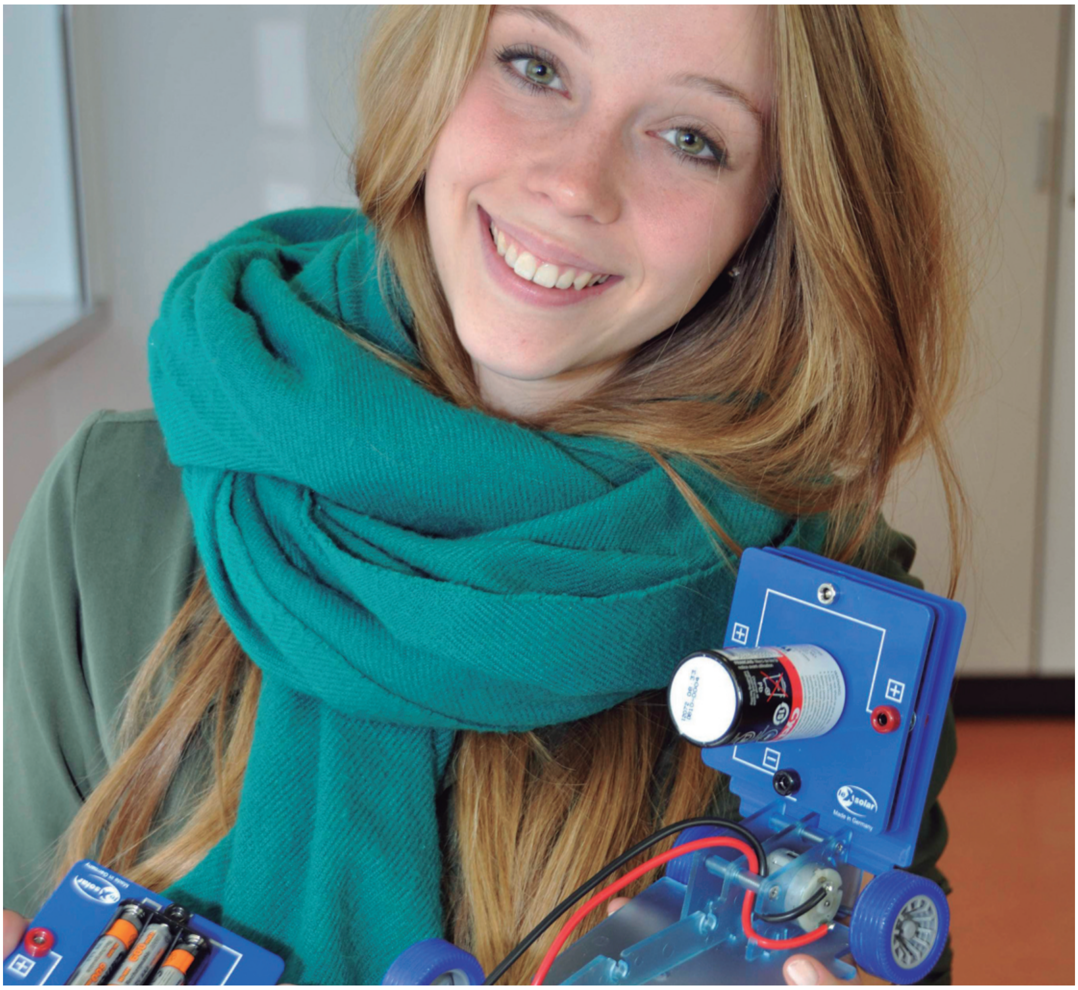
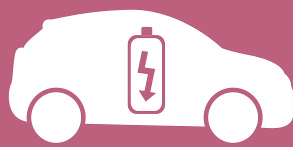
leXsolar-EMobility Ready-to-go





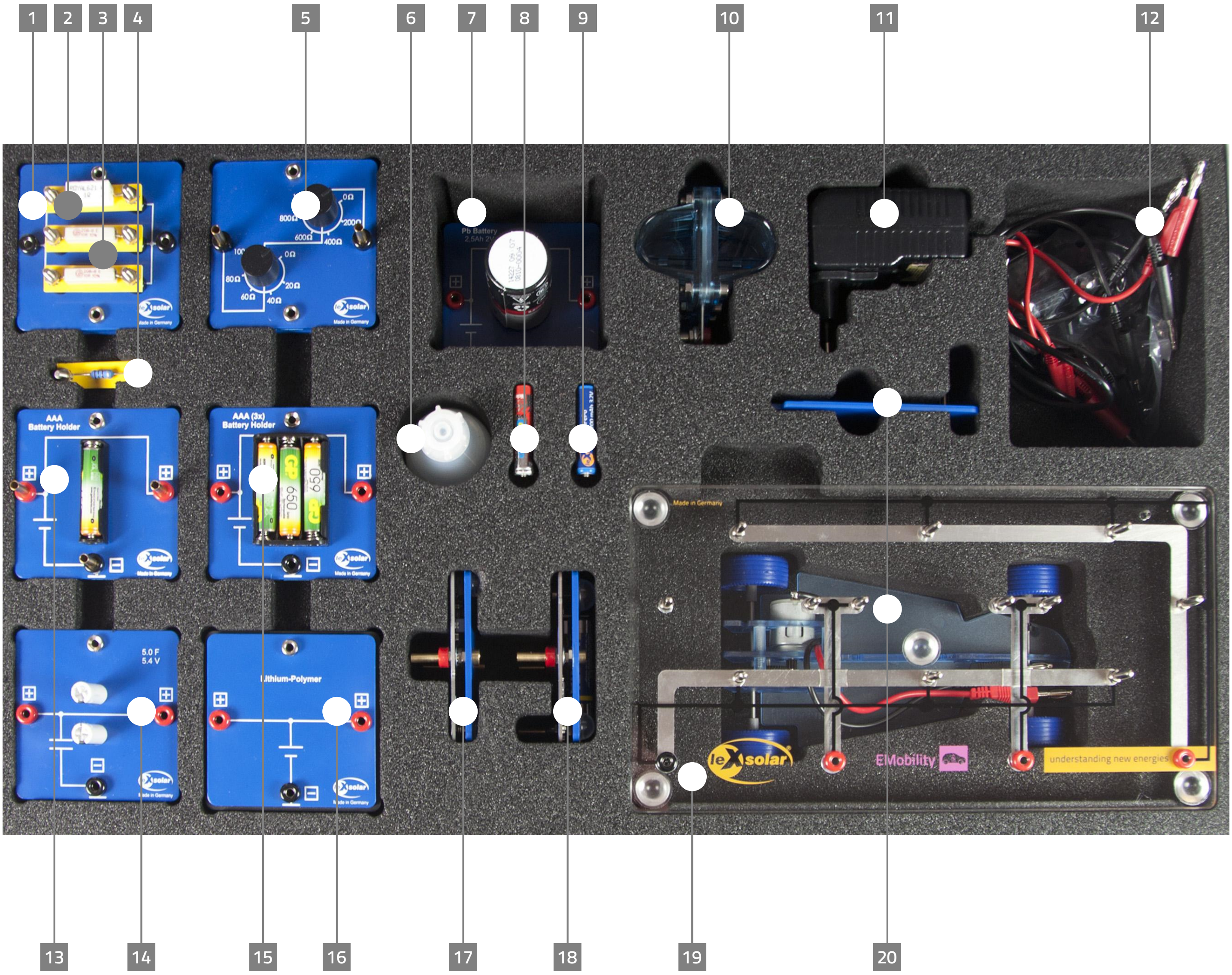
Teacher's Manual

Layout diagram leXsolar-EMobility Ready-to-go

Item-No.1803

Bestückungsplan leXsolar-EMobility Ready-to-go

Art.-Nr.1803



1	1800-01 Resistor module (triple) Pro 1800-01 Widerstandsmodul 3-fach Pro
2	1800-03 Resistor plug element 1 Ohm 1800-03 Widerstands-Steckelement 1 Ohm
3	2x1800-05 Resistor plug element 10 Ohm 2x1800-05 Widerstands-Steckelement 10 Ohm
4	1800-04 Resistor plug element 100 Ohm 1800-04 Widerstands-Steckelement 100 Ohm
5	1100-62 Potentiometer module 1100-62 Potentiometermodul
6	1800-15 Distilled water 1800-15 Destilliertes Wasser
7	1800-13 Lead (Pb)-battery module Pro 1800-13 Blei-Akkumodul Pro
8	L2-04-102 NiZn-battery AAA L2-04-102 NiZn-Akku AAA
9	1801-06 LiFePo-battery AAA 1801-06 LiFePo-Akku AAA
10	L2-06-067 Reversible Fuel cell Pro L2-06-067 Reversible Brennstoffzelle Pro
11	Universal-power supply with 17 Stromversorgungsgerät mit 17
12	2xL2-06-012/013 Test leads black/red 2xL2-06-012/013 Messleitung schw./rot
13	1800-08 Battery module holder 1xAAA Pro with L2-04-021 NiMH battery AAA 1800-08 Akkuhalterungsmodul 1xAAA Pro mit L2-04-021 NiMH-Akku AAA
14	1118-11 Capacitor modul Pro 1118-11 Kondensatormodul Pro
15	1118-09 NiMH Battery module 3xAAA Pro 1118-09 Akkumodul NiMH 3xAAA Pro
16	1800-07 Lithium-polymer-battery module 1800-07 Lithium-Polymer-Akkumodul Pro
17	9100-13 ChargerModule 9100-13 ChargerModul
18	9100-03 AV-Module 9100-03 AV-Modul
19	1801-07 leXsolar Base unit EMobility 1801-07 leXsolar Grundeinheit EMobility
20	1801-02 Electric model car 1801-02 Elektro-Modellfahrzeug

Version number
Versionsnummer

L3-03-167_02.02.2017

CE RoHS2

leXsolar-EMobility Ready-to-go

Teacher`s manual

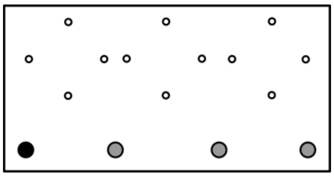
Content

I General Information

Components

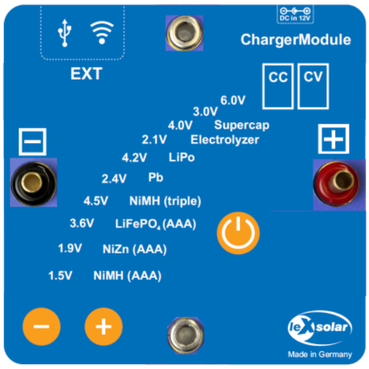
The following part contains information about the components of the experimental system. There is sketched a photograph and a small pictogram how the modules are displayed in the experimental setup. Furthermore you get information about the handling and the specifications of the components.

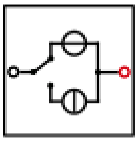
Base unit EMobility 1801-07



The base unit is a breadboard where up to 3 components can be plugged in a series and parallel connection. The current flows along the wires on the bottom side. To connect the components on the base unit with other components, there are 4 terminals at the lower end.

ChargerModule 9100-13





The ChargerModule is a universal battery charger for all batteries, the capacitor and the reversible fuel cell included in leXsolar-EMobility Ready-to-go. With the additional fixed-voltage outputs constant voltage of 3V or 6V can be applied. To operate the ChargerModule first the power adapter must be plugged in and connected to the input jack on the top right of the module. The charging program is selected by the "+" and “-“ button and is displayed by the LEDs. The Power button is used to switch on the ChargerModule. During the charging process, the Power Enable LED flashes once per second and all keys are locked. Pressing the Power Enable button for 0.5s cancels the selected program. When the charging process is complete, there occurs an acoustic signal (3 loud "medium high" beeps, a total of about 2 seconds) and the Power Enable LED is continuously lit.

The ChargerModule provides a constant voltage (cv-mode) or constant current (cc-mode) depending on the charge program. For most battery modules a combined cc/cv-mode is applied. The top LEDs (CC/CV) indicate the applied charging mode.

For open-circuit (for example no battery module is connected to the charger) five high beeps occur and the charging program is terminated immediately. If the voltage of the connected battery module is higher than the maximum charging voltage (for example, if an incorrect battery is connected) or below the specified end-of-discharge voltage the charging program is also terminated. Independent of the connected module the charger switches off after 1 hour to prevent accidental overloading of the battery module. The following charging programs can be selected:

NiMH (AAA):

- Only cc-mode (charge current I= 250 mA) without cv-process
- Upper voltage limit: 1.6V
- Lower voltage limit: 1V

NiZn (AAA):

- Starts with cc-mode (I=250mA) up to a switching voltage V=1.8V
- After reaching the threshold voltage switch to cv-mode, switch-off at a current of 100mA
- Upper voltage limit: 2V
- Lower voltage limit: 1.3V

LiFePo (AAA):

- Starts with cc-mode (I=200mA) up to a switching voltage V=3.6V
- After reaching the threshold voltage switch to cv-mode, switch-off at a current of 100mA
- Upper voltage limit: 3.7V
- Lower voltage limit: 2.8V

NiMH (triple):

- Only cc-mode (charge current I= 250 mA) without cv-process
- Upper voltage limit: 4.8V
- Lower voltage limit: 3V

Pb:

- Starts with cc-mode (I=500mA) up to a switching voltage V=2.35V
- After reaching the threshold voltage switch to cv-mode, switch-off at a current of 200mA
- Upper voltage limit: 2.45V
- Lower voltage limit: 1.8V

LiPo:

- Starts with cc-mode (I=500mA) up to a switching voltage V=4.1V
- After reaching the threshold voltage switch to cv-mode, switch-off at a current of 200mA
- Upper voltage limit: 4.3V
- Lower voltage limit: 3V

Electrolyzer:

- Only cv-mode (V=2.1V)

Supercap:

- Only cv-mode (V=2.1V), switch-off at a current of 50mA
- Upper current limit: 2A
- Switch-off after 10min, independent of current

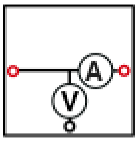
3V:

- Constant voltage of 3V

6V:

- Constant voltage of 6V

AV-Module 9100-03



The AV-Module is a combined voltage and current meter. It holds 3 buttons, whose features are described in the display respectively. By pushing a random button the module will switch on. In the disabled state the display shows the leXsolar emblem. When the display does not show anything or the word „Bat“ is shown, it is necessary to change the batteries in the back (2 x AA batteries 1.2 to 1.5V; Take care of the polarity marked on the bottom of the battery case! Do not touch the button while inserting the batteries).

With the top right button the measuring mode can be switched between voltage mode, current mode or combined voltage-current mode. Both measurement mode and required cable connection will be indicated by the circuit symbols on the display. Take care that in voltage mode no current is applied to the right jack. In the combined mode the voltage can be measured with the right jack as well as with the left one. The influence of the internal resistance of the current measurement is compensated internally. The measured values are signed. When the positive pole is connected to a red jack and the negative pole is connected to the black jack, the value of the voltage will be positive. When current is applied from the left to the right, the current value will be positive, as well. The other way around, the algebraic sign changes.

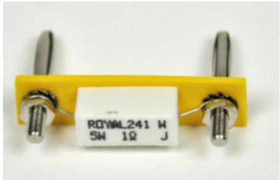
After 30 min without pushing a button or after 10 min of measuring a constant value, the module will switch off automatically. It can measure voltages up to 12 V and currents up to 2 A. In case of exceeding one of the values, the module interrupts the current flow and shows “overcurrent“ or “overvoltage”. This error message can be confirmed by touching a button. The module will resumes measuring, when the values attain acceptable values.

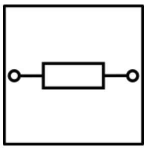
<u>Specifications:</u>

Voltage metering:
- range: 0...12 V
- accuracy: 1 mV
- automatic shutoff in case of overvoltage >12 V

Current metering:
- range: 0...2 A
- accuracy: 0,1 mA (0...199 mA) and 1mA (200 mA...1 A)
- automatic shutoff in case of overcurrent >2 A
- internal resistance <0,5 Ohm (0...200 mA); <0,2 Ohm (200 mA...2 A)

Resistor plug module, triple (1800-01) with resistor plug elements

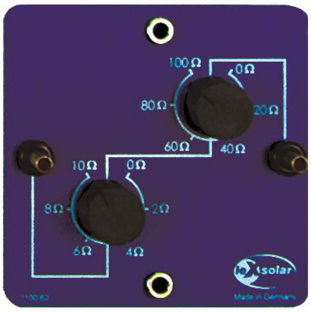



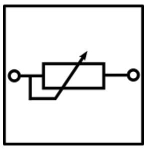


With the resistor plug module and the belonging resistor plug elements parallel connection and series connection of resistors are possible. For parallel connection use one resistor module (triple) with three slots. For series connection use two triple resistor modules. The following resistor plug elements are included:

1 x R=1Ω	1800-03
2 x R=10Ω	1800-05
1 x R=100Ω	1800-04

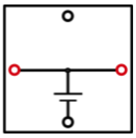
Potentiometer module 110Ohm Pro 1100-62





The potentiometer module holds a 0-10-Ω-potentiometer and a 0-100-Ω-potentiometer. Both are serially connected, so that the potentiometer can attain resistances between 0 Ω to 110 Ω. The measuring error amounts to 0.5 Ω for the small resistor and 3 Ω at other one. The maximum current amounts to 1A.

Capacitor module 1118-11

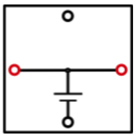


The capacitor module consists of 2 series-connected capacitors. Charging voltages for the capacitor should not exceed 5 V. It is possible to short-circuit the capacitor to discharge, because there are fuses to avoid damages.

<u>Specifications:</u>

Capacitance: 5 F
Maximum voltage: 5,4 V

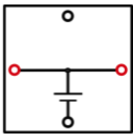
NiMH-battery module, single L2-04-021 with mount 1800-08



Specifications:

V=1,0V...1,35V
End-point voltage: 1V
Max. charging voltage: 1,6V

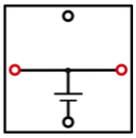
NiMH-battery module, triple 1118-09

Specifications:

V=3V…4,05V
End-point voltage: 3V
Max. charging voltage: 4,8V

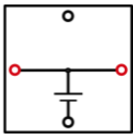
LiFePo-battery module 1801-06



Specifications:

V=3,2V…3,4V
End-point voltage: 2,8V
Max. charging voltage: 3,6V

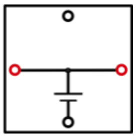
NiZn-battery module 1801-06



<u>Specifications:</u>

V=1,3V…1,8V
End-point voltage: 1,3V
Max. charging voltage: 1,9V

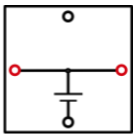
Lead-battery module 1800-13



<u>Specifications:</u>

V=1,9V…2,15V
End-point voltage: 1,9V
Max. charging voltage: 2,35V

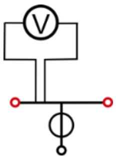
Lithium-Polymer-battery module 1800-07



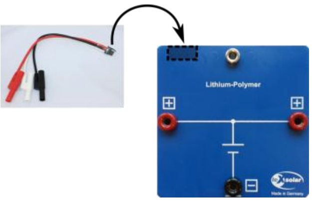
<u>Specifications:</u>

V=3V…4,2V
End-point voltage: 3V
Max. charging voltage: 4,2V

Expansion *(not included in EMobility Ready-to-go)*: Battery adapter cable 1800-09

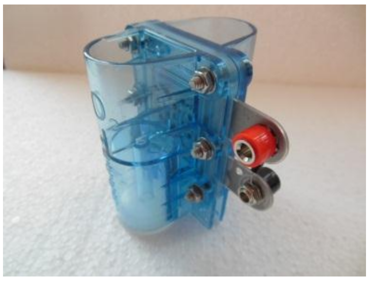


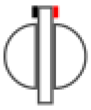
All battery modules are equipped with an additional connection for the four-point measurement. The adapter cable is connected with the black connector to this port:



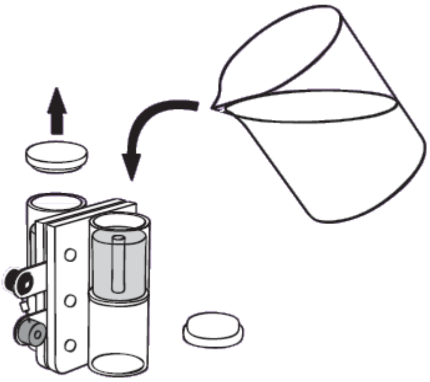
To measure the voltage, the red and the black cable are connected with the measurement device. For measuring the resistance the white cable instead of the red is used.

Reversible fuel cell (L2-06-067)





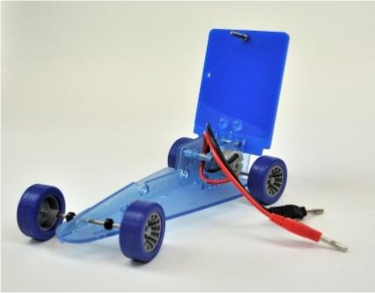
The reversible fuel cell consists of an electrolyzer and a fuel cell. To fill the reversible fuel cell you should proceed in the following way:



1. Fill the rev. fuel cell with distilled water as shown in the alongside figure.
2. Fill both storage cylinders up to the top of the tubules, which are inside the cylinders.
3. Knock the rev. fuel cell slightly on the table.
4. Continue filling in water until it flows through the tubules.
5. Close the storage cylinders with the plugs and turn over the rev. fuel cell (the plugs must be on the bottom).

!! Advice: To charge the reversible fuel cell the applied voltage should not exceed 1.5 V. Otherwise the resulting current could exceed 1 A, which would damage the fuel cell.

