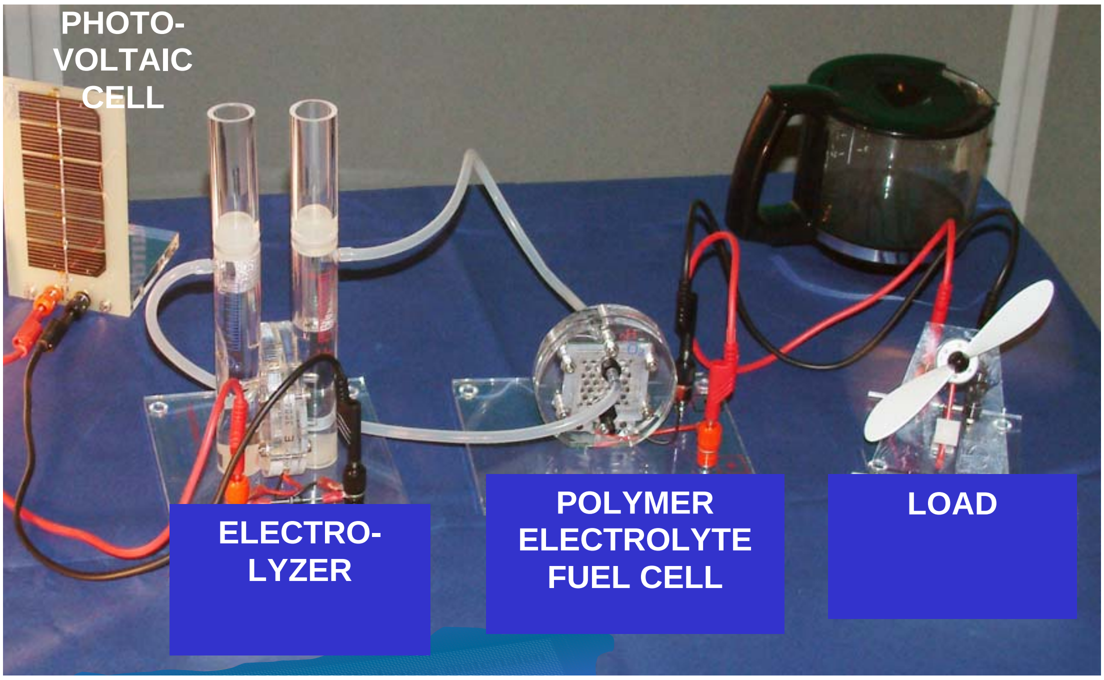
IX CHAPTER: APPENDIX ON SOLAR CELL, ELECTROLYSER AND FUEL CELL*

The Heliocentris demonstration set-up consists of a photovoltaic cell, an electrolyser and a fuel cell. The characteristics of these three components are investigated experimentally in this Appendix written by Kier Heeck*.



IX.1 MEASUREMENTS ON A SOLAR CELL

IX.1.1 THE SOLAR CELL MODULE

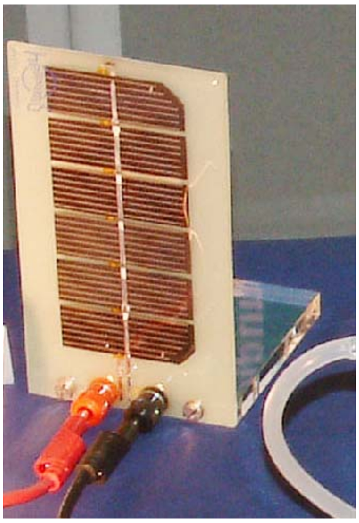


Fig.A. IX.1: The Heliocentris 371 Solar module

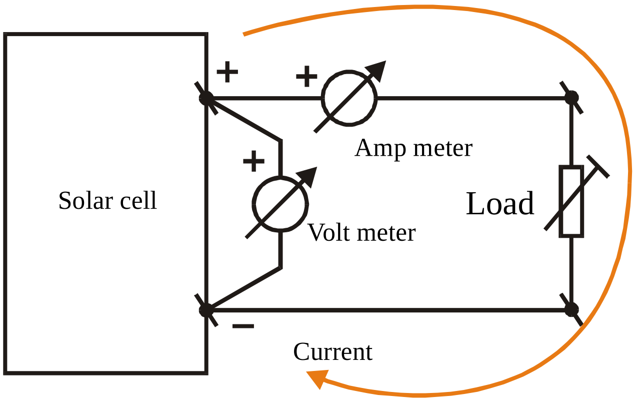


Fig.A. IX.2: The Heliocentris solar cell is a series circuit of two identical poly-silicon cells.

The components used in the experiment are:

● Solar cell	Heliocentris 371 Solar module
● Incandescent lamp	120 Watt 230 V minimum distance to the solar cell 20 cm
● Ruler	For measuring the lamp solar cell distance
● 2 Multimeters	A voltmeter for 0 .. 2 V range, the other for current 0 .. 1 A
● Measuring leads	5
● Power resistor chain	0.1 ; 0.2 ; 0.53 ; 1 ; 2 ; 5.3 ; 10 ; 20 ; 53 ; 100 Ω or
● resistor decade box	0 .. 1 kΩ in 0.1Ω steps
● Protractor	Measuring the tilt angles
● Spreadsheet	To do the calculations and making graphs
● Room	Not being sun-baked, should be rather dark

Electric connections as used in the measurements.

