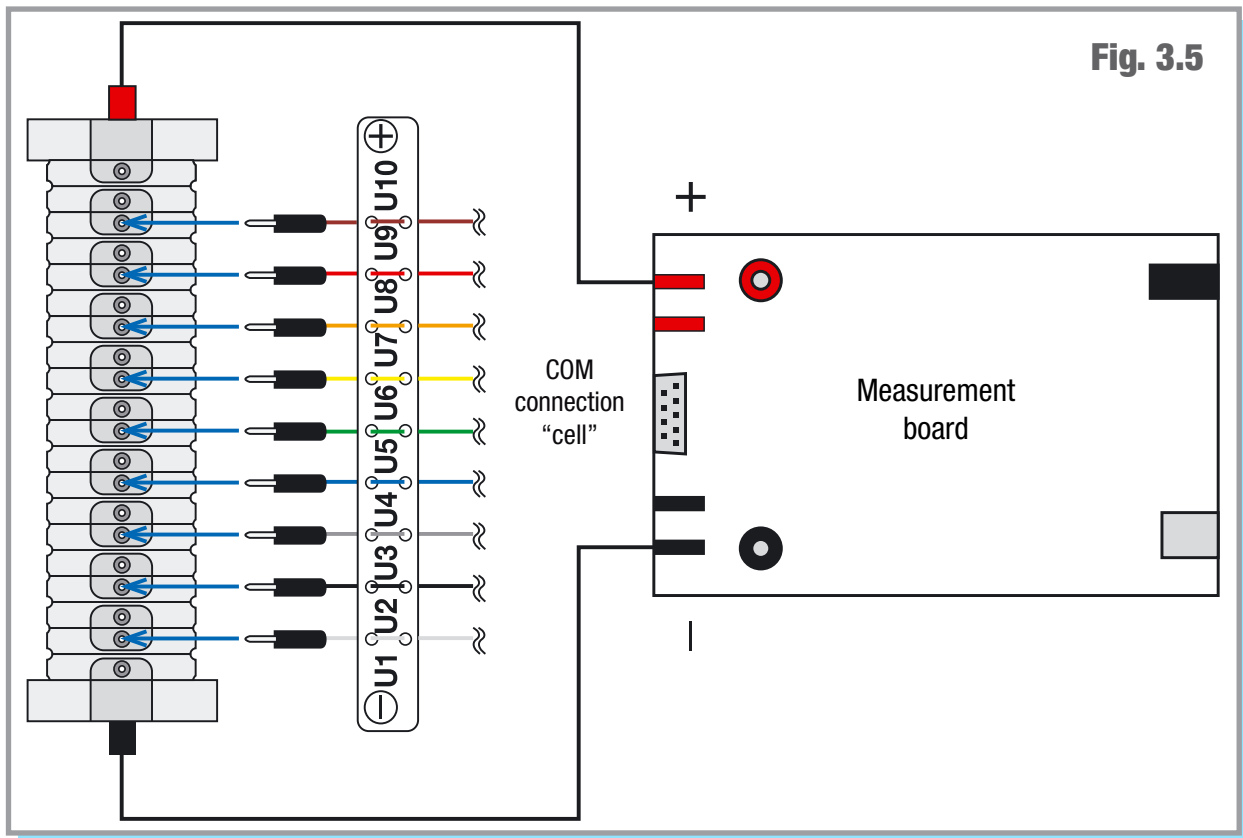


Fig. 3.5

**Note:**

If you connect a stack with less than ten cells, start at “U1” and connect the required number of measurement cables to the cells. Leave those not required disconnected (for example, in the case of a 5-cell stack, you would need the first four measurement cables between “U1” and “U5”).

Now click on the Start button. The characteristic curve of the fuel cell stack is first determined automatically. A dialogue window is displayed after this has been completed. Click on “OK” if the characteristic curve meets your expectations. If not, select “Cancel”. You can then restart the automatic characteristic curve recording.

**Note:**

The menu is disabled as the FCM is performing the measurement.

Now select a working point on the characteristic curve in the voltage/current graph at which you would like to measure the stack (default MPP - yellow cursor). Click on the cursor with the left mouse button and keep it pressed to move the cursor. Click on Start again. The individual voltage of the stack cells is now displayed and the total power of the fuel cell stack in the power/time graph (see Figure 3.6).