Electric model car with battery adapter 1801-02



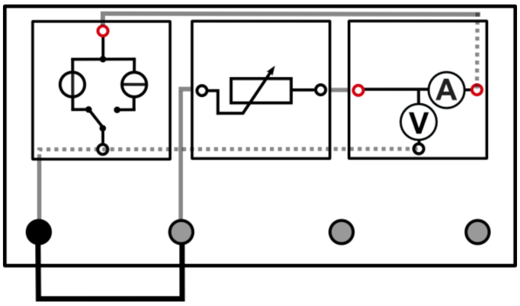
The electric model car can be used with the reversible fuel cell or the battery modules. The fuel cell can be plugged directly onto the car. The battery modules can be plugged with the adapter onto the car.
The car will move when both cables are connected with the voltage source. There will be a short circuit when the wires are held during the short circuit.

1.1 Relationship between current, resistance and voltage

Task

Examine the relationship between voltage, current and resistance in a simple electrical circuit.

Setup



Equipment required

- base unit
- 1 ChargerModule
- 1 Potentiometer module
- 1 AV-Module
- 1 cable

Procedure

1. Set up the experiment according to the circuit diagram. The Charger module is plugged into the base unit rotated by 90 ° (see sketch). Use the ChargerModule with constant voltage mode at 6V. For handling instructions see page 5.
2. Measure current I and voltage V for different resistances R at the potentiometer (for values see table). Use the AV-Module in voltage-current-mode. For handling instructions see page 7.
3. Note your measured values in the table.

Data

R (Ω)	100	80	60	40	20
V (V)	5.9	5.9	5.9	5.9	5.9
I (mA)	61.5	74.7	97.3	145.1	278.7
V/I (Ω)	95.9	79.0	60.6	40.7	21.2

Evaluation

1. Calculate for each measuring point the ratio V/I and note your values in the table.
2. Which law reflects your findings? Illustrate these principles using data from the table.

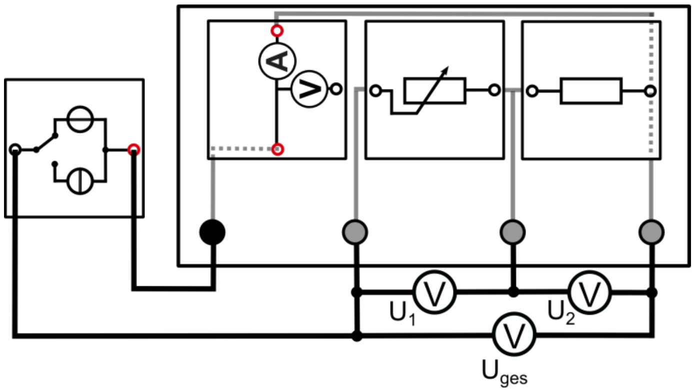
Ohm's law: R=V/I

1.2 Series connection of ohmic resistances

Task

Examine the series connection of ohmic resistances.

Setup



Required devices

- base unit
- 1 ChargerModule
- 1 Potentiometer module
- 1 resistor module, triple
- 1 resistor plug element (R=100Ω)
- 1 AV-Module
- 4 cables

Additionally needed:
- 1 voltage measurement device

Execution

1. Set up the experiment according to the circuit diagram. Use the ChargerModule with constant voltage mode at 6V. For handling instructions see page 5.
2. Adjust the resistance R of the potentiometer to a value of R_{Pot}=100Ω and use the resistor plug element of R_S=100Ω at the triple resistor module.
3. Measure each voltage V and current I over both resistances (V_{tot}) and the single voltage (V_1, V_2) .

   Note: The AV-Module is plugged into the base unit rotated by 90 ° (see sketch). It is used in current-mode. If no further measurement device is available, you can use the AV-Module in voltage mode to measure the voltage. For this purpose the slot of the AV module should be electrically bridged using a cable. For handling instructions see page 7.
4. Repeat your measurement for further resistance values at the potentiometer (see table).
5. Note your measured data in the table.

Measurements

R_S (Ω)	100	80	60	40	20
V_1 (V)	3.0	2.7	2.3	1.8	1.0
V_2 (V)	3.0	3.3	3.7	4.2	5.0
V_{tot} (V)	6.0	6.0	6.0	6.0	6.0
I (mA)	30.7	33.6	37.7	43.0	50.7
$R_{ges}= V_{tot}/I$ (Ω)	195.4	178.6	159.2	139.5	118.3

1.2 Series connection of ohmic resistances

Evaluation

1. Calculate each the ratio $R_{tot}=V_{tot}/I$ and note your values in the table above.
2. Calculate each the sum of the single voltages ($V_1 + V_2$) and compare it the voltage over both resistances (V_{tot}).
3. What is the influence of the resistance on the current I and the voltages $V_1 + V_2$, respectively V_{tot}?
4. What is the connection between the total resistance R_{tot} and the single resistances? Formulate a law for the calculation of the total resistance in a series connection of resistances.

2.

	$V_1 + V_2$	V_{tot}
R_{Pot} = 100Ω / R_S =100Ω	6.0	6.0
R_{Pot} = 80Ω / R_S =100Ω	6.0	6.0
R_{Pot} = 60Ω / R_S =100Ω	6.0	6.0
R_{Pot} = 40Ω / R_S =100Ω	6.0	6.0

→ $V_{tot}= V_1+V_2$

3.

The higher the resistance, the lower the current.

The higher the sum of the resistances, the lower the current.

If both resistances are equal, the voltage over the resistances is also equal.

If one resistance is higher, a higher voltage can be measured at the higher resistance.

The total voltage remains constant.

4.

The total resistance is nearly matching the sum of the single resistances.

Therefore the equation for the total resistance in a series connection can be written as:

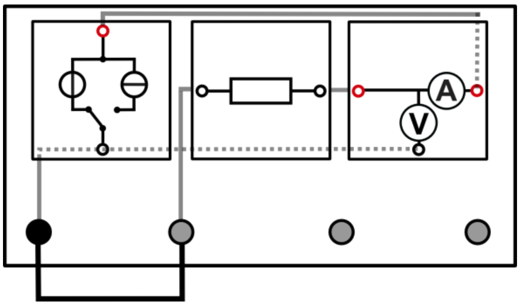
$R_{tot}= R_1+ R_2+\ldots+R_n$ (n… number of resistances)

1.3 Parallel connection of ohmic resistances

Task

Examine the parallel connection of ohmic resistances.

Setup



Required devices

- base unit
- 1 ChargerModule
- 1 resistor module, triple
- 3 resistor plug elements
  (2x R=10Ω, 1x R=100Ω)
- 1 AV-Module
- 1 cable

Execution

1. Set up the experiment according to the circuit diagram. The Charger module is plugged into the base unit rotated by 90 ° (see sketch). Use the ChargerModule with constant voltage mode at 3V. For handling instructions see page 5.
2. Start with 1 x 10 Ω resistance. Measure the voltage and current I. Use the AV-Module in current-voltage mode. For handling instructions see page 7.
3. Repeat your measurement for the parallel connection of the following resistances and note your measured data in the table:
   - R_1=10Ω / R_2=10Ω
   - R_1=10Ω / R_2=100Ω
   - R_1=10Ω / R_2=10Ω / R_3=100Ω

Measurements

	R_1=10Ω	R_1=10Ω / R_2=10Ω	R_1=10Ω / R_2=100Ω	R_1=10Ω / R_2=10Ω / R_3=100 Ω
V (V)	2.9	2.9	2.9	2.8
I (mA)	283.3	560.0	311.5	587.0
R_{ges}=V/I (Ω)	10.2	5.2	9.3	4.8

Evaluation

1. What is the influence of the resistance on the current I and the voltage V?
2. Formulate a law for the calculation of the total resistance in a parallel connection of resistances.

The more resistances are connected parallel the lower the total resistance.

Therefore the equation for the total resistance in a parallel connection can be written as:

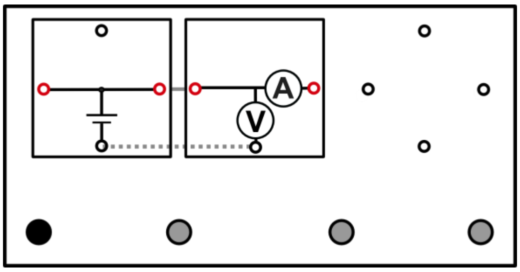
$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}$$ (n…number of resistances)

2.1 Nominal voltage and capacity of voltage sources

Task

Determine the open-circuit voltage and the capacity of single cells.

Setup



Equipment required

- base unit
- 1 AV-Module
- 1 battery module NiMH, single
- 1 battery module Pb
- 1 battery module LiPo
- 1 battery module NiZn
- 1 battery module LiFePo

Procedure

1. Set up the experiment according to the circuit diagram. Use the provided battery modules.
2. Measure the respective open-circuit voltages of the voltage sources V_0 and write down your measured values in the table below. Use the AV-Module in voltage mode. For handling instructions see page 7.

Evaluation

1. Use the open-circuit diagram below to determine the charge state of the voltage sources and note your values (in percent) in the table.
2. Calculate the remaining capacity of each battery using the determined charge states and the indicated maximum capacity. Use the following formula:

$$\frac{Remaining\ capacity}{Maximum\ capacity} = \frac{Charge\ State\ in\ \%}{100}$$

3. Caclculate the required battery capacity to operate a radio with a power of 20W for a period of 3h at a battery voltage of 12V.
4. A starter battery was loaded for 5h with a capacity of 40Ah. Calculate the discharge current.

Data

battery module	V_0 in V	Charge state in %
NiMH	1.25	71
NiZn	1.70	80
LiFePo	3.30	50
Pb	1.99	36
LiPo	3.52	43

Evaluation

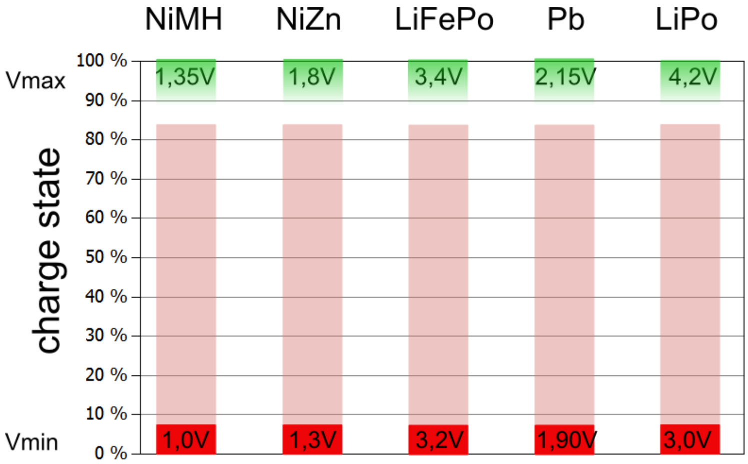


Diagram 2.1: Determination of the charge state

battery module	Capacity
NiMH	600mAh
NiZn	550mAh
LifePo	200mAh
Pb	2500mAh
LiPo	980mAh

Table 2.1: Maximum capacity of the battery modules

2.

NiMH:

$$\frac{x}{600mAh} = \frac{71}{100} \rightarrow x = 426mAh$$

NiZn:

$$\frac{x}{550mAh} = \frac{80}{100} \rightarrow x = 440mAh$$

LiFePo:

$$\frac{x}{200mAh} = \frac{50}{100} \rightarrow x = 100mAh$$

Evaluation

2.

Pb:

$$\frac{x}{2500mAh} = \frac{36}{100} \rightarrow x = 900mAh$$

LiPo:

$$\frac{x}{980mAh} = \frac{43}{100} \rightarrow x = 421mAh$$

3. To calculate the required capacity the following procedure is recommended:

- *First, the total power requirement needed is determined in Wh.*
- *For this requirement you add a spare capacity of 30%.*
- *This value is then divided by the battery voltage. The result is the battery capacity in Ah.*
- *To avoid deep-discharge of the module, the battery should be discharged only by 50%. That`s why the calculated capacity should be multiplied by the safety factor 2.*

$$P_{Radio} = 20W, time\ t = 3h \rightarrow \ total\ power\ requirement\ = 60Wh$$

$$spare\ capacity\ 30\% \rightarrow total\ power\ requirement = 60Wh * 1{,}3 = 78\text{Wh}$$

$$battery\ capacity\ = \frac{78Wh}{12V} = 6{,}5Ah$$

$$safety\ factor\ 2: \rightarrow battery\ capacity = 6{,}5Ah \cdot 2 = \underline{\underline{13Ah}}$$

4.

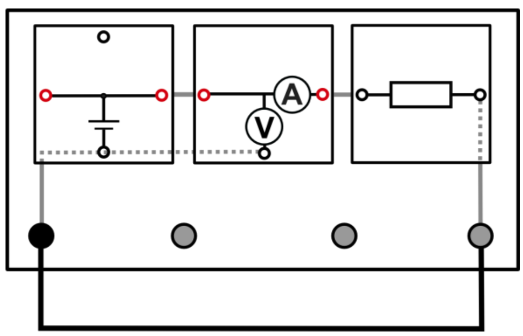
$$Amperage\ I = \frac{battery\ capacity\ Q}{time\ t} = \frac{40Ah}{5h} = \underline{\underline{8A}}$$

2.2 Internal resistance of voltage sources

Task

Determine the internal resistance of the provided voltage sources.

Setup



Equipment required

- base plate
- all battery modules
- 1 AV-Module
- 1 triple resistor module
- 1 resistor plug-element (10Ω)
- cables

Procedure

1. Set up the experiment according to the circuit diagram.
2. Measure first of all the open-circuit voltage of the voltage sources V_0 without a resistor and enter your data in the table.
3. Now measure the voltage V_{load} and the current I_{laod} by closing the circuit (plug in the resistor).

Evaluation

1. Determine the internal resistance R_i of the voltage sources and enter this value into the table too. The internal resistance of the cells is given by the following formula:

$$R_i = \frac{V_0 - V_{load}}{I_{load}} - R_C$$

Advice: The contact resistances R_C have to be subtracted from the calculated value in order to get the actual internal resistances. The contact resistances are also given in the data table.

2. In what way are the voltage sources different from each other?
3. What percentage of the power consumes the triple NiMH-battery module for its own heating in this example?
4. A starter battery has a voltage U_0 = 12V and an internal resistance R_i = 20mΩ. An external starter of 60mΩ is then connected.

   a) Which current is flowing during start?

   b) Calculate the voltage drop at the clamps during start.

2.2 Internal resistance of voltage sources

Data

	V_0 in V	V_{load} in V	I_{load} in mA	R_i in mΩ	R_c in mΩ
NiMH-battery module, single (R_{load} =5 Ω)	1.25	1.24	110	40.9	50
NiZn-battery module (R_{load} =5 Ω)	1.70	1.64	150	350.0	50
LiFePo-battery module (R_{load} =5 Ω)	3.34	3.24	290	294.8	50
Lead-battery module (R_{load} =5 Ω)	1.99	1.98	180	50.6	5
Lithium-polymer-battery module (R_{load} =10 Ω)	3.51	3.45	300	150.6	50
NiMH-battery module, triple (R_{load} =10 Ω)	3.75	3.42	300	880	220

Evaluation

1.

NiMH, single: $R_i = \frac{1.25\text{V}-1.242\text{V}}{0.11\text{A}} - 0.05\Omega = \underline{\underline{40.9\text{m}\Omega}}$

NiZn: $R_i = \frac{1.70\text{V}-1.64\text{V}}{0.15\text{A}} - 0.05\Omega = \underline{\underline{350.0\text{m}\Omega}}$

LiFePo: $R_i = \frac{3.34\text{V}-3.24\text{V}}{0.29\text{A}} - 0.05\Omega = \underline{\underline{294.8\text{m}\Omega}}$

Pb: $R_i = \frac{1.99\text{V}-1.98\text{V}}{0.18\text{A}} - 0.005\Omega = \underline{\underline{50.6\text{m}\Omega}}$

LiPo: $R_i = \frac{3.51\text{V}-3.45\text{V}}{0.30\text{A}} - 0.05\Omega = \underline{\underline{150.6\text{m}\Omega}}$

NiMH, triple: $R_i = \frac{3.75\text{V}-3.42\text{V}}{0.30\text{A}} - 0.220\Omega = \underline{\underline{880.0\text{m}\Omega}}$

2.

Voltage sources consisting of a single cell have a lower internal resistance than voltage sources consisting of several cells. The larger the area of the single cell, the smaller the internal resistance.

Evaluation

1.

The internal resistance of the cell is 880mΩ. The load resistance is 10Ω.

Hence, $\frac{0.88\Omega}{0.88\Omega+10\Omega} \cdot 100\% = \underline{\underline{8.1\%}}$ of the power output is expended for the heating of the module.

2.

a) To calculate the current the internal resistance of the battery R_i and the resistance of the starter R_S have to be considered. It is a series connection of resistance. Hence both values have to be added to the total resistance of $R_i + R_S$:

$$I=\frac{V_0}{R_i + R_S} = \frac{12V}{0{,}02\Omega + 0{,}06\Omega} = \underline{\underline{150A}}$$

b) The voltage drop at the clamps is caused by the internal resistance of the battery:

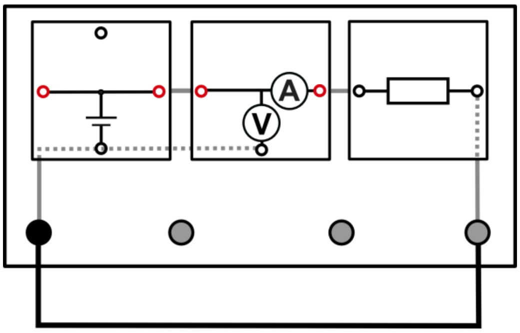
$$V_i=R_i \cdot I = 0{,}02\Omega \cdot 150A = \underline{\underline{3V}}$$

2.3 Series connection of voltage sources

Task

Investigate the behavior of voltage sources in a single cell setup and series connection respectively!

Setup



Equipment required

- base plate
- 1 battery module NiMH, single
- 1 battery module NiMH, triple
- 1 resistor module, triple
- 2 resistor plug elements (2x10Ω)
- 1 AV-Module
- cables

Procedure

1. Set up the experiment according to the circuit diagram. Use the single NiMH-battery module first. Set up a parallel connection with both resistor plug elements to achieve a load resistance of 5Ω. Do not plug in the triple resistor module yet to avoid a discharge of the battery module.
2. First measure the open-circuit voltage V_0 without the resistor and note your value in the table.
3. Plug in the triple resistor module and measure the voltage V_{Load} and current $I_{Load.}$ Use the AV-module in current-voltage-mode.
4. Repeat the experiment with two further NiMH single cells.
5. Now use the examined cells in the adapter for the triple NiMH-module and measure again the above values.

Data

Single battery module:

	V_0 in V	V_{Load} in V	I_{Load} in mA
1st cell (R$_C$= 50 mΩ)	1.24	1.21	210
2nd cell (R$_C$= 50 mΩ)	1.24	1.21	210
3rd cell (R$_C$= 50 mΩ)	1.24	1.21	210

Triple battery module:

	V_0 in V	V_{Load} in V	I_{Load} in mA
Triple cell (R$_C$= 220 mΩ)	3.72	3.40	560

2.3 Series connection of voltage sources

Evaluation

1. Calculate the internal resistance R_i for each individual cell and for the triple cell. The internal resistance of a cell is given by the following formula:

$$R_i = \frac{V_0\text{-}V_{load}}{I_{load}} - R_C$$

Advice: The contact resistances R_C have to be subtracted from the calculated value in order to get the actual internal resistances. The contact resistances are also given in the data table.

2. Why is it better to use a single cell with the same voltage as a triple cell rather than using a comparable battery with several cells connected in series?

1.

1st cell:

$$R_i = \frac{1.24V\text{-}1.21V}{0.21A} - 0.05\Omega = \underline{\underline{92.9m\Omega}}$$

2nd cell:

$$R_i = \frac{1.24V\text{-}1.21V}{0.21A} - 0.05\Omega = \underline{\underline{92.9m\Omega}}$$

3rd cell: $R_i = \frac{1.24V\text{-}1.21V}{0.21A} - 0.05\Omega = \underline{\underline{92.9m\Omega}}$

sum of three single cells:

$$R_i = 3 \cdot 92.9m\Omega = \underline{\underline{278.7m\Omega}}$$

Triple cell:

$$R_i = \frac{3.72V\text{-}3.40V}{0.56A} - 0.220\Omega = \underline{\underline{351.4m\Omega}}$$

2.

The internal resistance of the multimodules is higher because the contact resistances of the components also contribute to the total value. In the ideal case they can be added up to give one value.

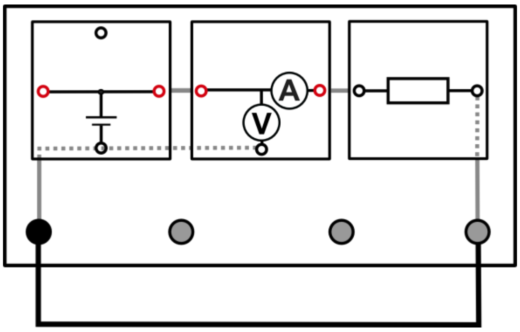
It is advantageous to pick the single cell type because of its lower internal resistance, which is due to a difference in setup. As soon as multiple cells are connected in series, the internal resistance of the total device increases.

2.5 The capacitance of a battery module

Task

Determine the capacitance of a battery module.

Setup



Equipment required

- base plate
- 1 LiFePo battery module
- 1 battery adapter cable
- 1 resistor plug module, triple
- 2 resistor plug elements (2x10Ω)
- 1 AV-Module
- cables

Additionally needed (optional):
- PC with data analysis software

Execution

1. Set up the experiment according to the circuit diagram. Set up a parallel connection with both resistor plug elements to achieve a load resistance of 5Ω. Do not plug in the triple resistor module yet to avoid a discharge of the battery module.
2. First measure the open-circuit voltage $V_0(1)$ without the resistor and note your value in the table.
3. Plug in the triple resistor module and measure 15min the voltage V_{Load} and current I_{Load} at intervals of 1min. Use the AV-module in current-voltage-mode.
4. Measure the open-circuit voltage $V_0(2)$ five minutes after the experiment.