IX.1.2 PHOTO CURRENT V.S. ANGLE OF INCIDENCE OF THE LIGHT

Place the incandescent lamp at a distance of about 30 cm of the solar cell. Put the solar cell in the up-right position and measure the short circuit current it generates. This value will be used for normalising the other current measurements. Increase the tilt angle in steps of 15 degrees and measure the current at every setting. The graph in Fig.A. IX.3 does not look too much as the expected cosine function. The reasons are at hand: the small distance to the lamp and its uneven light-cone are the mean culprits. Due to tilting the bottom and top part of the solar cell have appreciable different distances to the lamp. This makes both ends to receive different light fluxes. If one repeats the experiment in sun light with its perfect plane waves, then the cosine shows up.

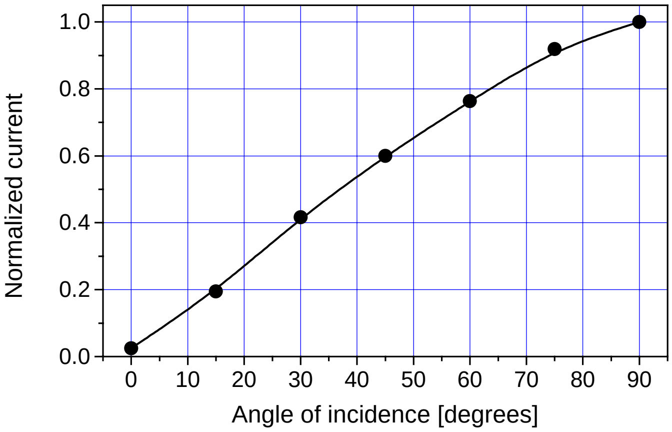


Fig.A. IX.3: Normalized short-circuit current of the solar module vs. angle of incidence

IX.1.3 PHOTO CURRENT VS DISTANCE OF THE LIGHT SOURCE

In the previous section the maximum current occurred when the light hits the solar cell's surface perpendicularly. In all measurements to come we use that position. We measure the short-circuit current while the lamp's distance is varied from 30 to 50 cm in 5 cm steps. Fig.A. IX.4 shows that the current is clearly not inversely proportional to de distance squared. The centre of the light-cone is much more intense than the sides. Therefore, with increasing distance a larger part of the solar cell gets into the intense central part. This causes the current at larger distances to be much higher than expected.

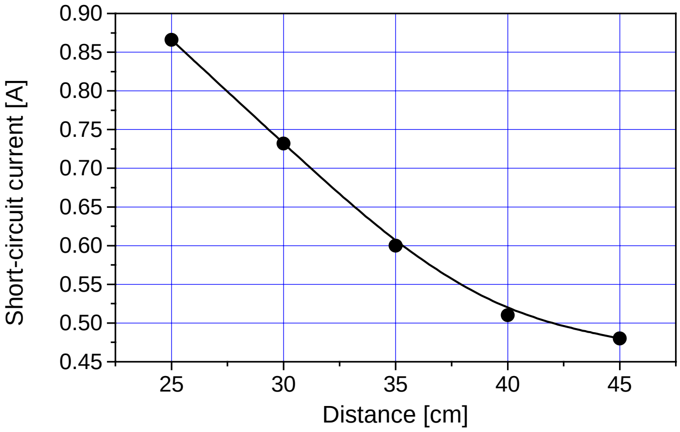


Fig.A. IX.4:Short-circuit current of the solar module vs. distance between lamp and module

IX.1.4 VOLTAGE CURRENT CHARACTERISTICS

The voltmeter is connected directly to the solar cell. The load resistance is connected in parallel and should be in the range of 0 .. 100 Ω (2 Watt). The resistance values used to make the graph below were 0.1; 0.2 ; 0.53 ; 1 ; 1.5 ; 2 ; 2.5 ; 2 ; 5.3 ; 10 ; 20 ; 53 ; 100 Ω.

The load resistance determines the voltage to current ratio. In the voltage vs. current graph this ratio is expressed by a line though the origin. The actual voltage will be the given by the intersection of this load line and the voltage vs. current characteristic of the solar cell for a given illumination.

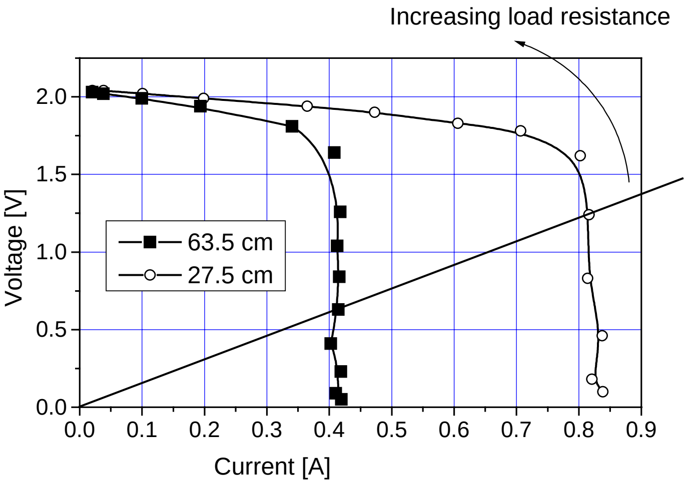


Fig.A. IX.5:Voltage versus current curve for two distances between the lamp and the solar module.