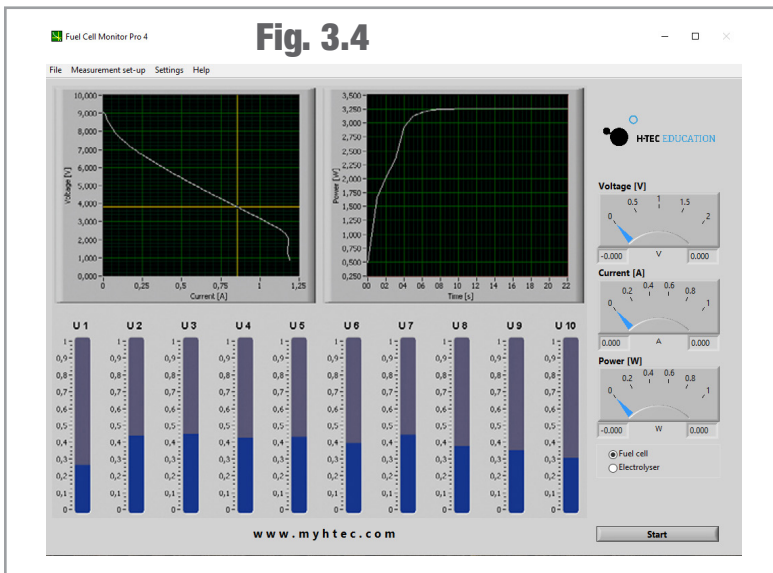
**Note:**

The working point can also be changed during the running measurement by moving the cursor by clicking on the working point with the left mouse button and keeping it pressed.

**Note:**

If the measurement bar changes color from blue to red during the measurement, this cell has no power. Among other things, this can be due to insufficient supply of hydrogen or that a water droplet is in the cell which prevents the supply of hydrogen. **Remedy:** check hydrogen supply; blow carefully through the stack; let the stack warm up for some time.





**Note:**

If the individual voltages seem implausible to you, check whether the connector between “U1” and “U2” is on the negative side of the stack.

**Note:**

During a longer measurement, it can happen that the power increases if the cursor is moved from the MPP. This initially seems illogical and wrong, however can be explained as follows: As this is a case of a current-regulated measurement in the background, the FCM takes over the current value of the characteristic curve and multiplies this by the current voltage value. However, as the parameters (temperature, humidity etc.) of the fuel cell change over longer operation, its power also changes, i.e. current and voltage and thus also the characteristic curve. The voltage value of the characteristic curve therefore no longer matches the current voltage value.

**Remedy:** Restart the measurement and let the fuel cell operate for a few minutes until it has reached its operating temperature before you start measurements. The power output is then more constant.

### 3.3.7 Efficiency of a Fuel Cell

**Note:**

The measurement of the efficiency is based on a simplified formula for the benefit of good usability. It refers exclusively to hydrogen powered fuel cells from the company H-TEC EDUCATION.

The measured values are recorded at system-controlled intervals for the recording of the efficiency. A resistance is automatically changed from large to small values for this. The typical characteristic curve course for fuel cells is thus produced. Thereby, the red characteristic curve with the heat value and the white characteristic curve with the fuel value are measured.

**Procedure:**

- Connect a fuel cell to the connection sockets of the measuring transformer card (see Figure 4.3). Pay attention here to the correct polarity (red= “+” and black= “-”).
- The value of the no-load voltage is now displayed in black by the top dial instrument and as a numeric value on the right under the dial instruments. The FCM is now in standby mode.
- Select the “Measurement Set-Up” menu item. Then select “Fuel Cell” > “Efficiency” and input the number of cells of the connected fuel cell.
- Click on the Start button.
- The FCM now automatically records the characteristic curve of the fuel cell from the no-load voltage to the short-circuit current, graphically displays the efficiency and is again in standby mode afterwards. The measurement can be canceled at any time using the “Cancel” button.

**Note:**

After the measurement is completed, you can move the cursor in the voltage/current graph by clicking on the working point with the left mouse button and keeping the button pressed. The values are taken over by the dial instruments and can be read there.