Advice: The battery module should have a rest capacity of 50% (corresponds to V_0=3.3V). The experiment has to be interrupted as soon as the discharge current drops significantly.

Measurements

V_0 (1)= 3.34V

t in min	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
V_{Load} in V	3.09	3.03	3.02	3.01	3.00	3.00	2.99	2.97	2.96	2.94	2.91	2.89	2.86	2.82	2.78	2.74
I_{Load} in mA	535	522	520	519	518	517	515	511	509	505	501	497	492	486	479	470

V_0 (2)= 3.23V

2.4 The capacitance of a battery module

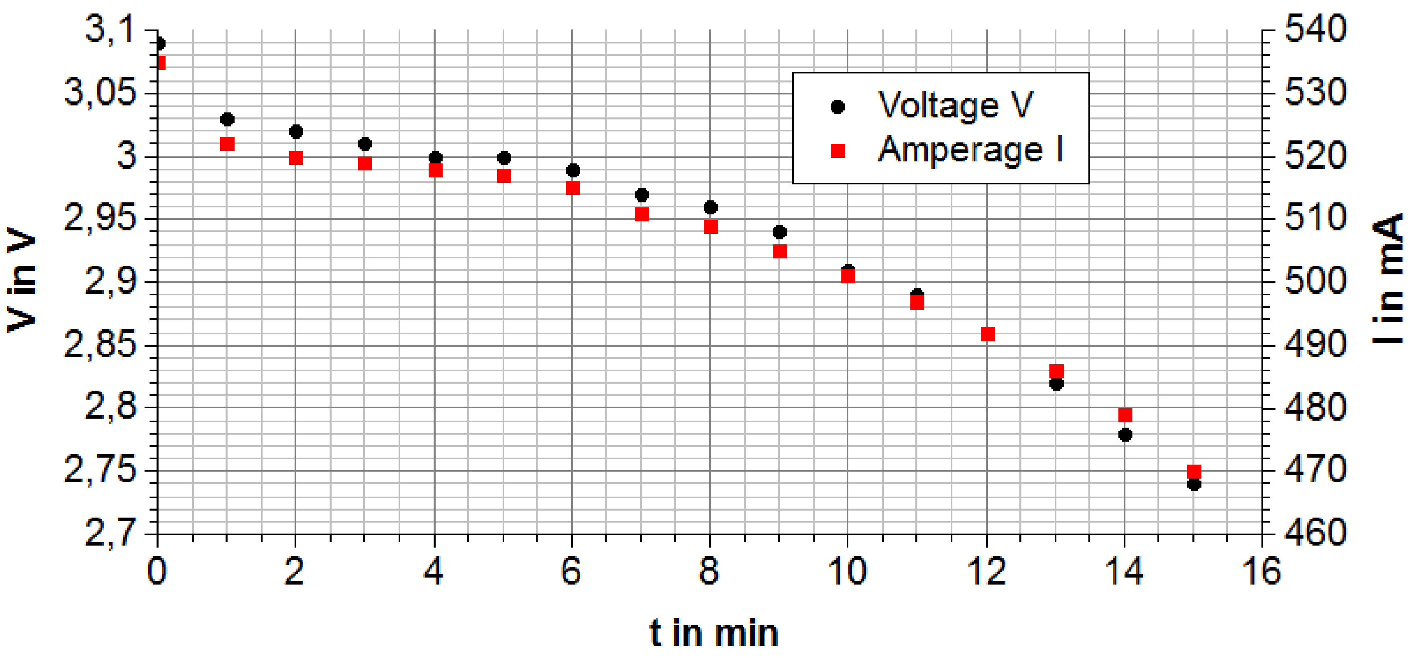
Evaluation

1. Enter your values in the given diagram.
2. Determine the charge state and capacity of the battery module before and after the experiment. Use the diagram and table from the experiment "Nominal voltage and capacity of voltage sources". Estimate from your values the loss of capacity during the experiment.
3. Explain why some parts of the discharge curve can lead to problems with the charge level indication of LiFePo batteries.
4. Transfer your experimentally determined values in a data analysis software. Define with the help of the software a polynomial curve which approximately describes the course of the I-t curve. Then determine the dissipated charge from the integral of the I-t-curve:

$$Q = \int_{t_1}^{t_2} I\,dt$$

3. Compare the estimated charge Q to the loss of capacity that you determined in task 2.

Diagram



2.4 The capacitance of a battery module

Evaluation

2.

Charge state before experiment: $V_0(1)$= 3.34V ~ 70%

Charge state after experiment: $V_0(2)$= 3.23V ~ 15%

Capacitance before experiment:

$$\frac{x}{200mAh} = \frac{70}{100} \quad \rightarrow x = 140mAh$$

Capacitance after experiment:

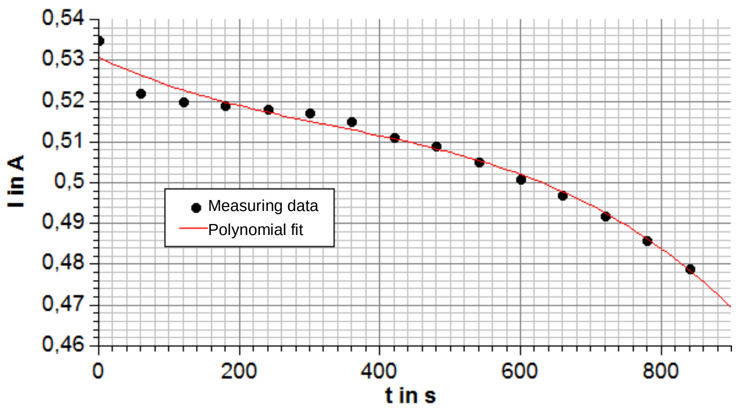
$$\frac{x}{200mAh} = \frac{15}{100} \quad \rightarrow x = 30mAh$$

Loss of capacitance: 140mAh-30mAh=110mAh

3.

Due to the relatively flat course of the curve at the beginning of the discharge process it is difficult to determine the state of charge solely from the voltage measurement. Towards the end, when the curve falls steeply, the voltage can be easier inferred from the charge state.

4. Polynomial curve of third degree



Charge from integral

$$\Delta Q = \int_{t_1}^{t_2} I \, dt = 455.8As$$

Loss of capacitance (from 2.)

$$\Delta Q = 110mAh \equiv 396\ As$$

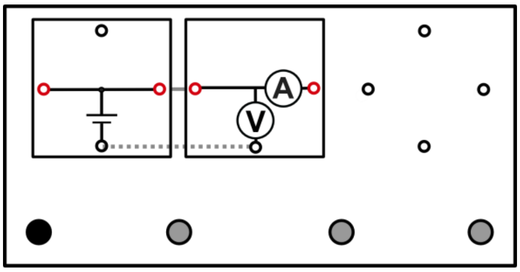
The actual decreasing of capacity during discharging (determined from integral) is higher than the loss of capacitance that was more inaccurately determined from the voltage measurement.

2.5 The energy density of battery modules

Task

Determine the energy density of several battery modules.

Setup



Equipment required

- base plate
- 1 AV-Module
- All battery modules

Execution

1. Set up the experiment according to the circuit diagram.
2. Measure each open-circuit voltage of the voltage sources V_0 and note your values in the table. Use the AV-module in voltage mode.

Evaluation

1. Use the illustration below (diagram 2.6) to determine the charge state of the voltage sources and note the respective percentage values in the table.
2. Calculate the remaining capacity Q_R with the following formula (maximum capacity is stated in table 2.6):

$$\frac{remaining\ capacity\ Q_R}{maximum\ capacity\ Q_{max}} = \frac{charge\ state\ in\ \%}{100}$$

3. Calculate the energy content of the various battery modules and enter your values into the table. The energy content can be calculated by the following formula (note units!):

$$E = V \cdot I \cdot t = V_0 \cdot Q_R$$

4. Calculate using the weight of the batteries (given in table 2.6) the mass-based energy ω [kJ/kg].
5. Why batteries with relatively low (mass-based) energy density like the lead-acid battery are widely used in various applications, despite their heavy weight?

2.5 The energy density of battery modules

Measurements

battery module	V_0 in V	charge state in %	Q_R in mAh	E in kJ
NiMH	1.25	71	426	1.92
NiZn	1.70	80	440	2.69
LiFePo	3.30	50	100	1.19
Pb	1.99	36	900	6.45
LiPo	3.52	43	421	5.33

Evaluation

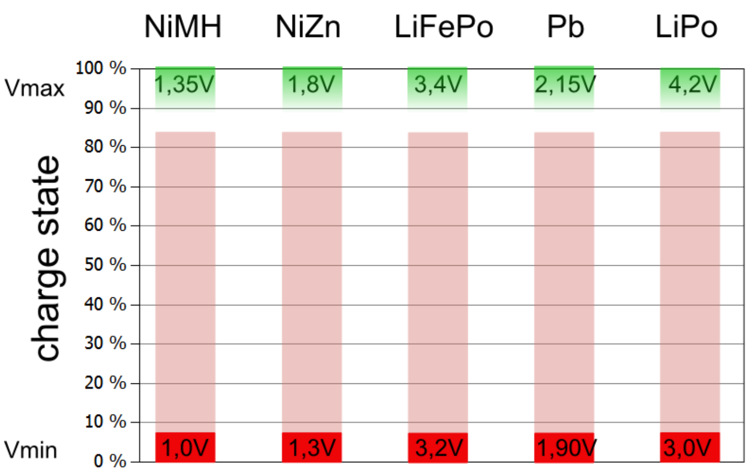


Diagram 2.6: Determination of charge state

battery module	maximum capacitance Q_{max}	weight m in g
NiMH	600mAh	11.3
NiZn	550mAh	11.2
LiFePo	200mAh	7.8
Pb	2500mAh	177.4
LiPo	980mAh	20.0

Table 2.6: Maximum capacitance and weight of the battery modules

Evaluation

2.

NiMH:

$$\frac{x}{600mAh} = \frac{71}{100} \rightarrow x = 426mAh$$

NiZn:

$$\frac{x}{550mAh} = \frac{80}{100} \rightarrow x = 440mAh$$

LiFePo:

$$\frac{x}{200mAh} = \frac{50}{100} \rightarrow x = 100mAh$$

Pb:

$$\frac{x}{2500mAh} = \frac{36}{100} \rightarrow x = 900mAh$$

LiPo:

$$\frac{x}{980mAh} = \frac{43}{100} \rightarrow x = 421mAh$$

3.

NiMH:

$$E = V \cdot I \cdot t = V_0 \cdot Q_R = 1.25V \cdot 426mAh = 1.25V \cdot 0.426A \cdot 3600s = 1.92kJ$$

NiZn:

$$E = V \cdot I \cdot t = V_0 \cdot Q_R = 1.7V \cdot 440mAh = 1.7V \cdot 0.44A \cdot 3600s = 2.69kJ$$

LiFePo:

$$E = V \cdot I \cdot t = V_0 \cdot Q_R = 3.3V \cdot 100mAh = 3.3V \cdot 0.1A \cdot 3600s = 1.19kJ$$

Pb:

$$E = V \cdot I \cdot t = V_0 \cdot Q_R = 1.99V \cdot 900mAh = 1.99V \cdot 0.9A \cdot 3600s = 6.45kJ$$

LiPo:

$$E = V \cdot I \cdot t = V_0 \cdot Q_R = 3.52V \cdot 421mAh = 3.52V \cdot 0.421A \cdot 3600s = 5.33kJ$$

Evaluation

3.

NiMH:

$$\omega = \frac{E}{m} = \frac{1.92kJ}{0.0113kg} = 169.9kJ/kg$$

NiZn:

$$\omega = \frac{E}{m} = \frac{2.69kJ}{0.0112kg} = 240.2kJ/kg$$

LiFePo:

$$\omega = \frac{E}{m} = \frac{1.19kJ}{0.0078kg} = 152.6kJ/kg$$

Pb:

$$\omega = \frac{E}{m} = \frac{6.45kJ}{0.1774kg} = 36.6kJ/kg$$

LiPo:

$$\omega = \frac{E}{m} = \frac{5.33kJ}{0.02kg} = 266.5kJ/kg$$

5.

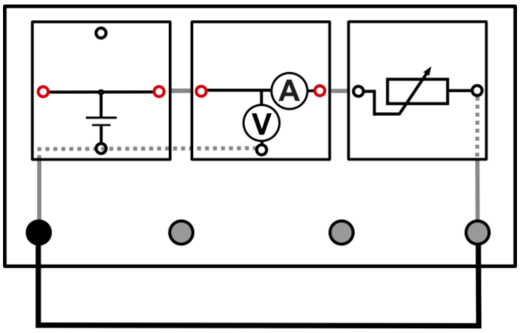
Batteries with higher energy density are often disproportionately expensive or have other adverse characteristics such as low lifetime. In applications where the weight of the battery plays a subordinate role, therefore cheap batteries as the lead battery are preferred

2.6 The R_i efficiency of a battery module

Task

Determine the R_i efficiency of a battery module.

Setup



Equipment required

- base plate
- 1 battery module
- 1 potentiometer module
- 1 AV-Module
- cables

Execution

1. Set up the experiment according to the circuit diagram.
2. Measure first of all the open-circuit voltage V_0 of the voltage sources without the potentiometer module and enter your data in the table.
3. Now plug in the resistor module and measure the voltage V_{load} and the current I_{load} for different resistances R_{pot} at the potentiometer. Use the AV-module in current-voltage-mode. Note your values in the table.

   Advice: Interrupt the current flow (for example, by removing the cable) after each individual measurement to prevent excessive discharge of the module during the experiment

Evaluation

1. Determine for each resistance R_{pot} at the potentiometer module the R_i efficiency η of the battery module and enter your values into the table. The R_i efficiency η can be found using the following formula:

$$\eta = \frac{P_{load}}{P_0} = \frac{V_{load} \cdot I_{load} \cdot}{V_0 \cdot I_{load}}$$

2. Enter your values into the diagram.
3. Describe and explain the behavior of the R_i efficiency in dependence of the current I_{load}.

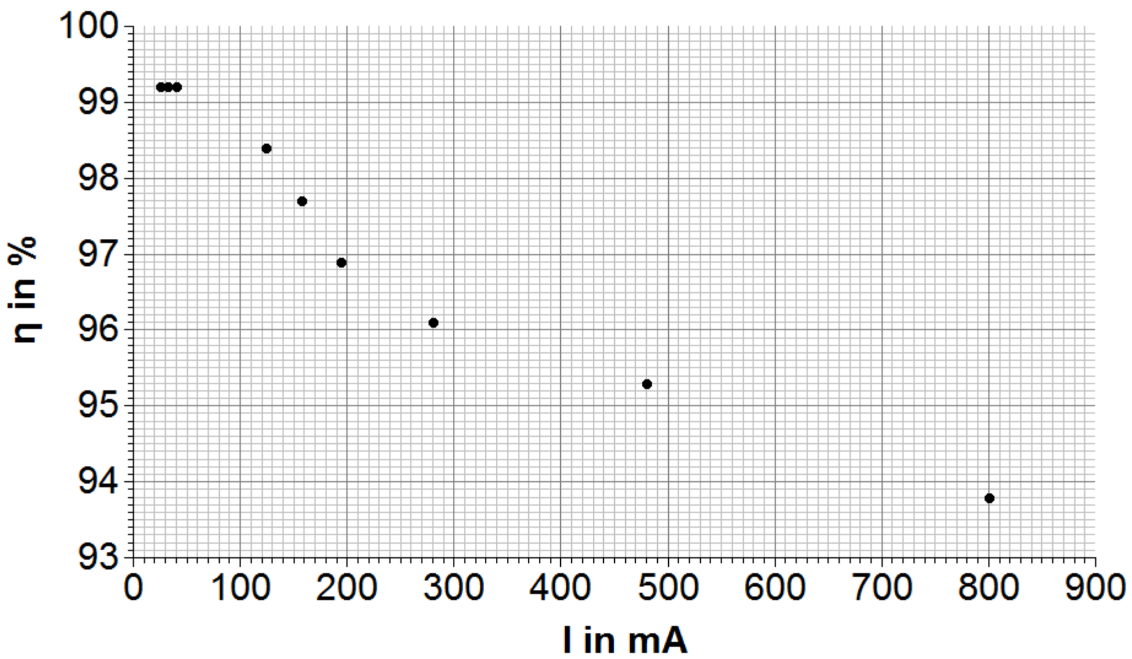
2.6 The R_i efficiency of a battery module

Measurement

V_0=1.28V (Measurement with single NiMH battery module)

R_{Pot} in Ω	40	30	20	10	8	6	4	2	1
V_{Load} in V	1.27	1.27	1.27	1.26	1.25	1.24	1.23	1.22	1.20
I_{Load} in mA	25.5	31.9	40.1	124	157	194	280	480	800
η in %	99.2	99.2	99.2	98.4	97.7	96.9	96.1	95.3	93.8

Diagram



Evaluation

1.

$$\eta_{40\Omega} = \frac{P_{Load}}{P_0} = \frac{V_{Load} \cdot I_{Load}}{V_0 \cdot I_{Load}} = \frac{1.27V \cdot 25.5mA}{1.28 \cdot 25.5mA} = 0.992$$ →analogous $\eta_{30\Omega}$ and $\eta_{20\Omega}$

$$\eta_{10\Omega} = \frac{P_{Load}}{P_0} = \frac{V_{Load} \cdot I_{Load}}{V_0 \cdot I_{Load}} = \frac{1.26V \cdot 124mA}{1.28 \cdot 124mA} = 0.984$$

→ analogous calculation of the remaining efficiencies (see Table)!

2.6 The R_i efficiency of a battery module

Evaluation

3.

At higher load currents (by reducing the load resistance at the potentiometer) the R_i-efficiency decreases.

This behavior can be explained by the greater losses at the internal resistance for higher load currents.

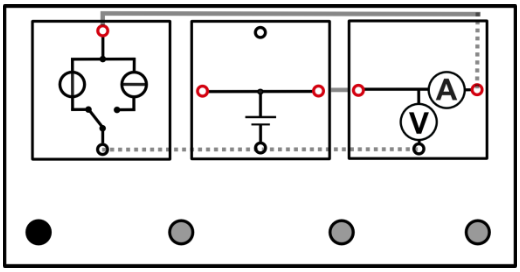
2.7 The total efficiency of a battery module

Task

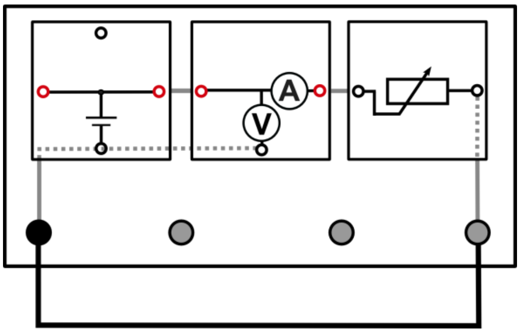
Determine the total efficiency of a battery module.

Setup

Part 1: Charging process



Part 2: Discharging process



Equipment required

- base plate
- 1 battery module NiMH, single
- 1 ChargerModule
- 1 AV-Module
- 1 potentiometer module
- cables

Execution

Part 1: Charging process

1. Set up the experiment according to the circuit diagram (Part 1). Use the ChargerModule in NiMH-mode (single). For advices about the handling of the ChargerModule, see page 5. Do not start the charger yet.
2. Measure first of all the open-circuit voltage $V_0(1)$ of the battery module and enter your data in the table.
3. Switch on the charger and measure for ten minutes in intervals of one minute, the voltage V and the current I. Use the AV-Module in current-voltage-mode. Enter your values in the table.
4. Measure 5 minutes after completion of the first part of the experiment again the open circuit voltage $V_0(2)$.

   Advice: The charge state of battery module should be maximal 50% before the beginning of the experiment (corresponds to an open circuit voltage of 1,18V). Optionally, the battery module must be discharged before the experiment with the help of the resistor modules.

2.7 The total efficiency of a battery module

Execution

Part 2: Discharging process

1. Set up the experiment according to the circuit diagram (Part 2). Do not plug in the potentiometer module yet to avoid the beginning of the measurement without recording the measured data.
2. Measure first of all the open-circuit voltage $V_0(1)$ of the battery module and enter your data in the table.
3. Plug in the potentiometer module and regulate the value of the discharge current to the value of charge current from part 1 of the experiment.
4. Measure then ten minutes the voltage V and the current I in intervals of one minute. Readjust if necessary the resistance of the potentiometer to keep the discharge current constant. Enter your values in the table.
5. Stop after ten minutes the current flow. Measure five minutes the open-circuit voltage $V_0(2)$ of the battery module immediately after completion of the experiment in intervals of one minute. Enter your values in the table.

Measurements

Part 1: Charging process

V_0 (1) = 1.17V

t in min	0	1	2	3	4	5	6	7	8	9	10
V in V	1.22	1.25	1.27	1.28	1.29	1.30	1.31	1.32	1.33	1.34	1.35
I in mA	230	230	230	230	230	230	230	230	230	230	230
W in J	0.0	17.3	35.1	53.0	71.2	89.7	108.5	127.5	146.8	166.4	186.3

V_0 (2) = 1.29V (Five minutes after the first part!)

Part 2: Discharging process

V_0 (1) = 1.29V

t in min	0	1	2	3	4	5	6	7	8	9	10
V in V	1.26	1.23	1.21	1.19	1.18	1.17	1.16	1.15	1.14	1.13	1.12
I in mA	230	230	230	230	230	230	230	230	230	230	230
W in J	0.0	17.0	33.4	49.3	65.1	80.7	96.0	111.1	125.9	140.3	154.6

Open-circuit voltage $V_0(2)$ after experiment:

t in min	0	1	2	3	4	5
$V_0(2)$ in V	1.15	1.17	1.18	1.18	1.19	1.19

2.7 The total efficiency of a battery module

Evaluation

1. Calculate each the energy W that was expended, respectively consumed during the charging/discharging process and enter your values in the table.