For the first measurement the lamp is placed at 27.5 cm distance (glass of the lamp to solar cell) and 63.5 cm during the next measurements. A spreadsheet programme saves our data by doing the calculations $I = U / R$ and $P = U^2 / R$ .The resistance of the measuring leads should be taken into account. In our measurements the total resistance of the wiring was about 20 mΩ. Correction for the unknown series resistance of the test leads is obligatory. From the graph one can read that the current stays essentially constant as long as the voltage is lower than say 1.5 V. So measure the short-circuit current. Next step is a voltage measurement across the solar cells terminals with the external resistor set at "0", while all leads stay in use. The unknown lead resistance is given by this voltage divided by the short-circuit current. This resistance has to be added to all settings of the external resistor. The influence of this correction is of course most pronounced at low voltages and high currents.

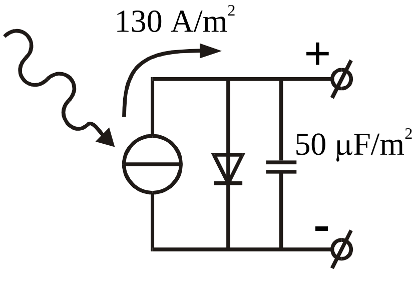


Fig.A. IX.6: The electrical equivalent diagram of a solar cell is a semi-conductor junction, which also has an electrical capacitance. The over-sized diode also shows up in the equivalent circuit. It is this diode that generates the photo-current, but regrettably also limits the maximum output voltage! The value of the photocurrent is given for a sunny day. The cell's capacitance amounts to ~50 µFm^{-2}. The output impedance of a solar cell is governed by this capacitance.

IX.1.5 POWER V.S. LOAD RESISTANCE

The foremost aspect of the solar cell still needs attention, namely the power that can be developed in a load resistance. Due to the nearly rectangular voltage vs. current characteristic of the solar cell one can directly see that the maximum delivered power occurs at the top right-hand corner of the characteristic Fig.A. IX.5. Below, in Fig.A. IX.7 we plot the power as a function current for two different illuminations. The optimal current loading should be linearly related to the usually unknown illumination.

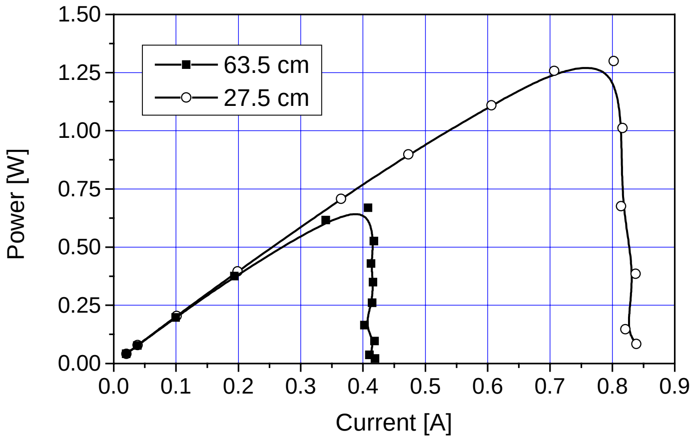


Fig.A. IX.7: Power vs. current curve of the solar module for two distances between the module and the lamp.

But there is a much better view at the same problem possible: plot power vs. voltage.
It's clear: the load resistance ought to be varied in such a way that the voltage across the solar cell stays always the same, irrespective of the illumination. This is a simple and productive way to solve the loading problem.

But, in semiconductors voltages are temperature dependent. This means that daily temperature variations still cause departures from the optimal loading.
Electronic maximum power point tracking uses a scheme of alternating the loading between two nearby values. An electronic circuit can deduce which of the two loads is nearest to the maximum and change the average load accordingly. This seems an elaborate way of working but isn't. In nearly all applications of solar cell a form of voltage conversion is necessary. A rather

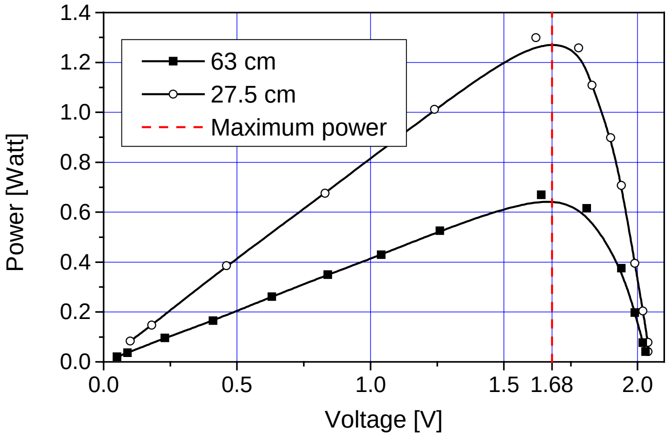


Fig.A. IX.8: Power vs. voltage curve of the solar module for two separation between lamp and module.

slight extension of the converter's circuitry makes a maximum power point tracker. By the way, they come under several different names: Pulse Width Solar Power Regulator or Maximum Power Point Controller or Maximum Power Point Tracker

IX.1.6 DC TO AC CONVERSION

In order the be able to integrate a solar cell in an existing power grid a conversion from Direct Current to Alternating Current has to be made. This can most easily be done by using the following two steps.