**Black pointer:** maximum value

**Blue pointer:** value at the cursor position

**Yellow pointer:** value at the cursor position in the Maximum Power Point (MPP).

### 3.3.8 Recording an Electrolyzer Characteristic Curve

**CAUTION!**

Absolutely ensure that an electrolyzer or reversible fuel cell (RFC) has been connected. A fuel cell would be destroyed during the measurement as a voltage is applied to the cell.

**CAUTION!**

The electrolysis mode of the FCM is only designed for single and double cells of the JUNIOR and TUTORIAL product groups and for the H-TEC EDUCATION Electrolyzer 65. Other electrolyzers or RFCs with higher power cannot be measured.

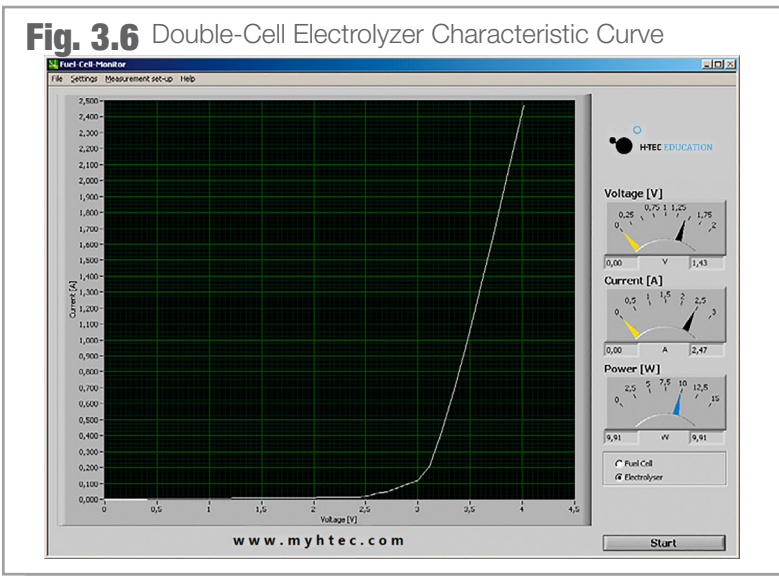
**CAUTION!**

Only use the power supply included in this package. If a different power supply is used, the measurement result can be falsified or the measurement board can be damaged.

**Procedure:**

- Select “Measurement Set-Up” > “Electrolyzer” > “Automatic” from the menu. If you have previously performed an automatic fuel cell measurement, you can also select the mode on the screen using the Start button.
- Connect a single or double cell to the measurement board using the measurement cables (see Figure 3.3).
- Connect the power supply to the measurement board.
- Click on the Start button. A dialogue window is displayed. Check whether you have connected a single-cell or double-cell electrolyzer as a single-cell electrolyzer would be destroyed if a double-cell measurement were accidentally started instead. The H-TEC EDUCATION Electrolyzer 65 is a double cell. Now input the number of cells.

The FCM records the characteristic curve by increasing the voltage at the cell of 0-2 Volts for single cells or 0-4 Volts for double cells (see Figure 3.5).



**Important information:**

As each electrolyzer is in principle also a fuel cell although with extremely low power, it can happen that a no-load voltage is set after the electrolyzer has already been measured. Due to this, another measurement at this electrolyzer would not start at 0-0.1 Volts but under certain circumstances at significantly higher values whereby the measurement result would be falsified and no correct characteristic curve course would be produced.

**Remedy:**

Flood the electrolyzer with water again and then click on “Fuel Cell” in the control section and start an automatic “measurement”. Check the no-load voltage after the automatic characteristic curve recording; this should be less than 0.1 V. If this is not the case, repeat the process. Afterwards, you can return to the electrolyzer measurement using the control section.

**Note:**

The axes assignment for the electrolyzer measurement can be defined under the “System Settings” menu item. You can select a current over voltage or a voltage over current display.

### 3.3.9 Recording the Efficiency Characteristic Curve of an Electrolyzer

#### **CAUTION!**

Absolutely ensure that an electrolyzer or reversible fuel cell (RFC) has been connected. A fuel cell would be destroyed during the measurement as a voltage is applied to the cell.

#### **CAUTION!**

The electrolysis mode of the FCM is only designed for single and double cells of the JUNIOR and TUTORIAL product groups and for the H-TEC EDUCATION Electrolyzer 65. Other electrolyzers or RFCs with higher power cannot be measured.

#### **CAUTION!**

Only use the power supply included in this package. If a different power supply is used, the measurement result can be falsified or the measurement board can be damaged.