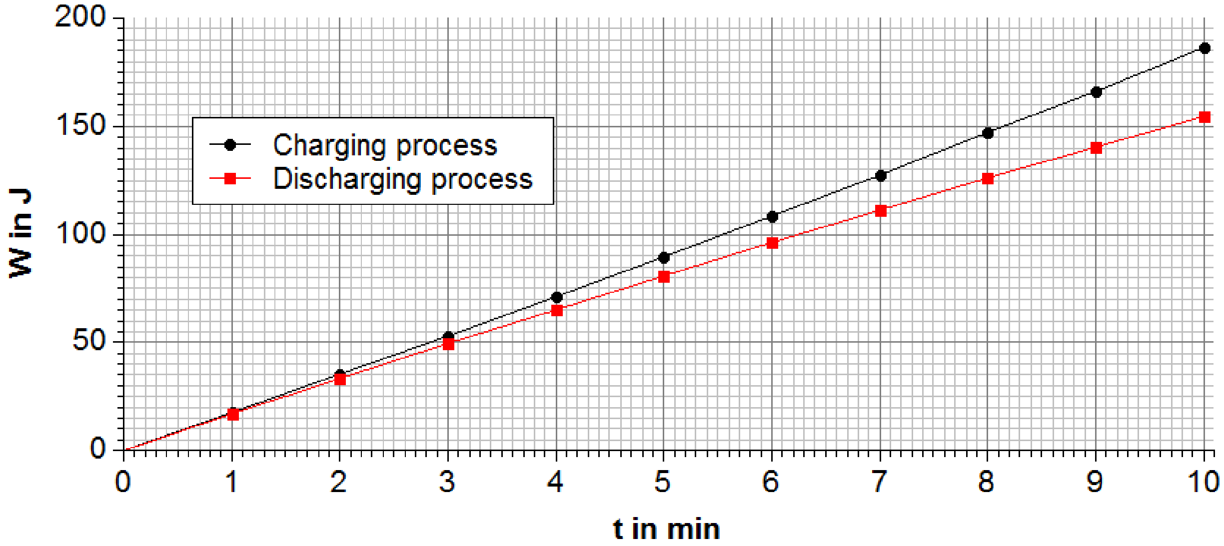
$$W = V \cdot I \cdot t$$

2. Enter your values in the given diagram.
3. Determine the electric energy W_1, that was required during the first part of the experiment for charging the battery (t=10min). Determine further the electric energy W_2, that was submitted during the second part of the experiment (t=10min). Calculate the total efficiency η of the battery module.

$$\eta = \frac{W_2}{W_1}$$

4. Describe what mainly affects the efficiency of battery modules.
5. Explain the so-called *Peukert-Effect*.

Diagram



Evaluation

1.

$W_1(1min) = V \cdot I \cdot t = 1.25V \cdot 0.23A \cdot 1 \cdot 60s = 17.3J$

$W_1(2min) = V \cdot I \cdot t = 1.27V \cdot 0.23A \cdot 2 \cdot 60s = 35.1J$

→ analogous proceed for further values (results see table)

Evaluation

3.

$$\eta = \frac{W_2}{W_1} = \frac{154.6J}{186.3J} = 0.83 \triangleq \underline{\underline{83\%}}$$

4.

Most of the losses during charging and discharging of the battery modules are caused by the internal resistance of the cells. At this resistance heat is released during the charging/discharging process thus a part of energy gets lost. The ration between the released energy during charging and the expended energy during discharging is called charging efficiency.

5.

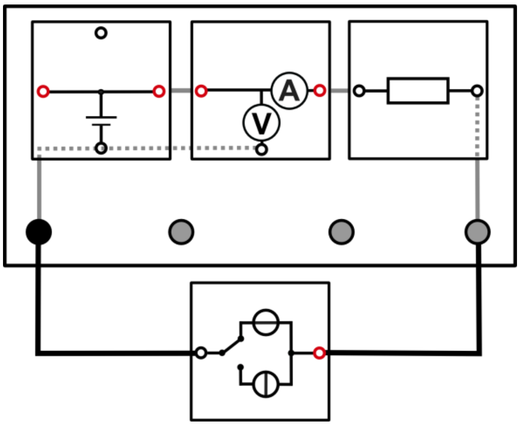
The decrease of charging efficiency due to fast charge/discharge at high currents is called Peukert-effect. It is caused by the increase of losses at the internal resistance with higher currents (see experiment "*R_i efficiency of a battery module*")

3.1 The charging process of a capacitor

Task

Record the charging curve of a capacitor.

Setup



Equipment required

- base plate
- 1 ChargerModule
- 1 AV-Module
- 1 capacitor module
- 1 resistor module, triple
- 2 resistor plug elements (2xR=10 Ω)
- cables

Execution

Part 1: Supercap-mode

1. Set up the experiment according to the circuit diagram. Use the ChargerModule in Supercap-mode. For handling instructions see page 5.
2. Plug in the resistor module of 10Ω and measure 90s the voltage V_{Load} and current I_{Load} in intervals of 10s. The AV-module is in current-voltage-mode.
3. Enter all your values in the table.
4. Discharge the capacitor and repeat the experiment for a resistance of 5Ω (parallel connection of 2x10Ω).

Part 2: Constant-voltage-mode

1. Set up the experiment according to the circuit diagram. Use the ChargerModule in Constant-voltage-mode with 3V.
2. Record analogously to part 1 the charging curve for different resistances. Measure now 120s voltage V_{Load} and Current I_{Load} in intervals of 10s and enter your values in the table.

Advice: The resistor module should be plugged off before the measurement to avoid starting the experiment without recording the data.

Evaluation

1. Enter your values in the diagram.
2. Describe the charging behavior of the capacitor.
3. Estimate the period of time after which the capacitor has a charge state of 60% (In constant-voltage-mode, where 3V≡100%).
4. Name scopes of application for supercaps.

3.1 The charging process of a capacitor

Measurements: Part 1

R_1= 10Ω:

t in s	0	10	20	30	40	50	60	70	80	90
V_{Load} in V	0.12	1.2	1.68	2.05	2.37	2.61	2.82	2.99	3.13	3.25
I_{Load} in mA	340	250	203	178	148	128	108	93	79	69

R_1= 5Ω:

t in s	0	10	20	30	40	50	60	70	80	90
V_{Load} in V	0.12	1.25	2.08	2.62	2.99	3.24	3.43	3.57	-	-
I_{Load} in mA	600	450	313	224	167	128	96	75	-	-

Measurements: Part 2

R_1= 10Ω:

t in s	0	10	20	30	40	50	60	70	80	90	100	110	120
V_{Load} in V	0.07	0.66	1.11	1.47	1.73	1.94	2.11	2.25	2.37	2.46	2.54	2.61	2.66
I_{Load} in mA	250	205	170	139	116	97	80	68	57	49	41	36	31

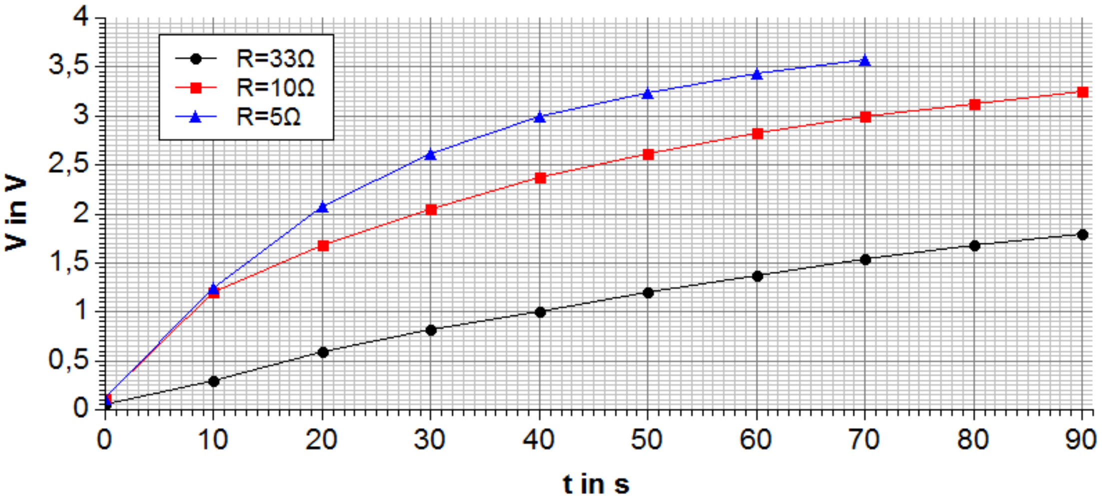
R_1= 5Ω:

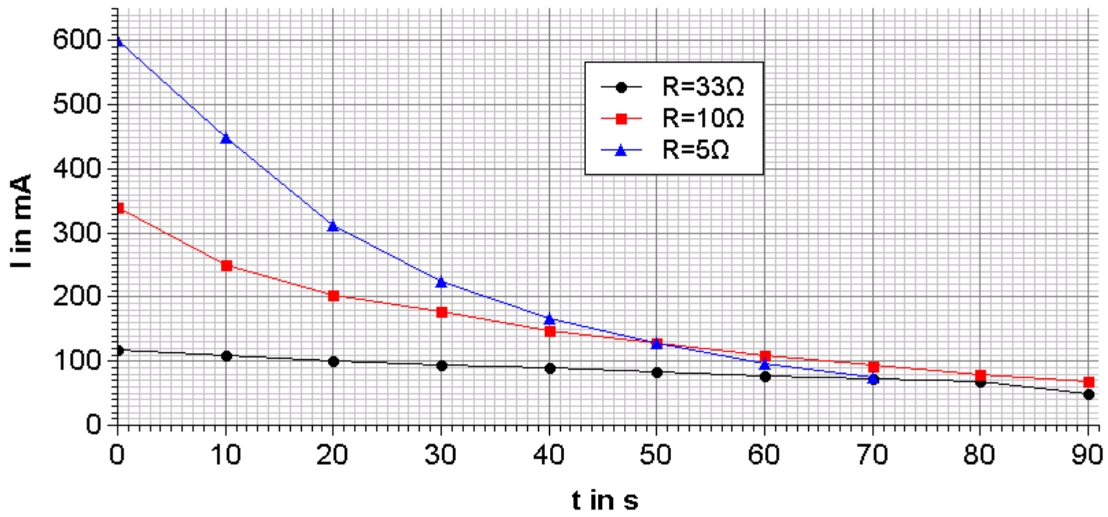
t in s	0	10	20	30	40	50	60	70	80	90	100	110	120
V_{Load} in V	0.18	1.02	1.65	2.04	2.29	2.49	2.61	2.70	2.78	2.83	2.87	2.90	2.92
I_{Load} in mA	450	317	213	156	115	84	62	47	37	28	22	17	14

3.1 The charging process of a capacitor

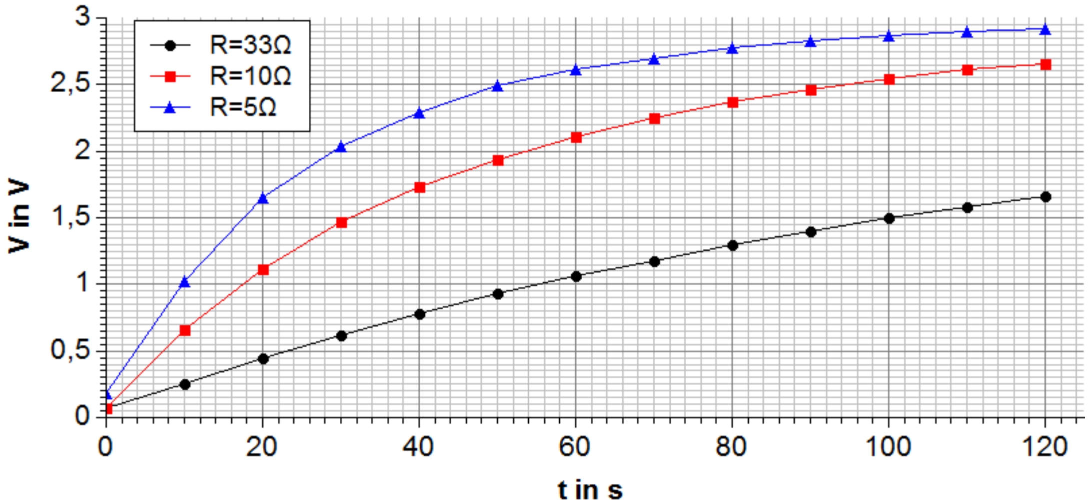
Diagrams

Part 1: Supercap-mode (additionally with R=33Ω)



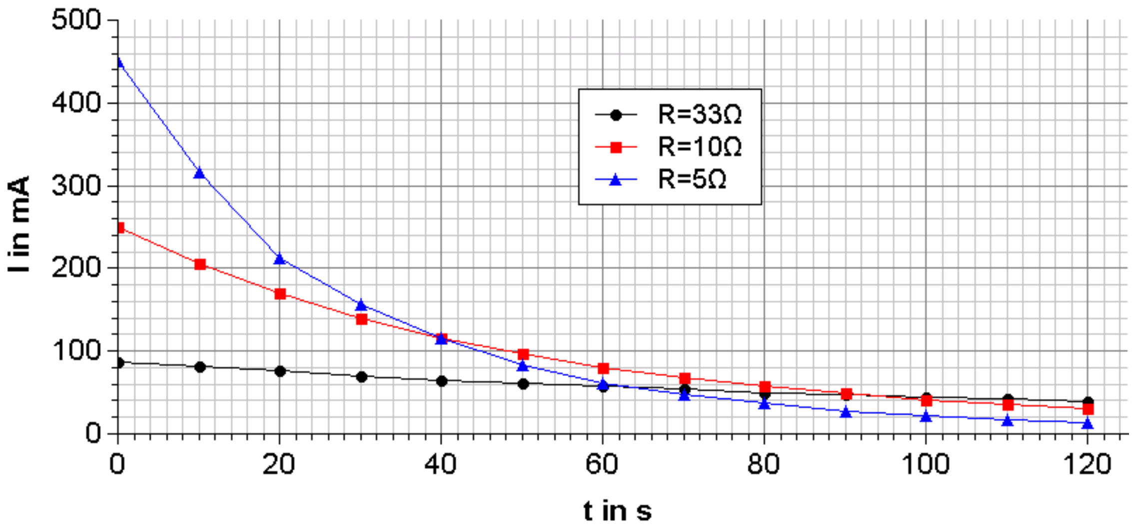


Part 2: Constant-voltage-mode (additionally with R=33Ω)



3.1 The charging process of a capacitor

Diagrams



Evaluation

2.

The voltage is increasing with time and the current is decreasing. The smaller the load resistance, the higher the current and the faster the maximum charge voltage is attained. Hence, the charging process runs faster at higher currents.

3.

R=10 Ω: t (60%) = 42s

R=5 Ω: t (60%) = 24s

4.

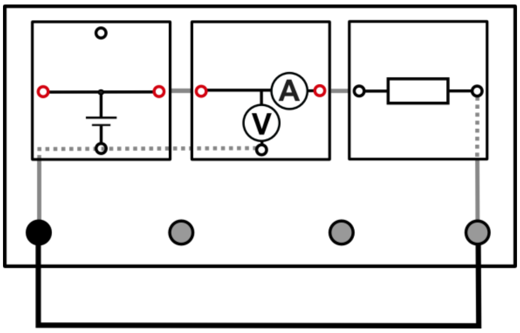
- Stabilization of the power supply at fluctuating load (for ex. Laptop, Smartphone…)
- All applications where their fast loading capacity is utilized (for ex. Emergency LED, flashlight, grid-independent speakers…)

3.2 The discharge process of a capacitor

Task

Record the discharge curve of the capacitor.

Setup



Equipment required

- base plate
- 1 AV-Module
- 1 resistor module, triple
- 2 plug-in resistor elements (2 x R=10Ω)
- 1 capacitor module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Do not plug in the resistor module yet.
2. Measure the open-circuit voltage V_0 of the capacitor and note your value.
3. Plug in the resistor module (R=10Ω) and measure 90s the voltage V_{Load} and current I_{Load} in intervals of 10s. Use the AV-module in current-voltage-mode.
4. Repeat the experiment for a resistance of 5Ω (parallel connection of 2 x 10Ω)

   Advice: The capacitor should have the same charge state before starting both parts of the experiment. Hence, charge the capacitor after the first part. For handling instructions see experiment “The charging process of a capacitor”

Evaluation

1. Enter your values in the given charts.
2. What can you conclude from the diagrams on the discharge behavior of the capacitor?
3. Estimate the time after which the capacitor has a charge state of 60%.
4. Calculate the charge state of the capacitor at the beginning and after 90s discharge time for a resistance of R=10Ω (capacity C=5,0F).
5. The capacitance of a capacitor is given as "n47". Which capacity corresponds to this specification?

3.2 The discharge process of a capacitor

Measurements

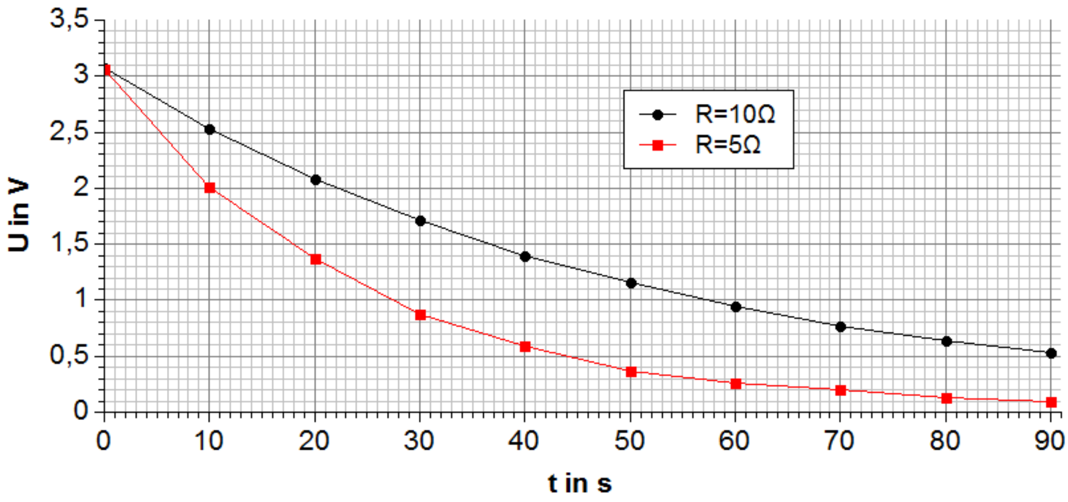
R_1= 10Ω:

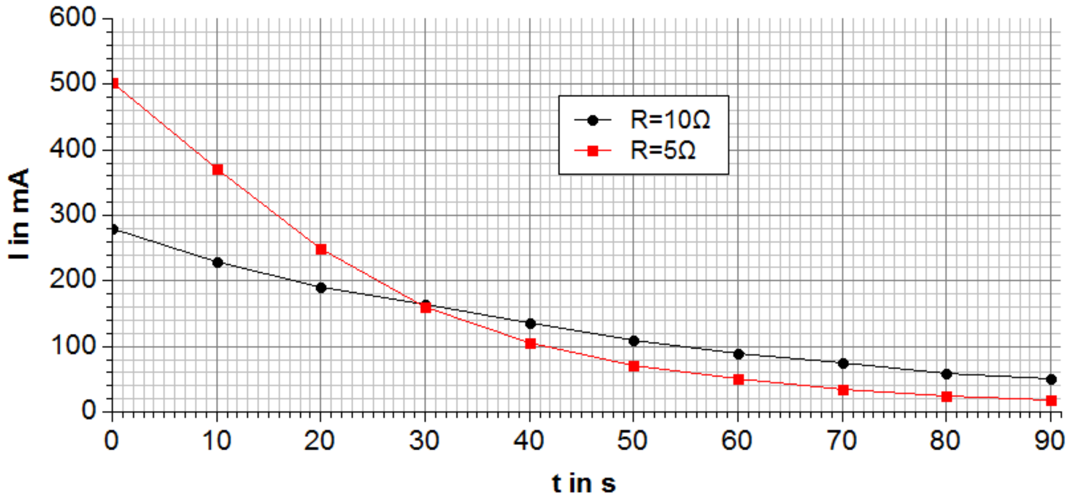
t in s	0	10	20	30	40	50	60	70	80	90
V in V	3.07	2.53	2.08	1.72	1.40	1.16	0.95	0.77	0.64	0.53
I in mA	280	230	190	165	135	110	90	74	59	50

R_2= 5Ω:

t in s	0	10	20	30	40	50	60	70	80	90
V in V	3.06	2.01	1.37	0.88	0.59	0.37	0.26	0.20	0.13	0.1
I in mA	503	370	250	160	105	70	50	35	25	18

Diagrams





3.2 The discharge process of a capacitor

Evaluation

2.

Voltage and amperage decrease during the discharge process. At smaller loading resistances higher discharge currents are flowing and the capacitor is discharging faster. Hence, the voltage, respectively the current drops significantly faster.

3.

$$R = 10\Omega:\ V_1 = 3{,}07V \ \rightarrow\ V_2(60\%) = 0{,}6 \cdot 3{,}07V = 1{,}84V \rightarrow \underline{\underline{t = 25s}}$$

4.

$$Q_1 = C \cdot V_1 = 5{,}0F \cdot 3{,}07V = \underline{\underline{15{,}35C}}$$

$$Q_2 = C \cdot V_2 = 5{,}0F \cdot 0{,}53V = \underline{\underline{2{,}65C}}$$

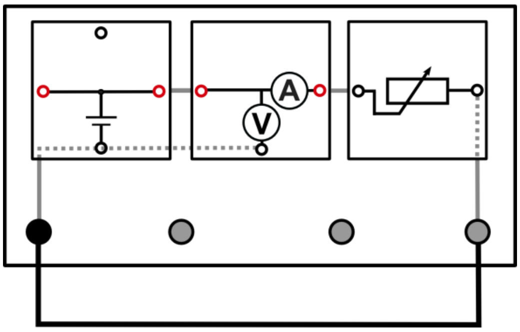
5. 470pF

4.1 I-V characteristics of the single NiMH battery module

Task

Obtain the I-V characteristics of a single NiMH battery module.