- The first step converts the variable DC current generated at rather low voltage by the solar cell to a high intermediate voltage. This stage is an interface between the different sizes of solar cell arrays and output DC to AC converter. The conversion is done by high frequency chopping of the incoming DC current in two anti-phase square-wave currents. Those square-wave currents are fed to a transformer for changing over the voltage. The volume of the transformers, like the one used in this stage, scales with one over the working frequency. The magnetic energy contained in the magnetic yoke of the transformer equals to $B^2/2\mu$ times the volume V of the yoke. Per period of the conversion the fixed amount of energy $VB^2/2\mu$ is transferred. This is why the transformer's volume scales with one over the frequency. The maximum useful induction in ferrites is about 0.3 T, about 1.6 T is the upper limit in iron. Although ferrites have a lower B_{sat} , their maximum working frequency is much higher, making them first choice in energy conversion.

- The second step is the DC to AC converter (in Dutch "wisselrichter") that does the actual conversion to the AC voltage of the grid and the current that is determined by the instantaneous amount of light that impinges on the solar cell array. Up to several tens of kW's this stage contains only MOSFET switches. The method is called Pulse Width Modulation. A simple L-C low-pass filter removes all the high harmonics from the pulse signal. After this averaging only a smoothly varying voltage remains, the sinusoidal output.

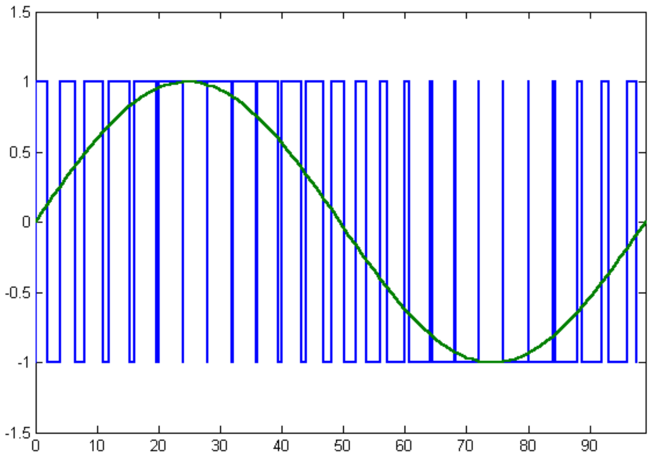


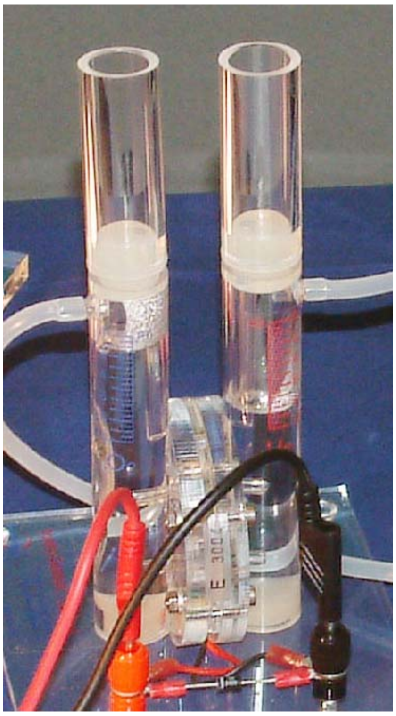
Fig.A. IX.9: Pulse Width Modulation method used for DC to AC conversion

IX.1.7 EFFICIENCY

Our demonstration solar cell generates in July in full sunlight 1.3 A. The maximum delivered power in that situation is 2 W. Given the area of 196 cm^2, this type of solar cell made of polycrystalline silicon, delivers about 100 Wm^{-2}. As the solar flux by clear sky is roughly 1 kWm^{-1}. we conclude that the efficiency is 10%, a normal value for terrestrial solar cell types.
Only in space applications, where sheer weight costs enormously to launch, the hetero-junction (junction of two different semiconductors) GaAs-AlGaAs solar cells with 28% efficiency are used.
The efficiency of electronic energy converters can be amazingly high: from 85 % for the small, 100 W size, up to at least 92% for the 10 kW size converters. This high efficiency makes them ideal for automatic power point tracking and for coupling solar cells to nearly any kind of power transmission system or load.

IX.2 MEASUREMENTS ON A ELECTROLYSER

IX.2.1 THE ELECTROLYSER SET-UP



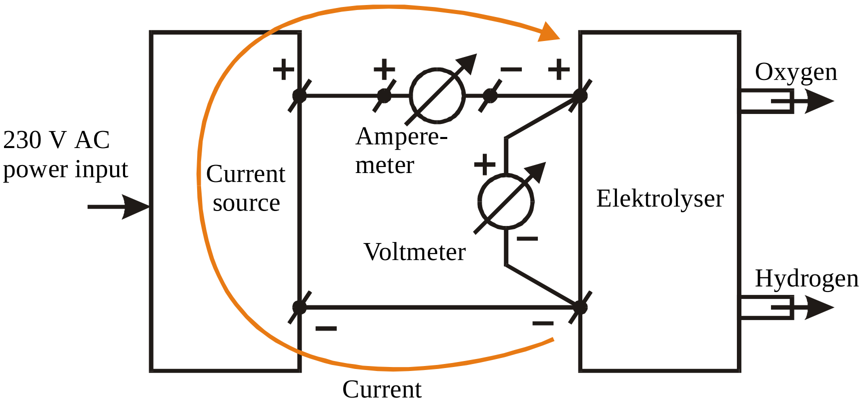


Fig.A. IX.10: The Heliocentris Electrolyzer makes use of Nafion® as a Proton Exchange Membrane.