#### **Note:**

The measurement of the efficiency is based on a simplified formula for the benefit of good usability. It refers exclusively to electrolyzers from the company H-TEC EDUCATION.

#### **Procedure:**

- Select “Measurement Set-Up” > “Electrolyzer” > “Efficiency” from the menu. If you have previously performed an automatic fuel cell measurement, you can also select the mode on the screen using the Start button.
- Connect a single or double cell to the measurement board using the measurement cables (see Figure 3.3).
- Connect the power supply to the measurement board.
- Click on the Start button. A dialogue window is displayed. Check whether you have connected a single-cell or double-cell electrolyzer as a single-cell electrolyzer would be destroyed if a double-cell measurement were accidentally started instead. The H-TEC EDUCATION Electrolyzer 65 is a double cell. Now input the number of cells. The FCM records the characteristic curve by increasing the voltage at the cell of 0-2 Volts for single cells or 0-4 Volts for double cells. Therefore, three efficiency characteristic curves are also displayed. The output efficiency refers to the fuel value of hydrogen.

#### **Important information:**

As each electrolyzer is in principle also a fuel cell although with extremely low power, it can happen that a no-load voltage is set after the electrolyzer has already been measured. Due to this, another measurement at this electrolyzer would not start at 0-0.1 Volts but under certain circumstances at significantly higher values whereby the measurement result would be falsified and no correct characteristic curve course would be produced.

#### **Remedy:**

Flood the electrolyzer with water again and then click on “Fuel Cell” in the control section and start an automatic “measurement”. Check the no-load voltage after the automatic characteristic curve recording; this should be less than 0.1 V. If this is not the case, repeat the process. Afterwards, you can return to the electrolyzer measurement using the control section.

### 3.3.10 Saving of Measured Data

The FCM provides the option to save recorded measured data (except stack individual voltages). The path and the file type in which the data should be stored must be specified in the menu under System Settings before saving measured data. Measurements can be saved either as standard text as .txt files or as comma separated values in .csv files (.csv is a common text file format for saving data or lists which can easily be imported by spreadsheet programs, such as, MS Excel or Open Office).

Now you can save the last recorded measurement using “File” > “Save measured data”.

A file is created in the specified directory which contains the values for time, voltage, current and power as well as the time and the type of the measurement.

The file name is formed from the date and time as follows: YearMonthDay\_Hour-Minute-Seconds.txt (the same applies for the CSV file format). Thus a recorded measurement in the year 2020 on August 25 at 13:46 and 29 seconds would have the file name “200825\_13-46-29.txt”.

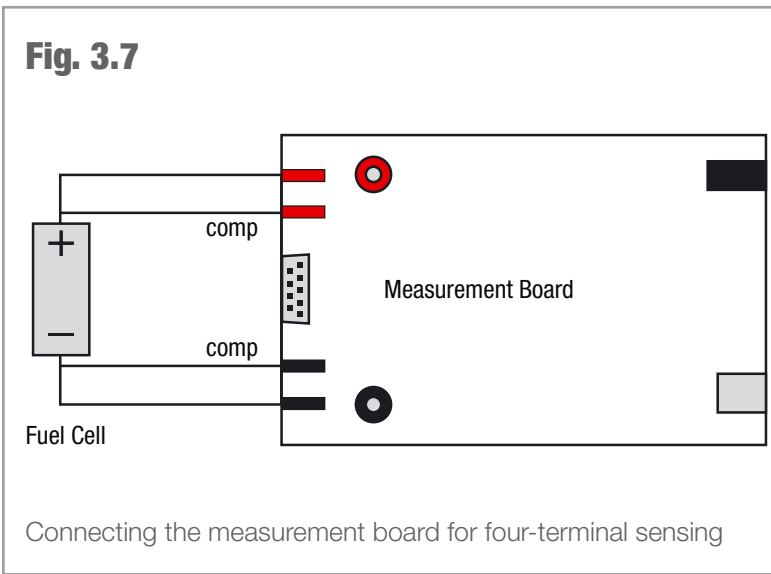
This type of naming convention guarantees a precise and unmistakable assignment of different measurements.