Setup



Equipment required

- base plate
- 1 NiMH battery module, single
- 1 AV-Module
- 1 potentiometer module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Do not plug in the potentiometer module yet.
2. Measure the open-circuit voltage V_0 of the capacitor and note your value.
3. Plug in the potentiometer module and adjust the resistance to 50Ω.
4. Measure the voltage V_{Load} and current I_{Load} and note your values in the table. Use the AV-module in current-voltage-mode.
5. Decrease in several steps the resistance R_{Pot} at the potentiometer and measure each the voltage V_{Load} and current I_{Load}. Note all your values in the table.

   Advice: Interrupt the current flow (for example by removing the cable) after each single measurement to avoid discharge of the battery module during the experiment.

Evaluation

1. Enter your values in the given chart.
2. Compare your measured characteristics with the added characteristics and make a statement about the charge state of the cell. Calculate the remaining capacity of the battery module. You find instructions for this in experiment “Nominal voltage and capacity of voltage sources”.
3. Name applications for NiMH batteries. Explain those according to their characteristics
4. Give reasons, why NiMH batteries can not be used in safety-related devices such as fire alarms or emergency flashlights.
5. What benefits have NiMH batteries over NiCd batteries?

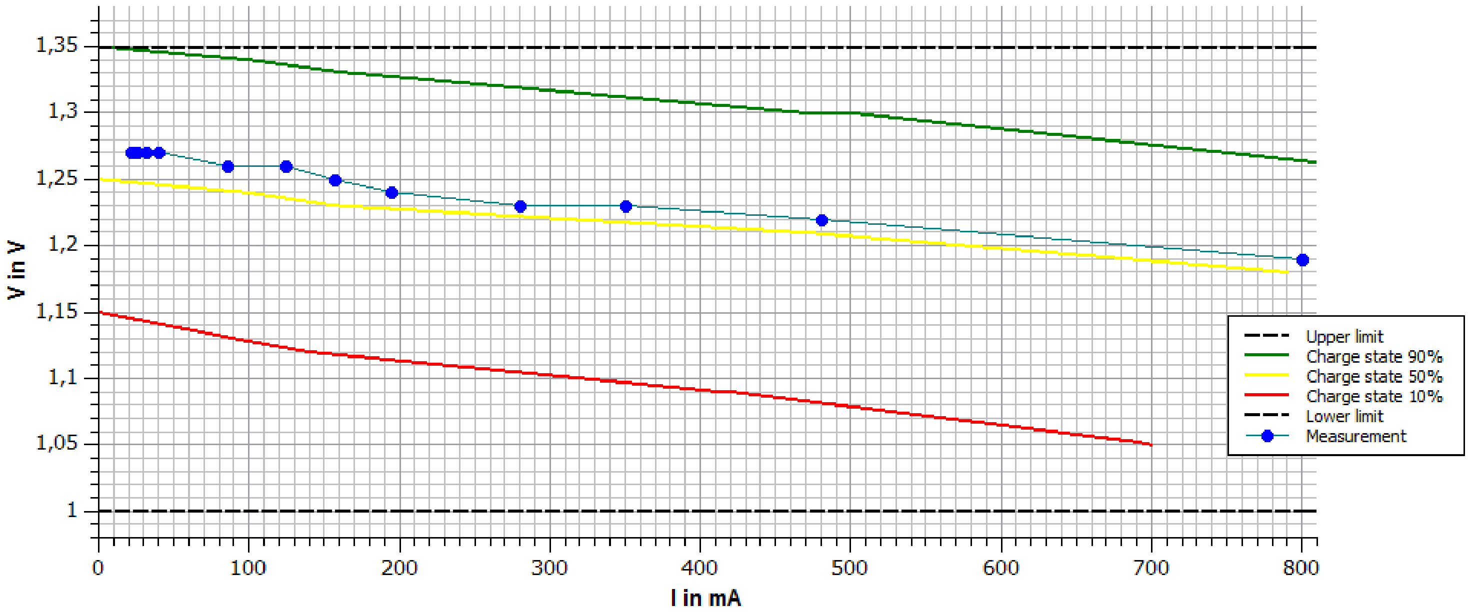
4.1 I-V characteristics of the single NiMH battery module

Measurements

V_0=1.27V

R_{Pot} in Ω	50	40	30	20	15	10	8	6	4	3	2	1
V_{Load} in V	1.27	1.27	1.27	1.27	1.26	1.26	1.25	1.24	1.23	1.23	1.22	1.19
I_{Load} in mA	21.7	25.5	31.9	40.1	85.8	124	157	194	280	350	480	800

Diagram



Evaluation

2.

Charge state ≈ 60%

Remaining capacity:

$$\frac{x}{600mAh} = \frac{60}{100} \rightarrow x = \underline{\underline{360mAh}}$$

4.1 I-V characteristics of the single NiMH battery module

Evaluation

3.

NiMH batteries are due to their relatively low cost and practical energy density with thus low weight mainly used in small devices like toys, remote controllers, audio-, photo- and video-equipment. Further applications are for example phones or GPS devices.

4.

Commercially available NiMH batteries have a relatively high self-discharge rate. This may be initially at up to 10% per day and stabilizes in the course of time to about 1% per day. However Safety devices require high battery life of several months or years what cannot be ensured for the storage of NiMH batteries due to their high self-discharge.

5.

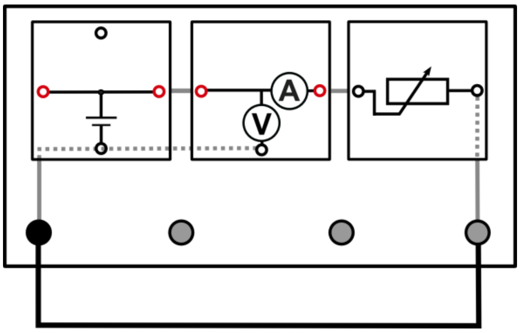
- NiMH batteries contain no heavy metals and are therefore regarded as environmentally friendly.
- Higher battery capacity for the same size due to the cell chemistry
- Longer maturities (up to 40% more)
- Charging without memory effect possible

4.2 I-V characteristics of the NiZn battery module

Task

Determine the I-V characteristics of the NiZn battery module.

Setup



Equipment required

- base plate
- 1 NiZn battery module
- 1 AV-Module
- 1 potentiometer module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Do not plug in the potentiometer module yet.
2. Measure the open-circuit voltage V_0 of the capacitor and note your value.
3. Plug in the potentiometer module and adjust the resistance to 60Ω.
4. Measure the voltage V_{Load} and current I_{Load} and note your values in the table. Use the AV-module in current-voltage-mode.
5. Decrease in several steps the resistance R_{Pot} at the potentiometer and measure each the voltage V_{Load} and current I_{Load}. Note all your values in the table.

   Advice: Interrupt the current flow (for example by removing the cable) after each single measurement to avoid discharge of the battery module during the experiment.

Evaluation

1. Enter your values in the given chart.
2. Compare your measured characteristics with the added characteristics and make a statement about the charge state of the cell. Calculate the remaining capacity of the battery module. You find instructions for this in experiment “Nominal voltage and capacity of voltage sources”.
3. Why was the NiZn battery practically used first in the 2000 years, although Adison has patented these battery types already in 1901?
4. Name advantages of the NiZn batteries over the NiMH systems, especially in the automotive industry.

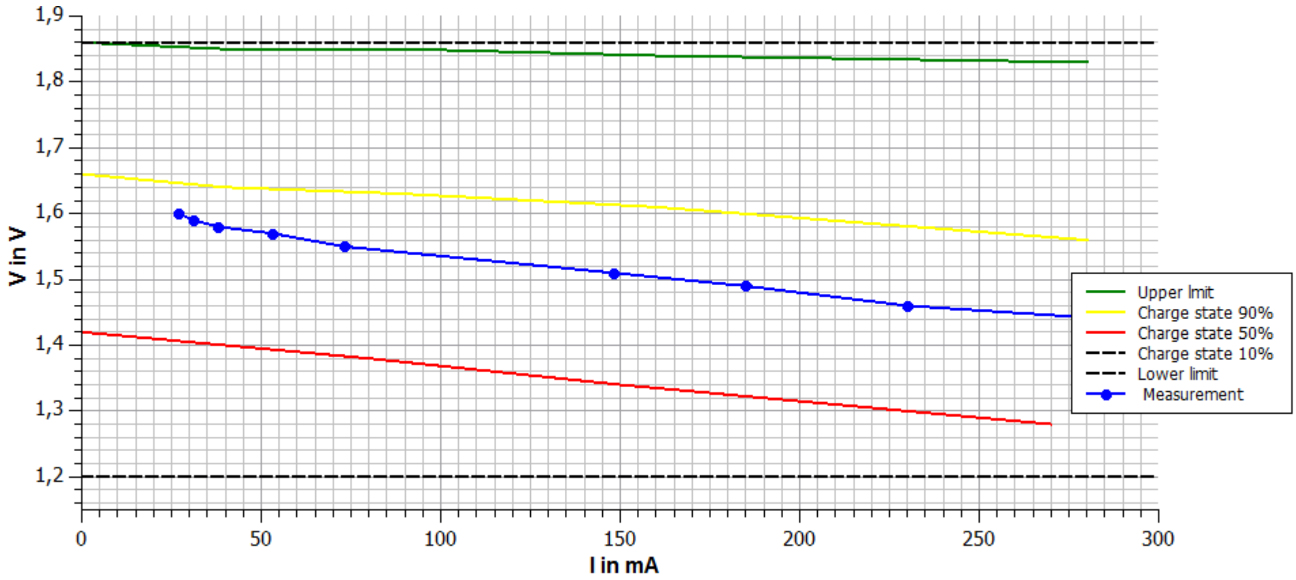
4.2 I-V characteristics of the NiZn battery module

Measurements

V_0= 1.65V

R_{Pot} in Ω	60	50	40	30	20	10	8	6	4
U_{Load} in V	1.60	1.60	1.59	1.57	1.55	1.51	1.49	1.46	1.43
IL_{oad} in mA	27	31	38	53	73	148	185	230	310

Diagram



Evaluation

2.

The charge state of the battery module at the beginning is about 40%. It decreases due to discharging processes to 30% in the course of the experiment. Thereby, the characteristic curve is not parallel to the predetermined characteristic curves.

4.2 I-V characteristics of the NiZn battery module

Evaluation

2.

Charge state ≈ 35%

Remaining capacity

$$\frac{x}{550mAh} = \frac{35}{100} \rightarrow x = \underline{\underline{192.5mAh}}$$

3.

The zinc electrode used in NiZn batteries could be stabilized only in the last 20 years so far that the battery could be actually used in practice. The problem of the first prototypes was mainly the low service life with a small number of charge cycles since the zinc electrode quickly lost its function by passivation. New technologies enabled in recent years to extend the life of NiZn batteries by a multiple.

4.

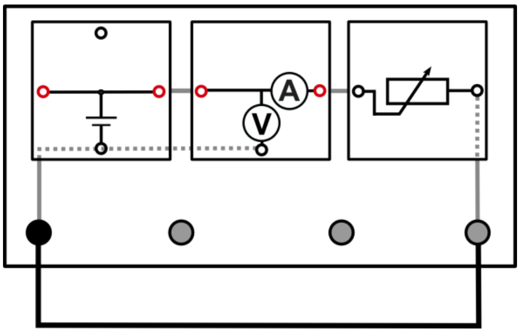
- NiZn batteries have higher nominal voltage → fewer cells are required → easier and more efficient (resistance decreases, the fewer cells are connected in series, see experiment „Series connection of voltage sources)
- NiZn batteries have higher specific energy than NiMH batteries (see experiment "The energy density of battery modules") → less weight
- NiZn do not use rare earth elements → cheaper

4.3 I-V characteristics of the LiFePo battery module

Task

Determine the I-V characteristics of the LiFePo battery module.

Setup



Equipment required

- base plate
- 1 LiFePo battery module
- 1 AV-Modul
- 1 potentiometer module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Do not plug in the potentiometer module yet.
2. Measure the open-circuit voltage V_0 of the capacitor and note your value.
3. Plug in the potentiometer module and adjust the resistance to 100Ω.
4. Measure the voltage V_{Load} and current I_{Load} and note your values in the table. Use the AV-module in current-voltage-mode.
5. Decrease in several steps the resistance R_{Pot} at the potentiometer and measure each the voltage V_{Load} and current I_{Load}. Note all your values in the table.

   Advice: Interrupt the current flow (for example by removing the cable) after each single measurement to avoid discharge of the battery module during the experiment.

Evaluation

1. Enter your values in the given chart.
2. Compare your measured characteristics with the added characteristics and make a statement about the charge state of the cell. Calculate the remaining capacity of the battery module. You find instructions for this in experiment “Nominal voltage and capacity of voltage sources”.
3. Name advantages and disadvantages of LiFePo batteries against other battery types.
4. What are the main fields of application for LiFePo batteries?

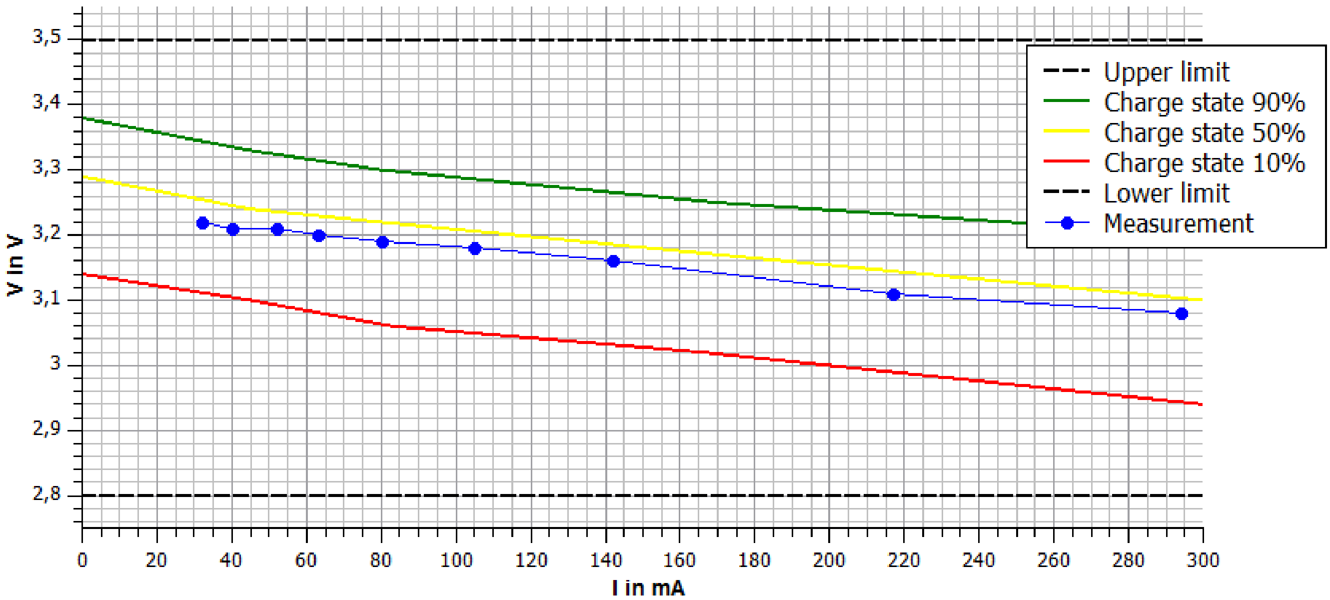
4.3 I-V characteristics of the LiFePo battery module

Measurements

V_0= 3.24V

R_{Pot} in Ω	100	80	60	50	40	30	20	15	10
V_{Load} in V	3.22	3.21	3.21	3.20	3.19	3.18	3.16	3.11	3.08
I_{Load} in mA	32	40	52	63	80	105	142	217	294

Diagram



Evaluation

2.

Charge state ≈ 40%

Remaining capacity:

$$\frac{x}{200mAh} = \frac{40}{100} \rightarrow x = \underline{\underline{80mAh}}$$

Evaluation

3.

Advantages:

- high (thermal) security
- high power density
- high charging currents possible
- high cycle stability
- flat voltage profile of the characteristic curve during charge and discharge process
- broad temperature range (storage/application)
- low self-discharge

Disadvantages:

- hardly standardized designs
- low energy density
- protection circuits and battery management systems necessary
- determining the charge state difficult by shallow characteristics

4.

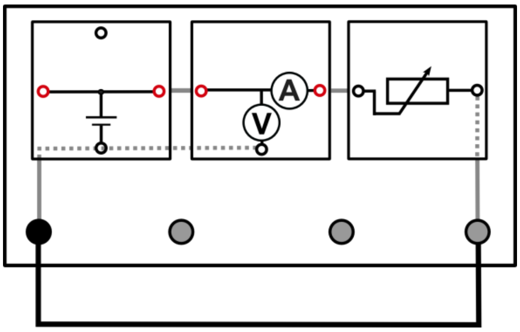
- especially in the field of mobility : Starter batteries, battery in boats and RVs , trucks
- electric buses, - boats, -motorcycles, bicycle
- storage battery for renewable energy , for ex. photovoltaic systems
- battery storage power plants
- battery -powered tools

4.4 I-V characteristics of the lead battery module

Task

Determine the I-V characteristics of the lead battery module.

Setup



Equipment required

- base plate
- 1 lead battery module
- 1 AV-Modul
- 1 potentiometer module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Do not plug in the potentiometer module yet.
2. Measure the open-circuit voltage V_0 of the capacitor and note your value.
3. Plug in the potentiometer module and adjust the resistance to 60Ω.
4. Measure the voltage V_{Load} and current I_{Load} and note your values in the table. Use the AV-module in current-voltage-mode.
5. Decrease in several steps the resistance R_{Pot} at the potentiometer and measure each the voltage V_{Load} and current I_{Load}. Note all your values in the table.

   Advice: Interrupt the current flow (for example by removing the cable) after each single measurement to avoid discharge of the battery module during the experiment.

Evaluation

1. Enter your values in the given chart.
2. Compare your measured characteristics with the added characteristics and make a statement about the charge state of the cell. Calculate the remaining capacity of the battery module. You find instructions for this in experiment “Nominal voltage and capacity of voltage sources”.
3. What is meant when a lead battery suffers from sulfation ?
4. Why are electrodes the in automotive industry often performed highly porous in lead-acid batteries?

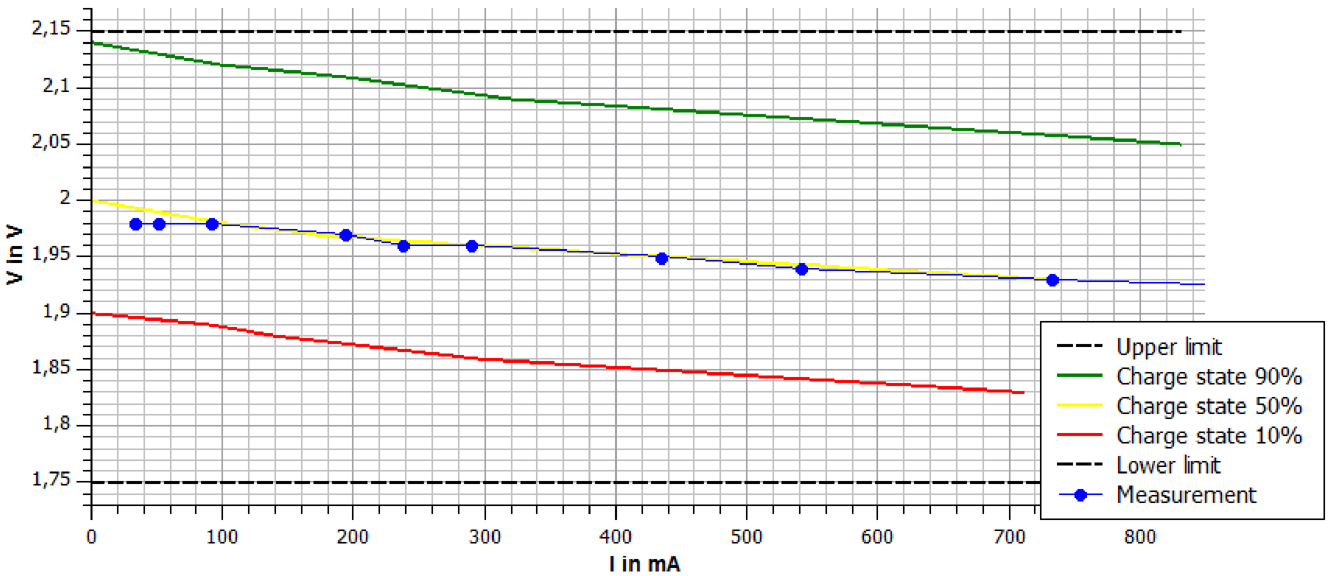
4.4 I-V characteristics of the lead battery module

Measurements

V_0=1.99V

R_{Pot} in Ω	60	40	20	10	8	6	4	3	2	1
V_{Load} in V	1.98	1.98	1.98	1.97	1.96	1.96	1.95	1.94	1.93	1.91
I_{Load} in mA	33	51	92	193	237	290	434	541	732	1220

Diagram



Evaluation

2.

Charge state ≈ 50%

Remaining capacity:

$$\frac{x}{2500mAh} = \frac{50}{100} \rightarrow x = \underline{\underline{1250mAh}}$$

Evaluation

3.