Fig.A. IX.11: The electrical diagram of the measurements.

The components used in the experiment are:

Electrolyser	Heliocentris 372 electrolyser
Variable **current** source	0 .. 1 A, at least 2 V open voltage
2 Multimeters	One for the 0 .. 2 V range and other 0 .. 1 A
Stopwatch	Time measurement
Measuring leads	5 pieces
Speadsheet	To do the calculations and making graphs.

Electric connections as used in the measurements.

IX.2.2 GAS PRODUCTION VS. SUPPLIED CURRENT

The essential chemical reaction is $2\ H_2O + 2e^- \rightarrow 2\ H_2 + O_2$. This reaction takes only place if enough energy (1.229 eV per molecule) is supplied. Let us first address the question about the amounts of matter involved in our demonstration. The mol mass of H equals 1 gram and one mol of O 16 gram. So one mol of H_2O equals 18 grams. Because of its density of 1000 $\mathrm{kgm^{-3}}$ this corresponds to 18 $\mathrm{cm^3}$. The volume of one mol of gas can be determined via the law of Boyle Gay-Lussac $pV = RT$ with $R=8.3144\ \mathrm{Jmol^{-1}K^{-1}}$, the universal gas constant. At room temperature T = 293 K and at the average pressure at see level p =101 kPa one mol gas has a volume of $8.3144\times293 / 101\times10^3\ \mathrm{m^3\,mol^{-1}} = 2.412\ 10^{-2}\ \mathrm{m^3\,mol^{-1}} = 24.12\ \mathrm{litre\ mol^{-1}} = 24120\ \mathrm{cm^3\,mol^{-1}}$. The collecting cylinders have a useful volume of 60 $\mathrm{cm^3}$. The amount of mole of hydrogen (H_2) gas that is produced by the water decomposition is equal to the mole mass of the water. The 60 $\mathrm{cm^3}$ equals to 60/24120 = 2.48 millimol of H_2 gas. The corresponding mass of water is $2.48\ 10^{-3} \times 18 = 44.78$ milligram. Please remind that 1 $\mathrm{cm^3}$ of water counts only 13 droplets of 77 milligram each. Another important aspect is the amount of time that is needed to produce this volume of hydrogen. We use the second law of Faraday (1834). This law says that the amount of charge needed for displacing one mole of substance is 96485 $\mathrm{Cmol^{-1}}$. By the way, this equals the charge of an electron $e = 1.60219\ 10^{-19}$ C times Avogadro's number (number of molecules per mol) $N_A = 6.022045\ 10^{23}\ \mathrm{mol^{-1}}$. For 2.48×10^{-3} mole to be transported 240 C is needed. At 1 A just 4 minutes will do to collect this amount of H_2. The duration of the experiment is reasonable.

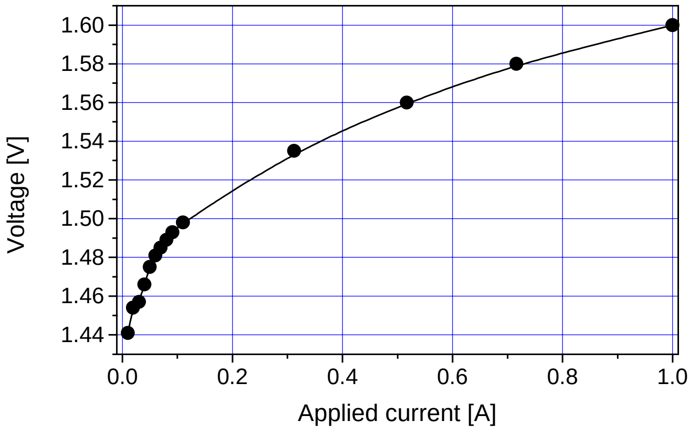


Fig.A. IX.12: Voltage vs. applied current for the PEM electrolyser.

The graph in Fig.A. IX.13 shows that the gas production increases linearly with the supplied current. The ratio H_2/O_2 behaves as expected i.e. it stays constant at 2.

The second law of Faraday says that 1 A transports 1/96485 = 1.056×10^{-5} $molsec^{-1}$ H. This is of course equal to 5.28 10^{-6} $molsec^{-1}$ H_2 or 127 mm^3 H_2 per sec, a few tiny bubbles.