### 3.3.11 Report

The saving or the printout of the graphical display of the characteristic curves can be found under “File” > “Report”. You have the options “Print report” and “Open as HTML file”. If you select “Print”, the current screen of the FCM is printed out in gray scale. If you open the report with your web browser, the current screen of the FCM is generated as an HTML file which you can save or otherwise process with your web browser according to your requirements.

### 3.3.12 Four-Terminal Sensing

The measurement board of the FCM provides the possibility to perform all fuel cell measurements as four-terminal sensing. For a four-terminal sensing, connect the fuel cell to the measurement board as follows:



**Note:**

First connect the fuel cell to be measured to the compensation cables. Then plug the “positive” and “negative” measurement cables into the compensation cables on the fuel cell. Pay attention here to the correct polarity (red= “+” and black= “-”).

The special feature of the four-terminal sensing is that the voltage measurement is performed with a lower (caused by the current) voltage drop and with a smaller influence of transition resistance. The current and the voltage here are tapped using different measurement lines. Ideally considered, it can be said (assuming an ideal voltmeter) that no current flows over the measurement lines to the voltmeter and thus no voltage drop also occurs. The interfering influence is thus compensated for and the measurement is more precise.

## 3.4 Technical Data - Fuel Cell Monitor Pro 4.0

### Measurement Board

H x W x D:..... 40 x 160 x 100 mm  
 Weight:..... approx. 360g  
 Connections:..... 2 and 4 mm

### Fuel Cell Mode

Permitted Voltage:..... 0 - 10 VDC  
 Permitted Current:..... 0 - 5 A  
 Power:..... 0 - 10 W

### Electrolyzer Mode:

Permitted Voltage:..... 0 - 4 V DC  
 Permitted Current:..... 0 - 3 A  
 Power:..... 0 - 10 W

### Power Supply

Output:..... 6 V / 4 A

### Cable Set

2 X..... 4 mm Red Cables  
 2 X..... 4 mm Black Cables  
 2 X..... 2 mm Red Cables  
 2 X..... 2 mm Black Cables  
 2 X..... 4 mm to 2 mm Adapter  
 1 X..... Wiring Harness for individual cell voltage measurement  
 1 X..... USB Cable

## 3.5 Troubleshooting

### General:

The screen display of the FCM does not show the desired homogeneous characteristic curve course.

Possible Cause:

- There is no fuel cell connected.
- The cell has been connected with the polarity reversed.
- The cell is only connected to the connection sockets for the four-wire measurement.

Solution:

- Check the connection of the cell to the measurement board.

### Fuel Cell Measurement:

First ensure whether there is a gas supply and whether the fuel cell is correctly connected to the measurement board.

The fuel cell does not achieve the stated power in the MPP.

Possible Cause:

- The membrane of the fuel cell is too dry or too moist.

Solution, if the fuel cell is too dry:

- Moisten the fuel cell with a drop of distilled water ( $\sigma < 2 \mu\text{S/cm}$ ).

Solution, if the fuel cell is too moist:

- Disconnect the cell from the gas supply. Blow once carefully through the connection hoses of the cell so that the water in the cell is pressed out. Reconnect the cell to the gas supply. Afterwards, let some gas flow through the cell so that there is no longer any air in the cell.

### Electrolyzer Measurement:

First ensure that no fuel cell is connected and whether the power supply and the electrolyzer are correctly connected to the measurement board.

The electrolyzer does not have the stated power.

Possible Cause:

- The electrolyzer does not have enough water

Solution:

- Flood the electrolyzer again and/or fill the water tank of the electrolyzer with distilled water ( $\sigma < 2 \mu\text{S/cm}$ ).

Possible Cause:

- You have clicked on single-cell for the start of the measurement, but you have connected a double cell.

Solution:

- Ascertain which type of cell you have connected and start the measurement again.

## 3.6 Maintenance

The components do not require maintenance.

## 3.7 Disposal

 **WARNING**

Fire hazard from catalytic substances  
The catalysts for the electrodes of fuel cells and electrolyzers promote burning when they come into contact with flammable substances.  
Avoid contact with hydrogen, alcohol fumes or other organic fumes. Ensure correct disposal.

According to European regulations, used electric and electronic devices may no longer be disposed of as unsorted household waste. The symbol of the crossed-out wheelee bin indicates the requirement for separate disposal.

Your local waste management company can provide you with additional information about disposal options.

**Notes:**

**Notes:**



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