Sulfation means the deposition of lead sulphate on the surface of the active material of the lead plates. This can lead to the formation of large crystals which can severely limit the efficiency of lead batteries , or even lead to the destruction of the battery. Cause of this process is mainly the storage of the battery in a discharged state or of operating at elevated temperatures.

4.

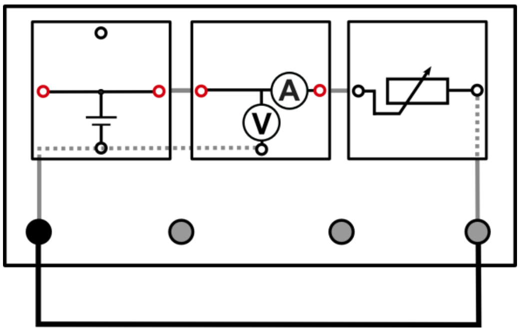
By porous design of the electrodes a much larger surface area per volume is achieved. Thus, the for lead-acid batteries typically high internal resistance is reduced. The large surface area of the battery can clearly . deliver more current than one with a simple metal electrode. Another advantage is the comparatively high capacity in a small volume.

4.5 I-V charachteristics of the lithium-polymer battery module

Task

Determine the I-V characteristics of the lithium-polymer battery module.

Setup



Equipment required

- base plate
- 1 LiPo battery module
- 1 AV-Modul
- 1 potentiometer module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Do not plug in the potentiometer module yet.
2. Measure the open-circuit voltage V_0 of the capacitor and note your value.
3. Plug in the potentiometer module and adjust the resistance to 60Ω.
4. Measure the voltage V_{Load} and current I_{Load} and note your values in the table. Use the AV-module in current-voltage-mode.
5. Decrease in several steps the resistance R_{Pot} at the potentiometer and measure each the voltage V_{Load} and current I_{Load}. Note all your values in the table.

   Advice: Interrupt the current flow (for example by removing the cable) after each single measurement to avoid discharge of the battery module during the experiment.

Evaluation

1. Enter your values in the given chart.
2. Compare your measured characteristics with the added characteristics and make a statement about the charge state of the cell. Calculate the remaining capacity of the battery module. You find instructions for this in experiment “Nominal voltage and capacity of voltage sources”.
3. Name the main fields of apllication of LiPo batteries.
4. How can you optimize the life time of a LiPo battery?

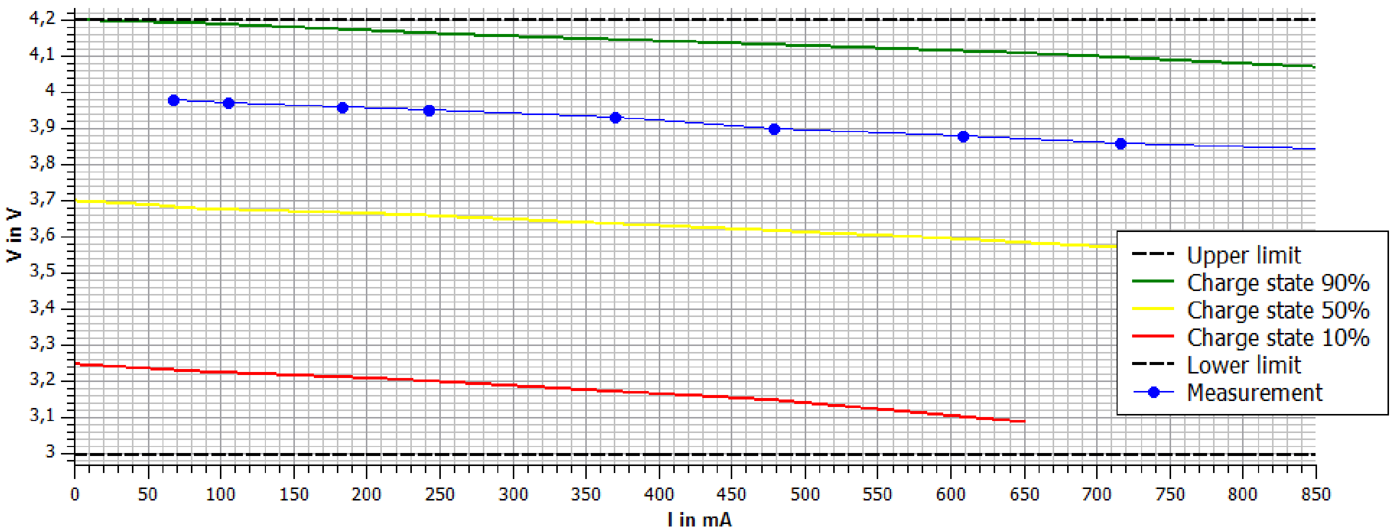
4.5 I-V charachteristics of the lithium-polymer battery module

Measurements

V_0=3.99V

R_{Pot} in Ω	60	40	20	15	10	8	6	5	4
V_{Load} in V	3.98	3.97	3.96	3.95	3.93	3.90	3.88	3.86	3.84
I_{Load} in mA	67	105	183	242	370	478	608	716	870

Diagram



Evaluation

2.

Charge state≈ 80%

Remaining capacity:

$$\frac{x}{980mAh} = \frac{80}{100} \rightarrow x = \underline{\underline{784mAh}}$$

Evaluation

3.

- electric cars
- models
- mobile phones
- electronic appliances such as MP3 players or laptops
- Stationary power plant energy storage

4.

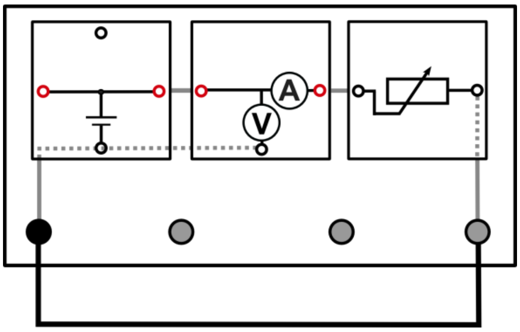
- frequent reloading without overcharging (shallow discharge cycles)
- high-quality electronics of the battery management system
- cool storage
- operation in optimum temperature range
- no storage at high charge state (ideally charge state of 50%)

4.6 I-V characteristics of the triple NiMH battery module

Task

Determine the I-V characteristics of the triple NiMH battery module.

Setup



Equipment required

- base plate
- 1 NiMH battery module, triple
- 1 AV-Modul
- 1 potentiometer module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Do not plug in the potentiometer module yet.
2. Measure the open-circuit voltage V_0 of the capacitor and note your value.
3. Plug in the potentiometer module and adjust the resistance to 100Ω.
4. Measure the voltage V_{Load} and current I_{Load} and note your values in the table. Use the AV-module in current-voltage-mode.
5. Decrease in several steps the resistance R_{Pot} at the potentiometer and measure each the voltage V_{Load} and current I_{Load}. Note all your values in the table.

   Advice: Interrupt the current flow (for example by removing the cable) after each single measurement to avoid discharge of the battery module during the experiment.

Evaluation

1. Enter your values in the given chart.
2. Compare your measured characteristics with the added characteristics and make a statement about the charge state of the cell. Calculate the remaining capacity of the battery module. You find instructions for this in experiment “Nominal voltage and capacity of voltage sources”.
3. Calculate the total voltage and capacity of a series connection of two batteries with each 12V open circuit voltage and a capacity of 50Ah.

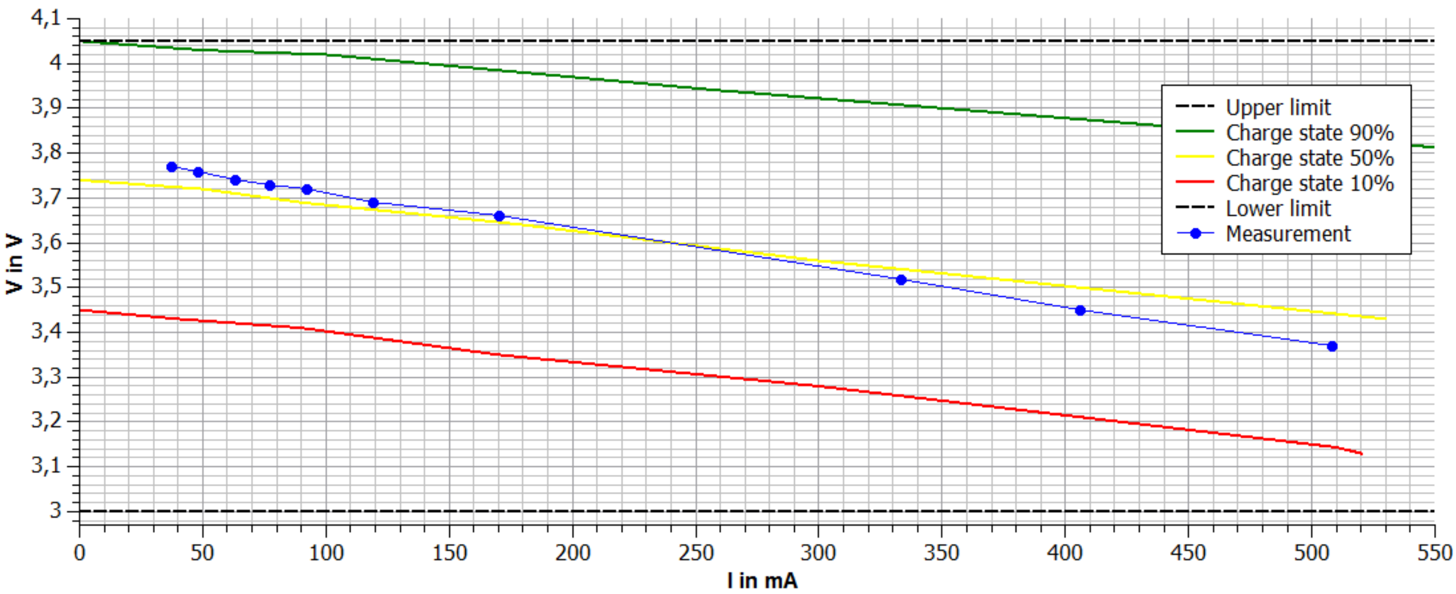
4.6 I-V characteristics of the triple NiMH battery module

Measurements

V_0=3.79V

R_{Pot} in Ω	100	80	60	50	40	30	20	10	8	6
V_{Load} in V	3.77	3.76	3.74	3.73	3.72	3.69	3.66	3.52	3.45	3.37
I_{Load} in mA	37	48	63	77	92	119	170	333	406	508

Diagram



Evaluation

2.

The charge state of the battery module at the beginning is about 60%. It decreases due to discharging processes to 40% in the course of the experiment. Thereby, the characteristic curve is not parallel to the predetermined characteristic curves.

4.6 I-V characteristics of the triple NiMH battery module

Evaluation

2.

Charge state ≈ 50%

Remaining capacity:

$$\frac{x}{600mAh} = \frac{50}{100} \rightarrow x = \underline{\underline{300mAh}}$$

3.

The total voltage ads to 12V+12V=24V

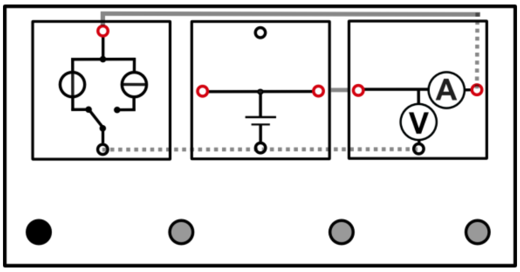
The total capacity equal to the capacity of the individual cells 50Ah.

5.1 The charging process of the NiMH battery

Task

Record the charge characteristics of a NiMH battery module.

Setup



Equipment required

- base plate
- 1 ChargerModule
- 1 NiMH battery module, single
- 1 AV-Module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Use the ChargerModule in NiMH-mode. For handling instructions of the ChargerModule see page 5. Do not switch on the ChargerModule yet.
2. Measure the open-circuit voltage V_0 of the battery module and note your value.

   Advice: The battery module should have a charge state of maximum 50% (this corresponds to an open-circuit voltage of 1.18V). If the charge state is over 50% you can discharge the battery module with the resistances or the electric car.

3. Switch on the ChargerModule and measure the voltage V_{Load} and current I_{Load} in intervals of 1min and note your values in the table. Use the AV-module in current-voltage-mode.

Evaluation

1. Enter your values in the diagram.
2. Describe and give reasons for the behavior of voltage and current during the charging process.
3. Explain the so-called *Memory-Effect* and the *Lazy-Effect.* Describe their influence on conventional NiMH batteries.

5.1 The charging process of the NiMH battery

Measurements

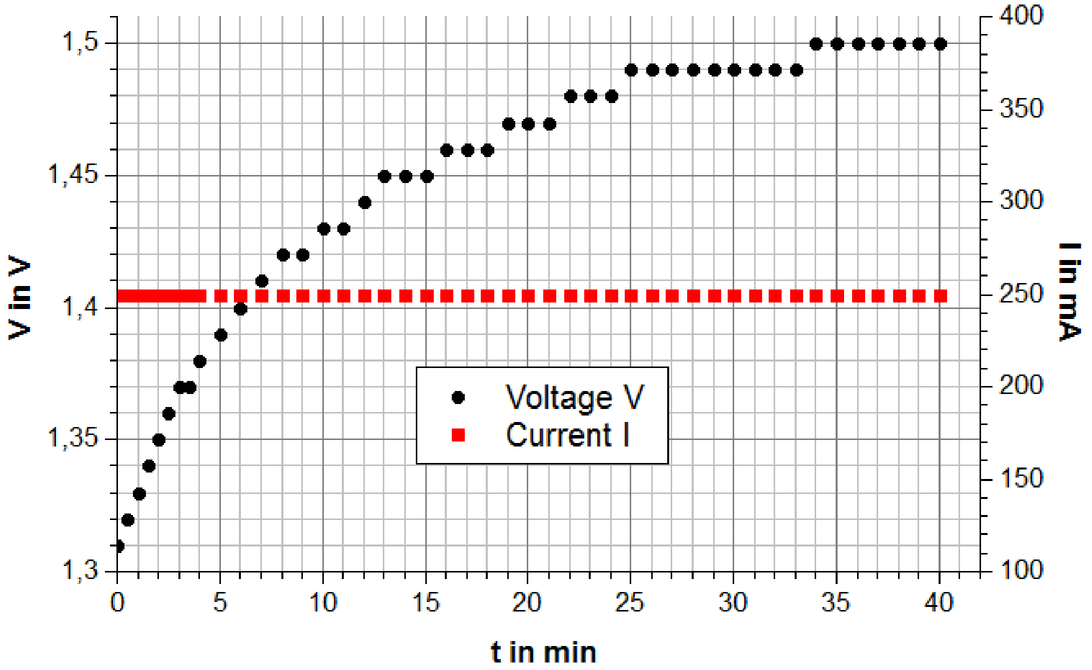
$V_0(1)$ = 1.22V

t in min	0	0.5	1	1.5	2	2.5	3	3.5	4	5	6	7	8
V in V	1.31	1.32	1.33	1.34	1.35	1.36	1.37	1.37	1.38	1.39	1.40	1.41	1.42
I in mA	250	250	250	250	250	250	250	250	250	250	250	250	250

t in min	9	10	11	12	13	14	15	16	17	18	19	20
V in V	1.42	1.43	1.43	1.44	1.45	1.45	1.45	1.46	1.46	1.46	1.47	1.47
I in mA	250	250	250	250	250	250	250	250	250	250	250	250

t in min	21	22	23	24	25	26	27	28	29	30	35	40
V in V	1.47	1.48	1.48	1.48	1.49	1.49	1.49	1.49	1.49	1.49	1.50	1.50
I in mA	250	250	250	250	250	250	250	250	250	250	250	250

Diagram



Evaluation

2.

The voltage is first strongly then more slowly increasing to a value of 1.5V.

Subsequently the charger switches off the charging process. The current remains constant during the charging process, because the charger uses the CC-mode (constant current) when charging the NiMH battery.

3.

Memory-Effect: This effect occurs when batteries are not fully discharged and then recharged. The battery "remembers" partial discharge and thus can no longer provide its full nominal capacity. The memory effect occurs particularly with NiCd batteries and is caused by crystal formation on the cadmium cathode. The effect can be partly reversed by deep-discharge or the so-called "*cycling*"

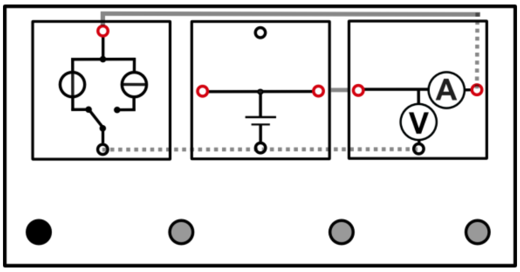
Lazy-Effect: A similar effect like Memory-Effect, the result instead is not a sudden loss of capacity, but a slow voltage drop. In contrast to the memory effect the battery is not damaged and the consequences can be completely eliminated by *cycling*.

5.2 The charging process of the NiZn battery

Task

Record the charge characteristics of a NiZn battery module.

Setup



Equipment required

- base plate
- 1 ChargerModule
- 1 NiZn battery module
- 1 AV-Module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Use the ChargerModule in NiZn-mode. For handling instructions of the ChargerModule see page 5. Do not switch on the ChargerModule yet.
2. Measure the open-circuit voltage V_0 of the battery module and note your value.

   Advice: The battery module should have a charge state of maximum 20% (this corresponds to an open-circuit voltage of 1.4V). If the charge state is over 20% you can discharge the battery module with the resistances or the electric car.

3. Switch on the ChargerModule and measure the voltage V_{Load} and current I_{Load} in intervals of 10s and note your values in the table. Use the AV-module in current-voltage-mode.

Evaluation

1. Enter your values in the diagram.
2. Describe and give reasons for the behavior of voltage and current during the charging process.
3. Determine the time after which the transition from cc-mode (constant current) to cv-mode (constant voltage) occurs.
4. Why does the voltage in cv-mode further increase slightly (despite an applied constant voltage)?

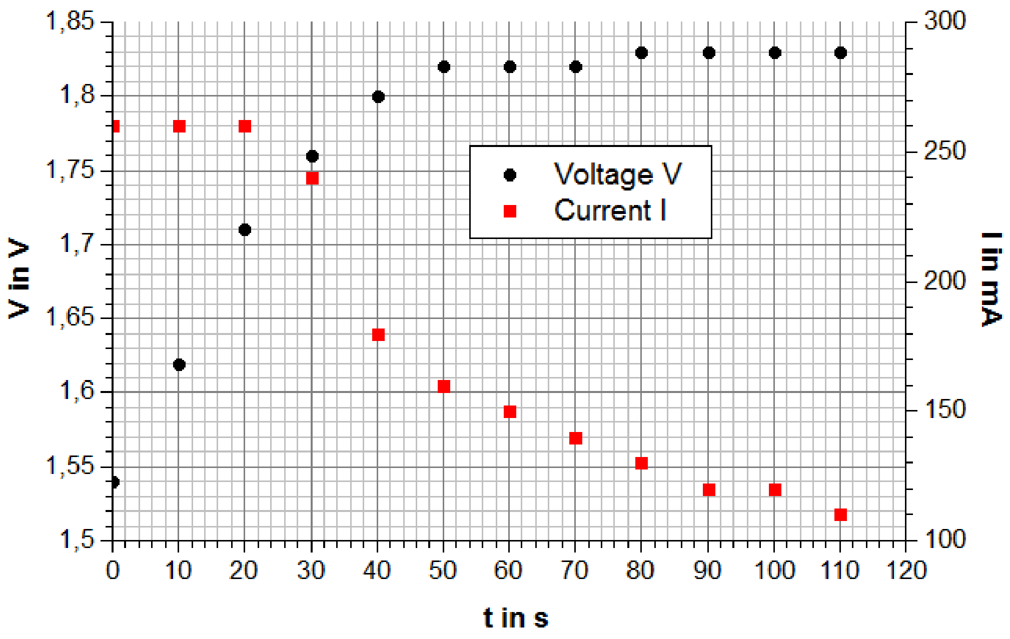
Measurements

$V_0(1)$ = 1.47V

t in s	0	10	20	30	40	50	60	70	80	90	100	110	120
V in V	1.54	1.62	1.71	1.76	1.80	1.82	1.82	1.82	1.83	1.83	1.83	1.83	1.83
I in mA	260	260	260	240	180	160	150	140	130	120	120	120	110

5.2 The charging process of the NiZn battery

Diagram



Evaluation

2.

When loading the NiZn batteries, a cc-cv-method is applied (cc=constant current, cv=constant voltage). The charging process starts with the cc-method in which the current remains constant. In this region, the voltage increases to about 1.8V. If the threshold is reached, there is the change in cv-mode. In cv-mode, the voltage remains nearly constant and the current strength decreases until the termination of the charge program

3. t_c=30s

4.

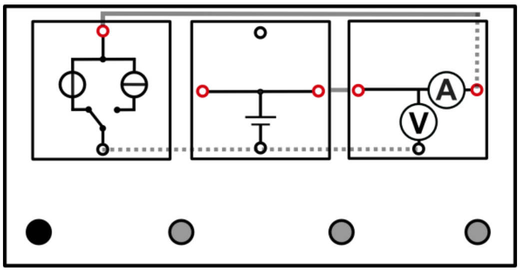
When charging in cv-mode the charger delivers a constant voltage. A part of this voltage thereby is applied at the internal resistance of the PTC fuse of the battery module. When the current decreases (which is a characteristic feature of the cv-charge process) the voltage at the internal resistance drops as well. Thus, the voltage which is actually applied to the module increases still slightly (since the total voltage remains constant).

5.3 The charging process of the LiFePo battery

Task

Record the charge characteristics of a LiFePo battery module.