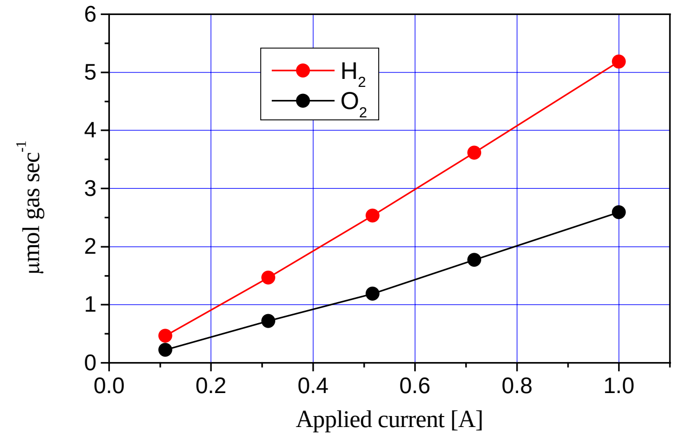


Fig.A. IX.13: Hydrogen (red) and oxygen (black) production as a function of the applied current to the electrolyser.

IX.2.3 EFFICIENCY

The amount of energy needed to dissociate one molecule of water equals 1.229 eV=1.969×10^{-19}J. The equivalent of 118.6 $kJmol^{-1}$ is found by using Avogadro's number N_A= 6.022045 10^{23} mol^{-1}. The overall efficiency is easy to determine. From measurement we know that 5.18 10^{-6} mol H_2 per second is formed at 1 A. The number of moles H_2 equals that of H_2O. The heat of formation of water is 285 $kJmol^{-1}$. The produced H_2 gas can generate 5.18 $10^{-6}\times285\times10^3$ = 1.48 W. The amount of electric energy that we supply to the electrolyser is 1.0 *1.60 = 1.6 W. The ratio output / input is thus 0.92. If we fit a straight line to the curve in the interval 0.11 .. 1 A, the internal resistance equals only (1.6-1.5) / (1.0-0.11) = 112 mΩ. Without this internal resistance of 112 mΩ the efficiency would be 1.48/(1.6 - 1.0^2*0.112) = 0.995! The already low internal resistance is the limiting factor of the efficiency! One could think that lowering the current would increase the efficiency. But at low supplied currents the electron leakage through the membrane becomes more important.

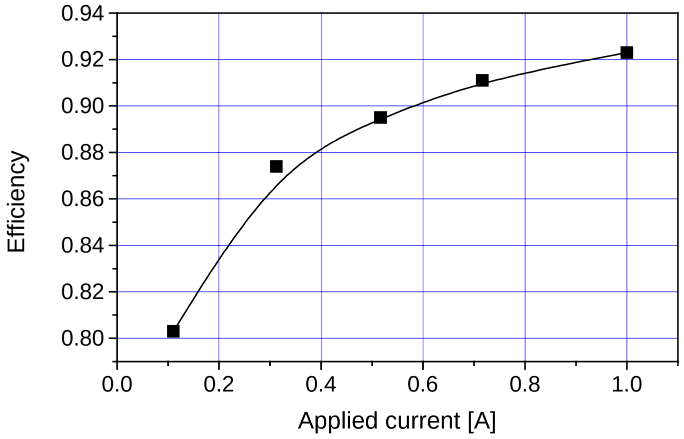


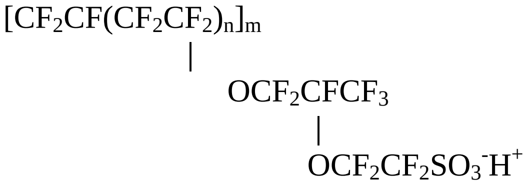
Fig.A. IX.14: Efficiency of the electrolyser as a function of applied current

From Fig.A. IX.14, where the efficiency vs. current is plotted, one can see that at 1 A the efficiency still increases. This means that the losses in the internal resistance $\boldsymbol{I^2R}$ are still not dominating the overall losses. Higher current can thus be considered. The manual of the electrolyser gives 4 A as an allowable maximum.

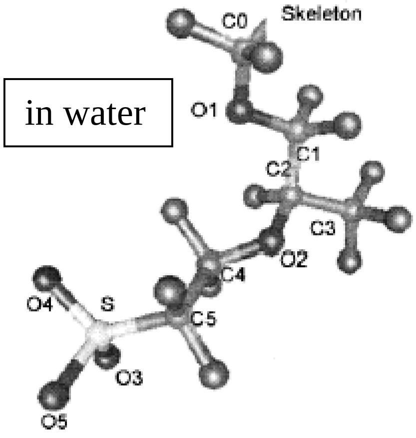
IX.2.4 ABOUT THE ELECTROLYSER ITSELF

After Giovanni Volta discovered the modern battery in 1799 (in Mesopotamia there was already 2000 BC a kind of battery known!), a huge wave of research on electro-chemical processes started. In 1800 William Nicholson and Antony Carlisle discovered the hydrolysis ("ontleding") of water by means of an electrical current.

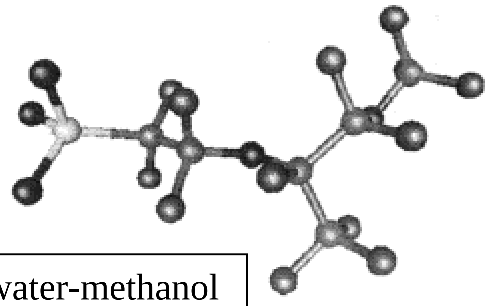
The demonstration electrolyser consists of three parts: two electrodes and the Proton Exchange Membrane. The requirements that must be fulfilled by the PEM are strange and rather conflicting. The H^+ ion must be free to move through the substance, while being a good insulator for electrons. It is quit remarkable that one of the best insulators known, teflon, by adding sulfon groups proves to be an excellent proton conductor while remaining insulating for electrons!
A closer look at what happens in the cell shows more details. The supplied water (H_2O) needs to be split apart. This happens at the positive terminal under application of an electric current. At this terminal oxygen bubbles are formed. The electric potential should be at least 1.23V. The transition from liquid to electrode cost in most electrolysers an appreciable amount of energy: the surface polarisation. The application of a catalyst (platinum) onto the surface virtually removes this nuisance. The negative terminal on the other side of the membrane attracts the positive hydrogen ions. At the negative electrode the electrons from the external current source join the protons, forming H. These H atoms pair to H_2 molecules that escape as bubbles from the liquid. The structure of the Dupont material Nafion® looks like:



$$\begin{array}{l} [CF_2CF(CF_2CF_2)_n]_m \\ \qquad\qquad\quad | \\ \qquad\qquad\qquad OCF_2CFCF_3 \\ \qquad\qquad\qquad\qquad\quad | \\ \qquad\qquad\qquad\qquad OCF_2CF_2SO_3^-H^+ \end{array}$$



in water



in water-methanol solution

It has the following properties:

- Swells 10% in water
- Swells 50 % in methanol
- Swells 60% in glycerine
- Swells 60% in glycerine
- Polymer structure with polar clusters at both ends
- Must be hydrated to conduct
- It is basically sulfonised teflon
- n~ 6.56 in case of Nafion 115 , the molecular weight is larger than 1100

When it swells, the electric resistance decreases. The swelling makes it also easy in assemblies to increase the pressure on the contacts. In that way the internal resistance also drops. At the outside of the PEM something special has to happen, as already mentioned before. At the positive terminal protons have to enter the polymer, while the electron current goes in the opposite direction. To make this happen the membrane is covered on both sides with a very thin carbon layer that contains minuscule (~ 2 nm) platinum particles. These form the catalyst that spurs the breakdown of water molecules. It is a pity, but exactly these Pt particles are an economic hindrance. Per side of the membrane about 0.5 mg/cm^2 Pt is needed, giving 1 mg/cm^2 of foil. These foils can withstand about 0.5 A/cm^2. Combined with the 1.5 V across the membrane, the energy uptake is 0.75 Wcm^2. For larger cells, e.g. 100 kW electrolyser we need $10^5/0.75$ = 133333 cm^2 of PEM. This means 133333 cm^2 ×1 mg = 133 grams Pt. Given a market price of untreated platinum of $985 /ounce = € 30.2 / gram (Nov 4th 2003) about € 4000.- worth of crude platinum is needed.
Other catalysts able to replace Pt have so far not been discovered. The major problem is the resistance to oxidation at the oxygen side, combined with resistance to water.

IX.3 MEASUREMENTS ON A FUEL CELL

IX.3.1 THE FUEL CELL SET-UP

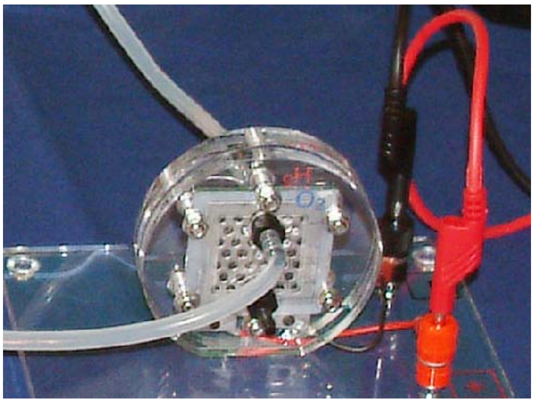


Fig.A. IX.15: Fuel cell with a Nafion Proton Exchange Membrane

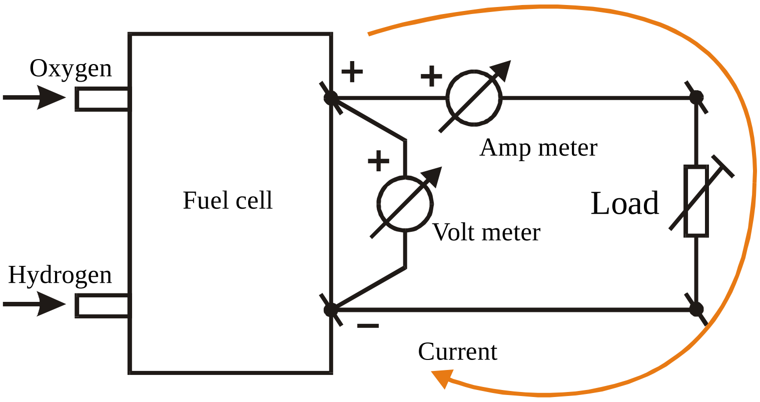


Fig.A. IX.16: Electrical circuit used for the measurements.

The components used in the experiment

Fuel cell	Heliocentris 374 fuel cell
2 Multimeters	One at 0 .. 2 V range and other 0 .. 1 A
Measuring leads	5 pieces
Spreadsheet	To do the calculations and making graphs.