Setup



Equipment required

- base plate
- 1 ChargerModule
- 1 LiFePo battery module
- 1 AV-Module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Use the ChargerModule in LiFePo-mode. For handling instructions of the ChargerModule see page 5. Do not switch on the ChargerModule yet.
2. Measure the open-circuit voltage V_0 of the battery module and note your value.

   Advice: The battery module should have a charge state of maximum 50% (this corresponds to an open-circuit voltage of 3.3). If the charge state is over 50% you can discharge the battery module with the resistances or the electric car.

3. Switch on the ChargerModule and measure the voltage V_{Load} and current I_{Load} in intervals of 1min and note your values in the table. Use the AV-module in current-voltage-mode.

Evaluation

1. Enter your values in the diagram.
2. Describe and give reasons for the behavior of voltage and current during the charging process.
3. Determine the time after which the transition from cc-mode (constant current) to cv-mode (constant voltage) occurs.
4. Describe the influence of the depth of discharge (DOD) on the lifetime of LiFePo batteries.

5.3 The charging process of the LiFePo battery

Measurements

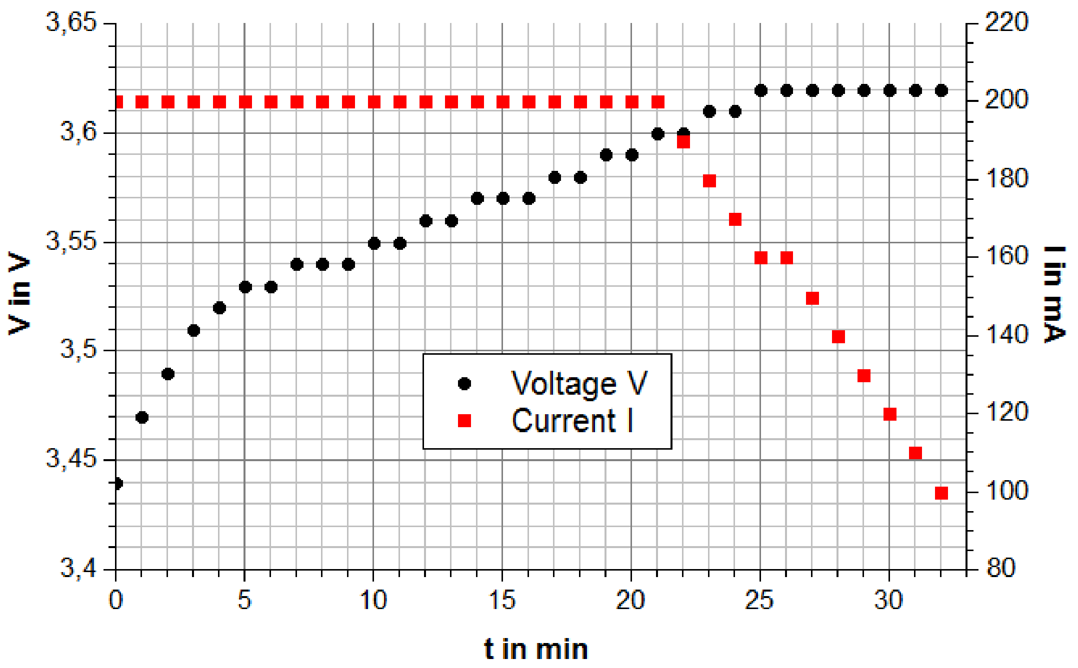
$V_0(1)$ = 3.32V

t in min	0	1	2	3	4	5	6	7	8	9	10	11
V in V	3.44	3.47	3.49	3.51	3.52	3.53	3.53	3.54	3.54	3.54	3.55	3.55
I in mA	200	200	200	200	200	200	200	200	200	200	200	200

t in min	12	13	14	15	16	17	18	19	20	21	22	23
V in V	3.56	3.56	3.57	3.57	3.57	3.58	3.58	3.59	3.59	3.6	3.6	3.61
I in mA	200	200	200	200	200	200	200	200	200	200	190	180

t in min	24	25	26	27	28	29	30	31	32
V in V	3.61	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
I in mA	170	160	160	150	140	130	120	110	100

Diagram



Evaluation

2.

When loading the LiFePo batteries, a cc-cv-method is applied (cc=constant current, cv=constant voltage). The charging process starts with the cc-method in which the current remains constant. In this region, the voltage increases to about 3.6V. If the threshold is reached, there is the change in cv-mode. In cv-mode, the voltage remains nearly constant and the current strength decreases until the termination of the charge program.

3. t_c=22min

4.

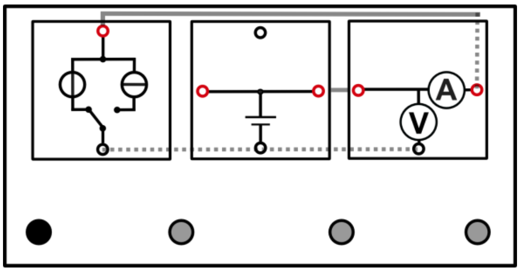
Above all, the regularly used depth of discharge affects the lifetime of LiFePo batteries. Here, the excessive unloading or storage on the lower voltage limit reduces the lifespan significantly as it comes in this case to irreversible processes within the cell. The observance of low depths of discharge is generally guaranteed by battery management systems.

5.4 The charging process of the lead battery

Task

Record the charge characteristics of a lead battery module.

Setup



Equipment required

- base plate
- 1 ChargerModule
- 1 lead battery module
- 1 AV-Module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Use the ChargerModule in lead-mode. For handling instructions of the ChargerModule see page 5. Do not switch on the ChargerModule yet.
2. Measure the open-circuit voltage V_0 of the battery module and note your value.

   Advice: The battery module should have a charge state of maximum 50% (this corresponds to an open-circuit voltage of 2.03). If the charge state is over 50% you can discharge the battery module with the resistances or the electric car.

3. Switch on the ChargerModule and measure the voltage V_{Load} and current I_{Load} in intervals of 1min and note your values in the table. Use the AV-module in current-voltage-mode.

Evaluation

1. Enter your values in the diagram.
2. Describe and give reasons for the behavior of voltage and current during the charging process.
3. Determine the time after which the transition from cc-mode (constant current) to cv-mode (constant voltage) occurs.

5.4 The charging process of the lead battery

Measurements

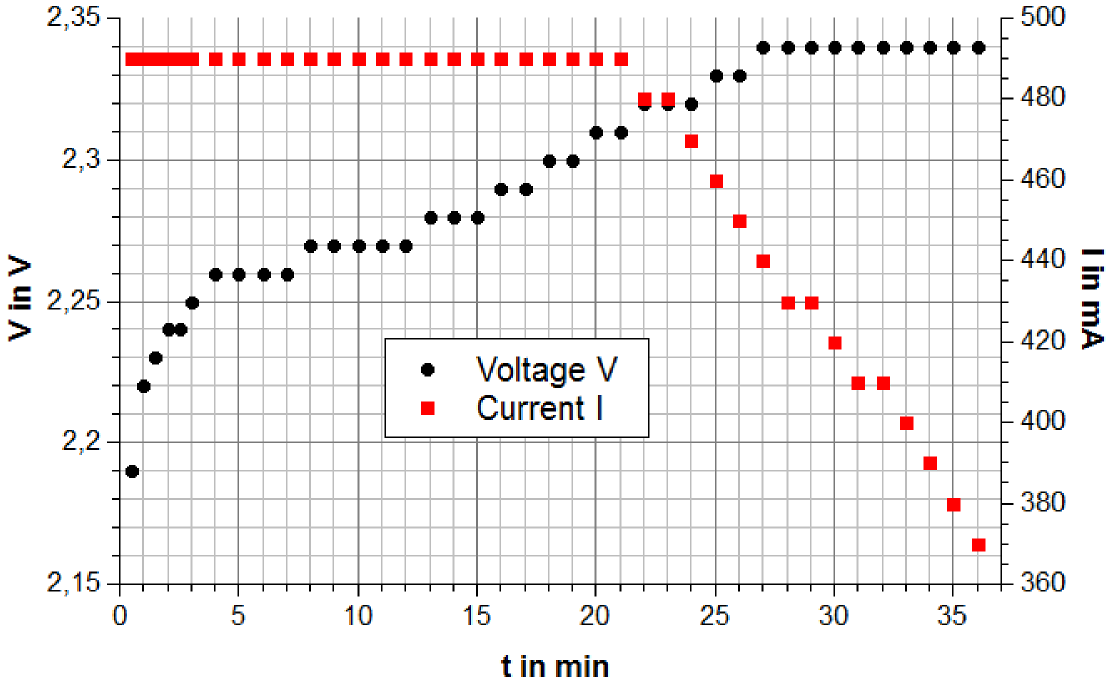
$V_0(1)$ = 1.99V

t in min	0.5	1	1.5	2	2.5	3	4	5	6	7	8	9	10
V in V	2.19	2.22	2.23	2.24	2.24	2.25	2.26	2.26	2.26	2.26	2.27	2.27	2.27
I in mA	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49

t in min	11	12	13	14	15	16	17	18	19	20	21	22	23
V in V	2.27	2.27	2.28	2.28	2.28	2.29	2.29	2.30	2.30	2.31	2.31	2.32	2.32
I in mA	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.48	0.48

t in min	24	25	26	27	28	29	30	31	32	33	34	35	36
V in V	2.32	2.33	2.33	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34	2.34
I in mA	0.47	460	450	440	430	430	420	410	410	400	390	380	370

Diagram



5.4 The charging process of the lead battery

Evaluation

2.

When loading the lead batteries, a cc-cv-method is applied (cc=constant current, cv=constant voltage). The charging process starts with the cc-method in which the current remains constant. In this region, the voltage increases to about 2.35V. If the threshold is reached, there is the change in cv-mode. In cv-mode, the voltage remains nearly constant and the current strength decreases until the termination of the charge program.

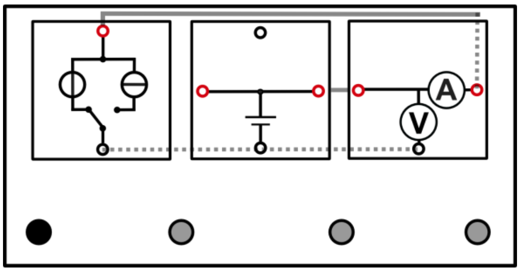
3. t_c=22min

5.5 The charging process of the lithium-polymer battery

Task

Record the charge characteristics of a lithium-polymer battery module.

Setup



Equipment required

- base plate
- 1 ChargerModule
- 1 lithium-polymer battery module
- 1 AV-Module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Use the ChargerModule in lithium-polymer-mode. For handling instructions of the ChargerModule see page 5. Do not switch on the ChargerModule yet.
2. Measure the open-circuit voltage V_0 of the battery module and note your value.

   Advice: The battery module should have a charge state of maximum 75% (this corresponds to an open-circuit voltage of 3.9). If the charge state is over 75% you can discharge the battery module with the resistances or the electric car.

3. Switch on the ChargerModule and measure the voltage V_{Load} and current I_{Load} in intervals of 1min and note your values in the table. Use the AV-module in current-voltage-mode.

Evaluation

1. Enter your values in the diagram.
2. Describe and give reasons for the behavior of voltage and current during the charging process.
3. Determine the time after which the transition from cc-mode (constant current) to cv-mode (constant voltage) occurs.
4. Why does the voltage in cv-mode further increase slightly (despite an applied constant voltage)?
5. Why it is dangerous to apply a purely cc-charge method for Lithium-based batteries?

5.5 The charging process of the lithium-polymer battery

Measurements

$V_0(1)$ = 3.80V

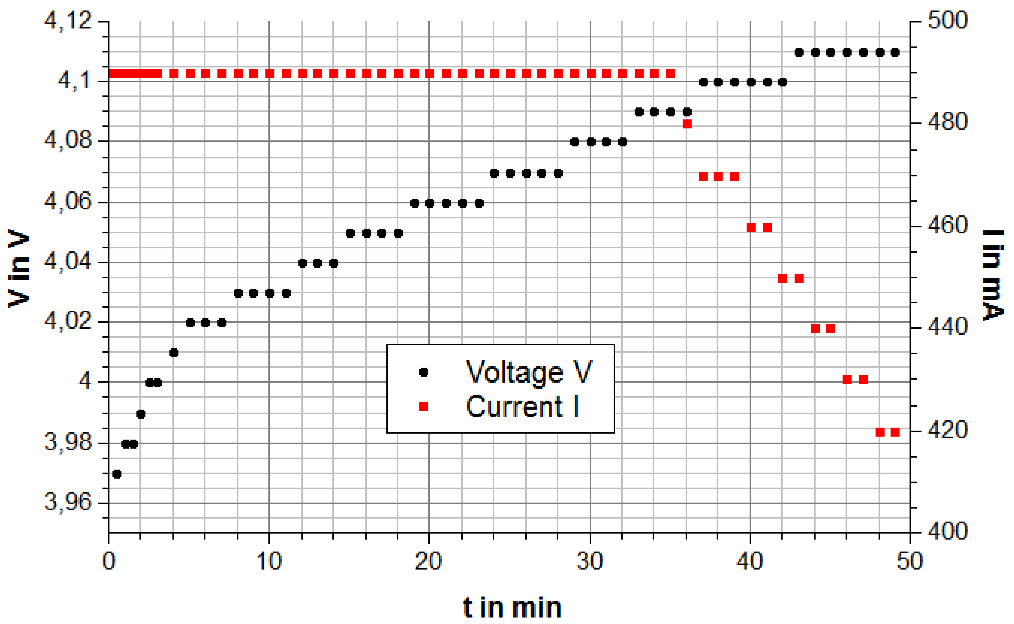
t in min	0	0.5	1	1.5	2	2.5	3	4	5	6	7	8	9	10
V in V	3.95	3.97	3.98	3.98	3.99	4.00	4.00	4.01	4.02	4.02	4.02	4.03	4.03	4.03
I in mA	490	490	490	490	490	490	490	490	490	490	490	490	490	490

t in min	11	12	13	14	15	16	17	18	19	20	21	22	23	24
V in V	4.03	4.04	4.04	4.04	4.05	4.05	4.05	4.05	4.06	4.06	4.06	4.06	4.06	4.07
I in mA	490	490	490	490	490	490	490	490	490	490	490	490	490	490

t in min	25	26	27	28	29	30	31	32	33	34	35	36	37	38
V in V	4.07	4.07	4.07	4.07	4.08	4.08	4.08	4.08	4.09	4.09	4.09	4.09	4.10	4.10
I in mA	490	490	490	490	490	490	490	490	490	490	490	480	470	470

t in min	39	40	41	42	43	44	45	46	47	48	49	50	55	60
V in V	4.10	4.10	4.10	4.10	4.11	4.11	4.11	4.11	4.11	4.11	4.11	4.11	4.12	4.12
I in mA	470	460	460	450	450	440	440	430	430	420	420	410	390	370

Diagram



5.5 The charging process of the lithium-polymer battery

Evaluation

2.

When loading the LiPo batteries, a cc-cv-method is applied (cc=constant current, cv=constant voltage). The charging process starts with the cc-method in which the current remains constant. In this region, the voltage increases to about 4.1V. If the threshold is reached, there is the change in cv-mode. In cv-mode, the voltage remains nearly constant and the current strength decreases until the termination of the charge program

3. t_c=35min

4.

When charging in cv-mode the charger delivers a constant voltage. A part of this voltage thereby is applied at the internal resistance of the PTC fuse of the battery module. When the current decreases (which is a characteristic feature of the cv-charge process) the voltage at the internal resistance drops as well. Thus, the voltage which is actually applied to the module increases still slightly (since the total voltage remains constant).

4.

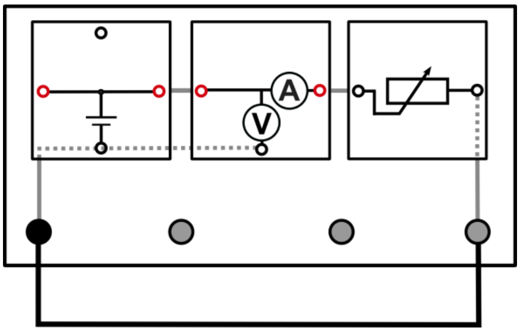
The risk of charging in cc-mode consists principally in the fact that the battery is overcharged when the charging process is not completed in time. For lithium-based batteries, this is particularly critical since they react very sensitive to overload. Even small overloads could cause an increase in pressure within the cell what with permanent overload can even lead to burst and burning of the cell.

5.6 The discharging process of a battery module

Task

Record the discharging curve of a battery module.

Setup



Equipment required

- base plate
- 1 NiMH battery module, single
- 1 AV-Modul
- 1 potentiometer module
- cables

Execution

1. Set up the experiment according to the circuit diagram. Do not plug in the potentiometer module yet to avoid the start of the experiment without recording data.
2. Measure the open-circuit voltage $V_0(1)$ of the battery module and note your value.
3. Adjust the resistance of the potentiometer so that a discharge current of 250mA is flowing. The AV-module on the base plate is operated in current-voltage-mode.
4. Measure 10min the voltage V and current I in intervals of 1min and note your values in the table. Adjust the potentiometer if necessary to keep the discharge current constant. Remove after ten minutes the cable from the base unit.
5. Measure 5min after termination of the experiment again the open-circuit voltage $V_0(2)$.

Advice: Before the experiment the battery module should have a charge state of minimum 75% (this corresponds to an open-circuit voltage of 1.26V)

Measurements

V_0 (1) = 1.29V V_0 (2) = 1.19V

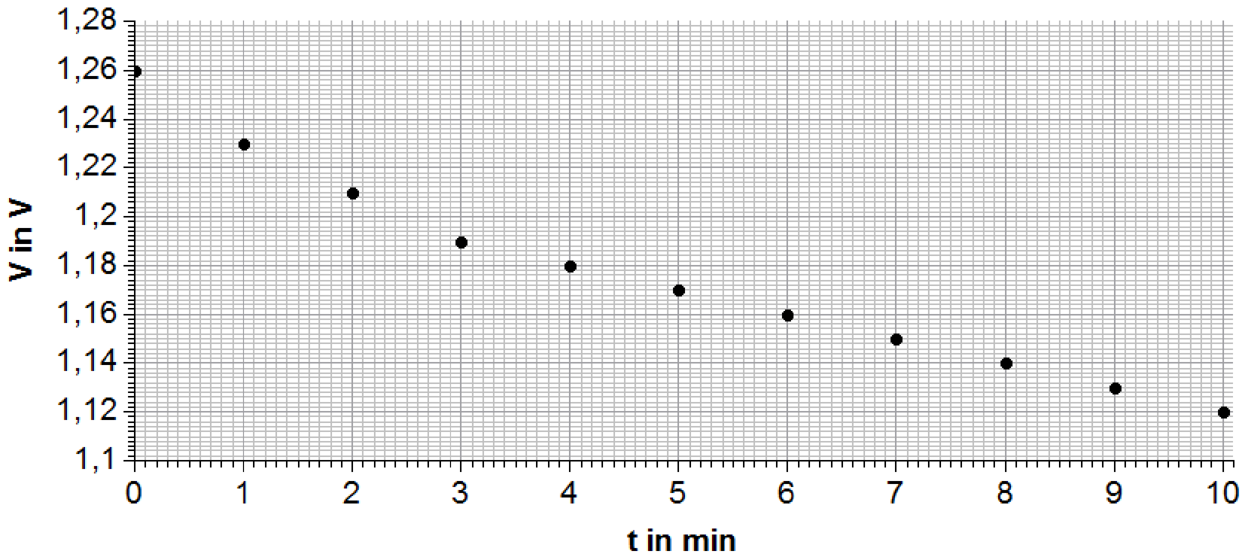
t in min	0	1	2	3	4	5	6	7	8	9	10
V in V	1.26	1.23	1.21	1.19	1.18	1.17	1.16	1.15	1.14	1.13	1.12

Evaluation

1. Enter your values in the diagram.
2. Calculate the capacity of the battery module before and after the experiment from the open-circuit voltage. You find instructions in experiment “Nominal voltage and capacity of voltage sources”.
3. Name reasons for the deep-discharge of battery modules. Describe possibilities to protect the modules from this process.

5.6 The discharging process of a battery module

Diagram



Evaluation

2.

1) OC-voltage before experiment: $V_0(1)$=1.29V (≡ charge state 83%)

Capacity before experiment:

$$\frac{x}{600mAh} = \frac{83}{100} \rightarrow x = \underline{\underline{498mAh}}$$

2) OC-voltage after experiment: $V_0(2)$=1.19V (≡ charge state 54%)

Capacity after experiment:

$$\frac{x}{600mAh} = \frac{54}{100} \rightarrow x = \underline{\underline{324mAh}}$$

3.

There are many reasons for deep-discharge possible. Thus, for example, the aging or incorrect charging of batteries lead to deep discharge. Even a defective or not suitable charger is dangerous for the battery. When using a consumer the passive current drain or the untimely disconnection of the load can cause a deep-discharge.

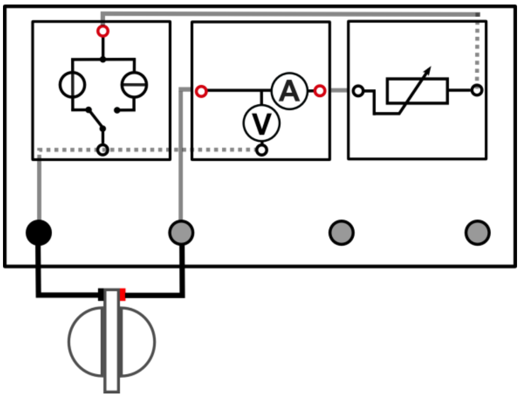
To prevent the module from deep-discharge you can use a so called deep-discharge protection. This disconnects the consumer, when a specified charge level falls below.

6.1 Hydrogen production in the reversible hydrogen fuel cell

Task

Investigate the hydrogen production in a reversible hydrogen fuel cell.