Electric connections as used in the measurements.
The Heliocentris fuel cell makes use of Nafion® as a Proton Exchange Membrane and has two cells in series connected. It is essential to flush gasses at both sides in order to obtain the maximum efficiency. The cause of this poisoning might be nitrogen leakage from the air.

IX.3.2 VOLTAGE VS. CURRENT MEASUREMENT

This is done in the same fashion as for the solar cell measurement, with one precaution. A fuel cell is **not** a constant current source, so short circuit conditions should be prevented. From Fig.A. IX.17 one sees that the internal resistance in the range between 1 and 2.4 A loading is (1.05-0.72) / (2.4-1.05) = 0.24 Ω. The reason for the sharp drop in voltage at high currents might be the flooding of water across the membrane, preventing hydrogen and / or oxygen to reach the membrane.
Another strange phenomenon is the formation of water at both sides of the foil. One expects water to form at the oxygen side only.

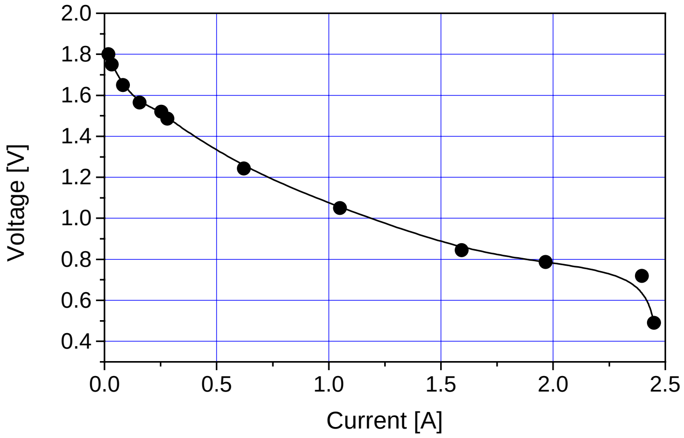


Fig.A. IX.17: Voltage vs. current curve for the fuel cell.

The output delivered is easily calculated and is depicted in Fig.A. IX.18. Once again the fuel cell behaves as a constant voltage source, for the output power increases nearly linearly with the load current.

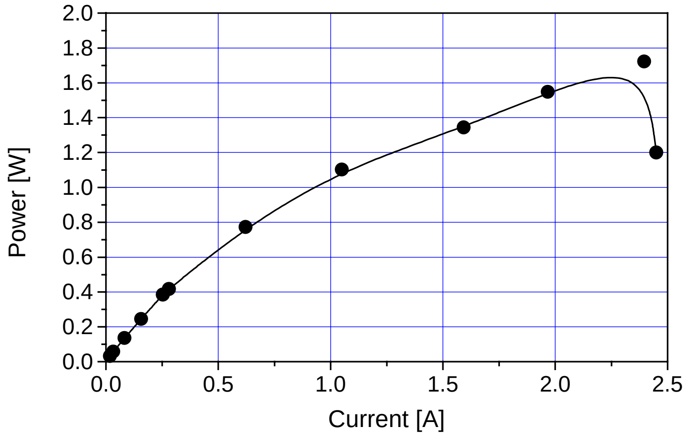


Fig.A. IX.18: Output power vs. current for the fuel cell.

IX.3.3 EFFICIENCY

The efficiency of the fuel cell is measured by using the electrolyser fuel cell combination. When we supply a constant electric current to the electrolyser, a constant flow of hydrogen is produced. We change the electric load of the fuel cell in such a way that the water level in the collecting cylinders stays constant. The results for various currents, corrected for the electrolyser's efficiency, are shown in Fig.A. IX.19.

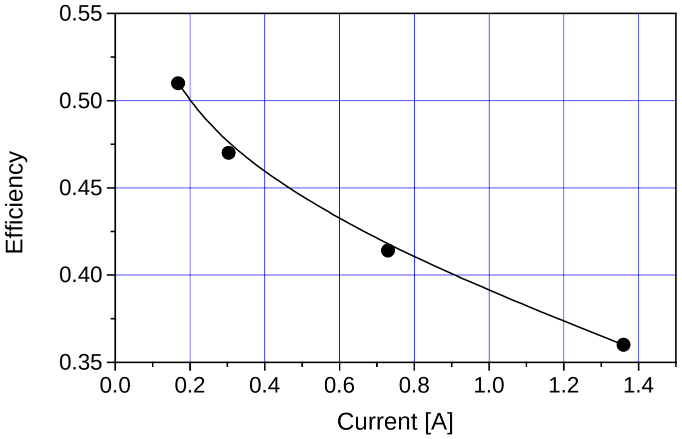


Fig.A. IX.19: Efficiency vs. load current of the fuel cell

The efficiency at the higher current doesn't drop off in the expected I^2R way. This also points to another efficiency limiting mechanism, like the flooding of the electrodes by liquid water. Commercial fuel cells do better than this little demo, on the average 60 % efficiency for gas to electricity is quite normal. In case of high power several other types of fuel cell exist, that work at elevated temperatures. This allows also for the practical use of the heat that otherwise would be lost. These total-energy systems do of course much better: ~ 80% of the energy carried by the gas can be used in these systems.