Setup



Equipment required

- base plate
- 1 reversible hydrogen fuel cell
- 1 ChargerModule
- 1 AV-Module
- 1 Potentiometer module
- cables

Procedure

1. Fill the reversible hydrogen fuel cell with distillated water. You find handling instructions on page 11.
2. Set up the experiment according to the circuit diagram. Pay attention to the polarity of the connections.
3. The Charger module is plugged into the base unit rotated by 90 ° (see sketch). Use the ChargerModule in Electrolyzer-mode. For handling instructions see page 5.
4. Adjust the resistance of the potentiometer to 2Ω and measure voltage V and current I at the fuel cell. The AV-module on the base plate is operated in current-voltage-mode.
5. Repeat the experiment for different resistances resistances at the potentiometer (see table) and measure each the time which is required for the production of 3 ml of hydrogen (H_2).

Advice: Make sure that the circuit is open before the start of each measurement (for ex. by removing a cable) so that the experiment does not start without recording data.

Evaluation

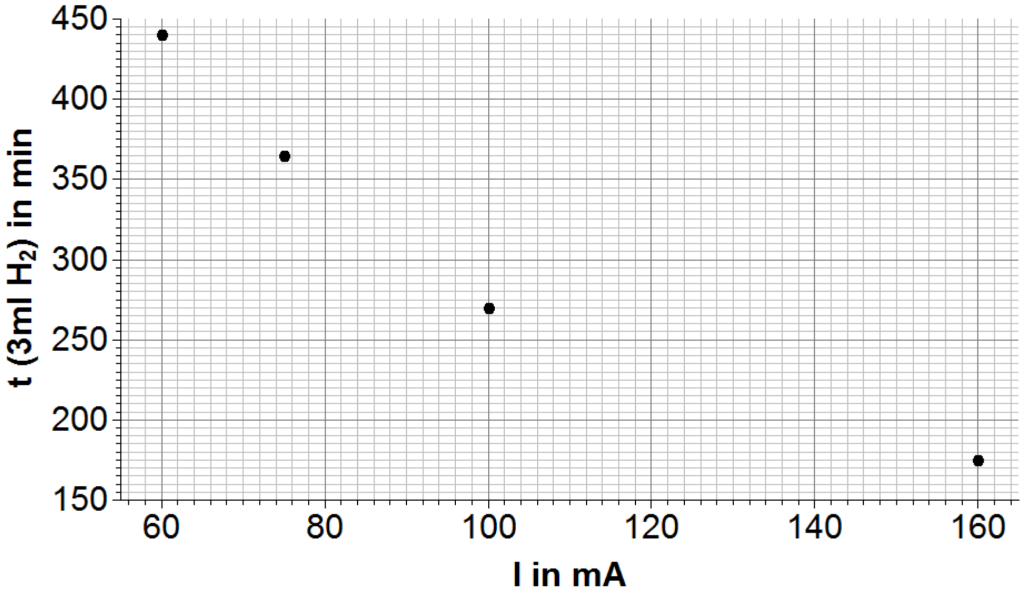
1. 1. Enter your values in the diagram.
2. How does the oxygen production rate cohere with the current of a fuel cell?
3. Explain the behavior of voltage and current in dependence from the resistance.

Data

R in Ω	2	4	6	8
V in V	1.58	1.56	1.55	1.54
I in mA	160	100	75	60
t (3ml H_2) in min	175	270	365	440

6.1 Hydrogen production in the reversible hydrogen fuel cell

Diagram



Evaluation

2.

• voltage remains nearly constant, current and time vary

• the smaller the resistance, the higher the current, with higher currents faster production of hydrogen

3.

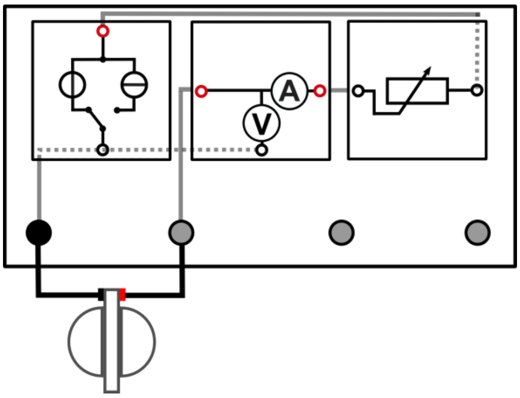
The behavior coheres with the characteristics of the electrolyzer (in the production of hydrogen, the reversible fuel cell is operated as an electrolyzer). You find details regarding the characteristics in experiment “Characteristic curve of the electrolyzer”.

6.2 Characteristic curve of the electrolyzer

Task

Use the electrolyzer to produce hydrogen and record the corresponding I-V-curve.

Setup



Equipment needed

- base plate
- 1 ChargerModule
- 1 AV-Module
- 1 reversible fuel cell
- 1 potentiometer module
- cables

Execution

1. Fill the reversible hydrogen fuel cell with distillated water. You find handling instructions on page 11.
2. Set up the experiment according to the circuit diagram. Pay attention to the polarity of the connections.
3. The Charger module is plugged into the base unit rotated by 90 ° (see sketch). Use the ChargerModule in constant voltage-mode at 3V. For handling instructions see page 5.
4. Adjust the potentiometer to the maximum resistance of 110Ω and measure the voltage V and current I at the reversible fuel cell. Use the AV-module in current-voltage-mode. Note your values in the table.
5. Decrease the resistance at the potentiometer module in several steps and measure each the voltage V and current I. Note your values in the table.

   Advice: The current circuit should be open at the beginning (for example by removing a cable) to avoid the start of the experiment without recording data.

Measurements

V in V	1.49	1.50	1.51	1.52	1.53	1.54	1.55	1.56
I in mA	13	18	22	33	45	60	76	100

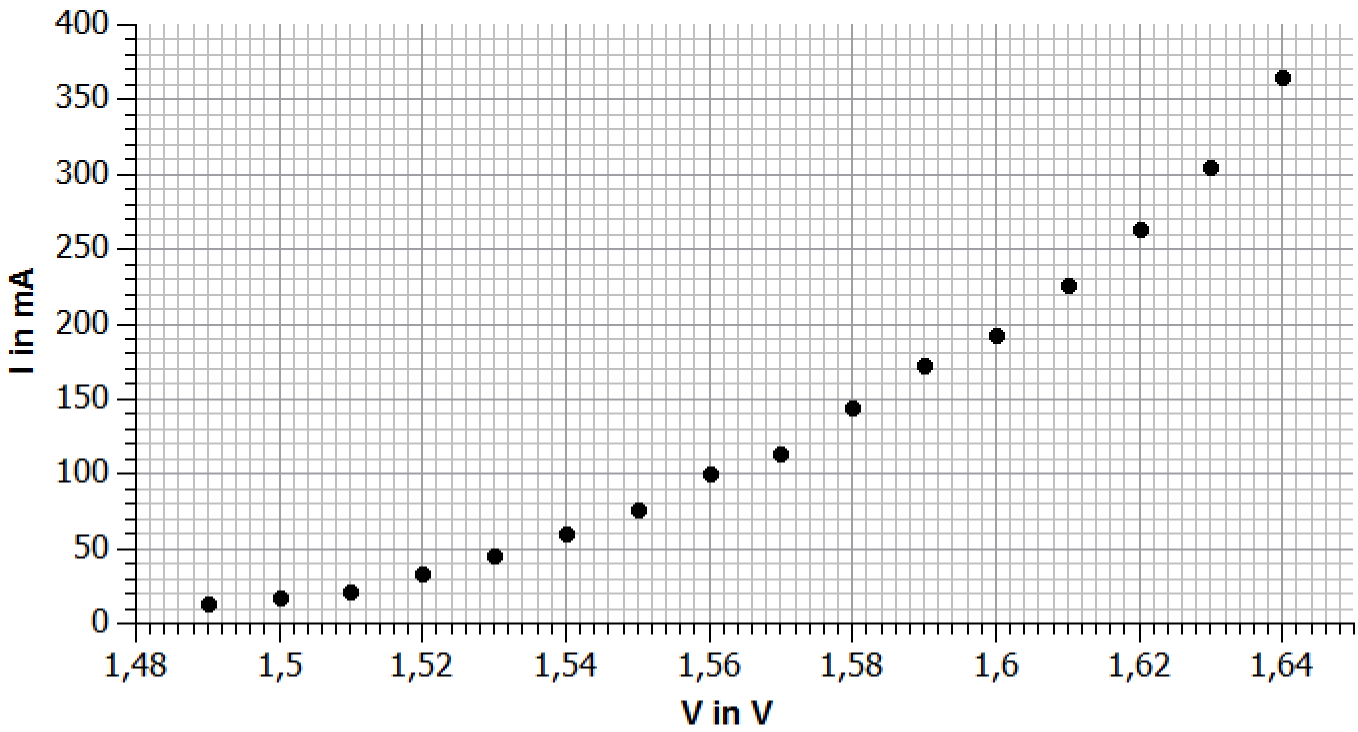
V in V	1.57	1.58	1.59	1.60	1.61	1.62	1.63	1.64
I in mA	114	145	173	193	226	263	305	365

6.2 Characteristic curve of the electrolyzer

Evaluation

1. Enter your values in the diagram.
2. Describe and interpret the characteristic curve of the electrolyzer.

Diagram



Evaluation

2.

The curve shows that a certain threshold voltage is needed to measure a current, which produces the gases. The voltage of the galvanic cell amounts to 1.23V. This so called decomposition voltage is the minimum voltage at which water decomposes into hydrogen and oxygen. The measured minimum voltage, however, amounts to 1.44 V. The difference between the experimental and theoretical values is called overvoltage.

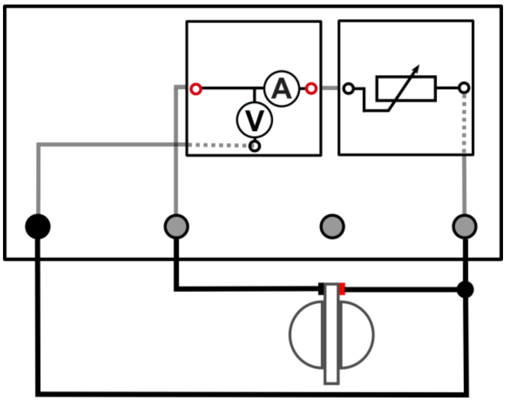
The overvoltage depends on the electrode material, the surface condition of the electrodes, type and concentration of the electrolyte as well as current density (current per area) and temperature. Overvoltages are low for reactions where metals are deposited, but particularly high for reactions where gases are created.

6.3 Hydrogen consumption of a fuel cell

Task

Determine the hydrogen consumption of the reversible fuel cell.

Setup



Equipment needed

- base plate
- 1 AV-Module
- 1 reversible fuel cell
- 1 potentiometer module
- cables

Execution

1. Before starting the experiment an amount of 8ml hydrogen has to be produced. You find handling instructions in experiment „Hydrogen production in the reversible hydrogen fuel cell".
2. Set up the experiment according to the circuit diagram. Use the AV-module in current-voltage-mode.
3. Adjust the potentiometer to a resistance of 4Ω and measure 5min voltage V, current I and the hydrogen consumption at the reversible fuel cell in intervals of 1min. Note your values in the table.
4. Refill the fuel cell with 12ml hydrogen and repeat the experiment with a potentiometer resistance of 2Ω.

Evaluation

1. Enter your values in the diagram.
2. Describe the behavior of voltage V, current I and hydrogen production in the course of the experiment.
3. Describe the influence of the loading resistance on the operation of the fuel cell.

Measurements

R=4Ω

t in min	1	2	3	4	5
V in V	0.72	0.72	0.72	0.72	0.72
I in mA	190	190	190	190	190
H_2 in ml	1	2	3	4	5

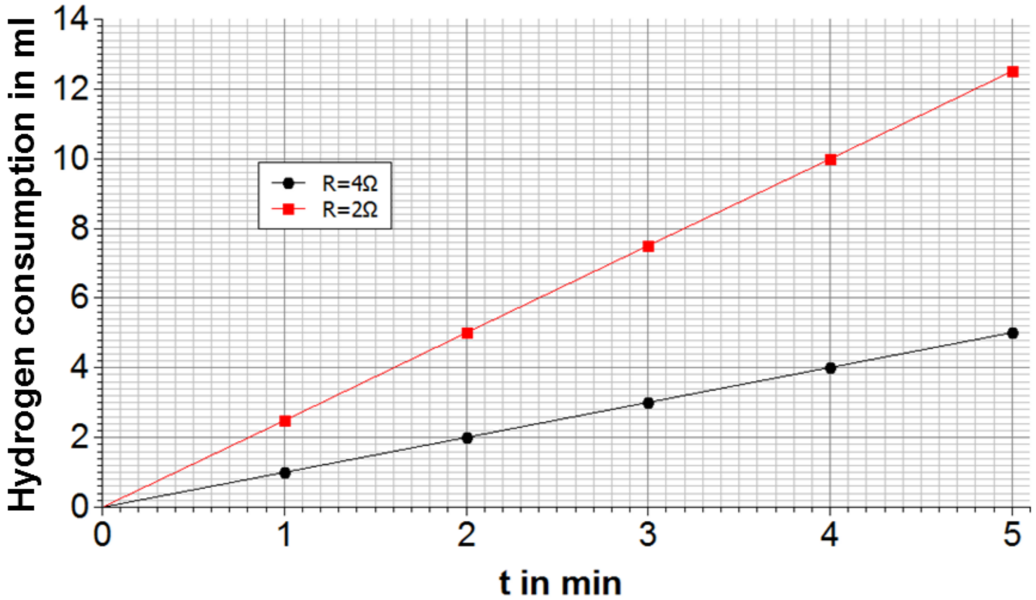
6.3 Hydrogen consumption of a fuel cell

Measurements

R=2.0Ω

t in min	1	2	3	4	5
V in V	0.74	0.74	0.74	0.74	0.74
I in mA	290	290	290	290	290
H_2 in ml	2.5	5	7.5	10	12.5

Diagram



Evaluation

1.

Voltage and current remain nearly constant. The hydrogen production is increasing with time, a linear correlation can be observed. The slope of the curve (hydrogen consumption in dependence of time) depends on the loading current.

3.

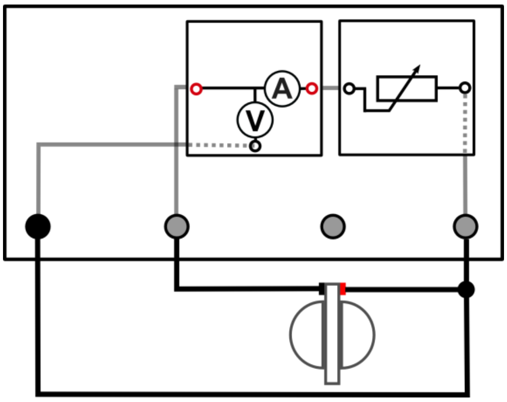
At smaller resistances higher loading currents are flowing and the hydrogen is consumed faster. In both cases a linear correlation can be observed.

6.4 Characteristic curve of the fuel cell

Task

Record the I-V-curve of a PEM fuel cell.

Setup



Equipment needed

- base plate
- 1 AV-Module
- 1 reversible fuel cell
- 1 potentiometer module
- cables

Preparation

First, you have to produce appr.10ml of hydrogen. For handling instructions see experiment „Hydrogen production in the reversible hydrogen fuel cell". Directly after H_2 production the hydrogen fuel cell will behave like a capacitor. For this reason you should decrease its voltage down to approximately 0.9 V before measurement by letting a current of roughly 500 mA flow for 20 seconds.

Execution

1. Set up the experiment according to the circuit diagram. Do not plug in the potentiometer yet.
2. Measure the open-circuit voltage of the fuel cell and note your value in the table.
3. Plug in the potentiometer and adjust it to the maximum resistance of 110Ω. Measure the voltage V and current I at the reversible fuel cell. Use the AV-module in current-voltage-mode. Note your values in the table.
4. Decrease the resistance at the potentiometer module in several steps and measure each the voltage V and current I. Note your values in the table.

Evaluation

1. Enter your values in the diagram.
2. Describe the course of the I-V-characteristic.
3. Which area of the curve should be used for the operation of a consumer? Justify your answer.
4. Explain the decrease of voltage at higher currents.

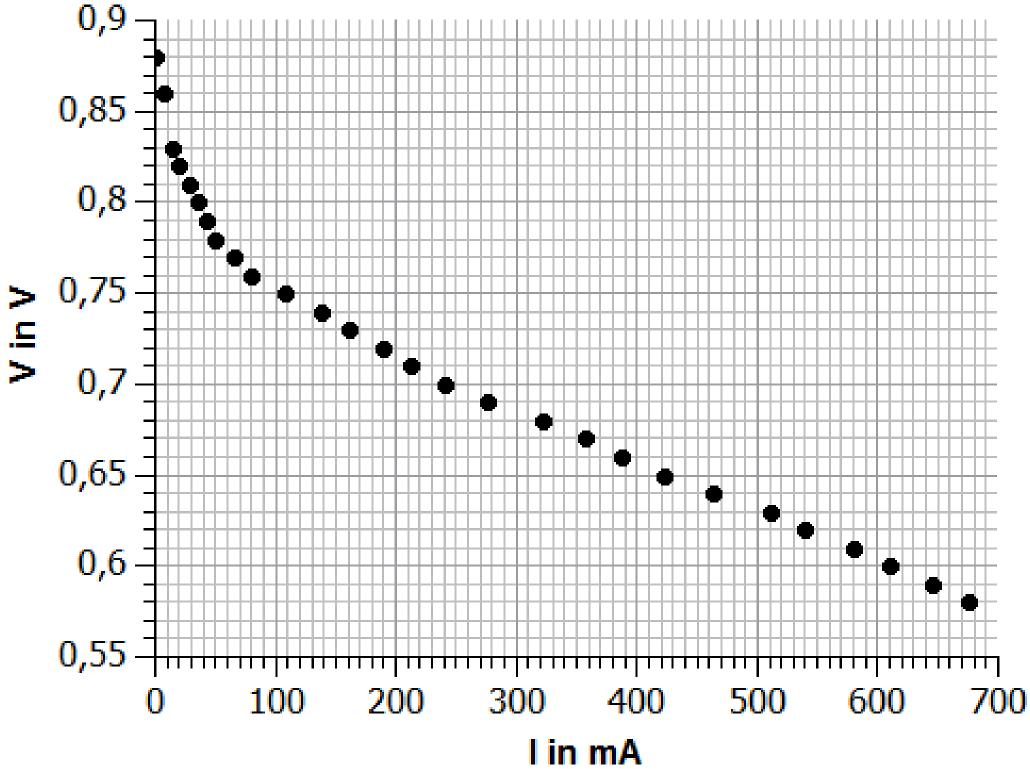
6.4 Characteristic curve of the fuel cell

Measurements

V in V	0.88	0.86	0.83	0.82	0.81	0.8	0.79	0.78	0.77	0.76	0.75	0.74	0.73	0.72
I in mA	0	7	15	20	28	35	43	50	65	80	107	137	160	189

V in V	0.71	0.70	0.69	0.68	0.67	0.66	0.65	0.64	0.63	0.62	0.61	0.60	0.59	0.58
I in mA	213	240	276	321	357	387	422	463	510	540	580	609	645	675

Diagram



Evaluation

2.

The first part of the I-V-curve strongly decreases. After that, the curve progresses more shallowly.

The highest possible voltage of this cell amounts to 0.9 V. The power of the fuel cell increases with current.

Here, the slope also becomes flatter with increasing current.

6.4 Characteristic curve of the fuel cell

Evaluation

3.

The first part of the I-V-curve strongly decreases. Meaning, the voltage decreases heavily at low currents. This marks a characteristic behavior of a PEM fuel cell.

With increasing current the slopes becomes shallower. Therefore, the working voltage of the fuel cell should be in this area.

4.

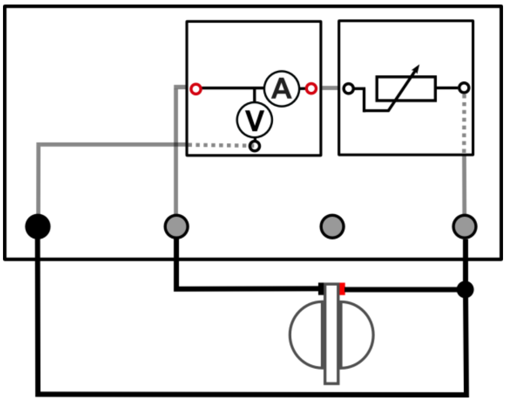
When the cell is idling, there is no measurable current. However, when a resistor is connected, the electron flow starts. For this, hydrogen molecules are split into protons and electrons, which happens at the anode. Fewer electrons are travelling through the circuit than protons through the membrane. Therefore, per unit of time more protons than electrons reach the cathode. Because of this, the electrode potentials are altered. The potential difference decreases and with this the total voltage of the cell does also.

6.5 The efficiency of the hydrogen fuel cell

Task

Determine the efficiency of the reversible hydrogen fuel cell.

Setup



Equipment required

- base plate
- 1 reversible hydrogen fuel cell
- 1 potentiometer module
- 1 AV-module
- cables

Preparation

First, you have to produce appr.5ml of hydrogen. For handling instructions see experiment „Hydrogen production in the reversible hydrogen fuel cell". Directly after H_2 production the hydrogen fuel cell will behave like a capacitor. For this reason you should decrease its voltage down to approximately 0.9 V before measurement by letting a current of roughly 500 mA flow for 20 seconds.

Procedure

1. Set up the experiment according to the circuit diagram.
2. Adjust the resistance of the potentiometer to 5Ω. Use the AV-Module in current-voltage-mode.
3. Measure the time it takes for the circuit to use up 2 ml of H_2 and record voltage V and current I at this point.

Data

V=0.73V I= 137.8mA t=2min

Evaluation

1. Calculate the electrical energy which was used up during the experiment. The electrical energy can be found using the following formula:

$$W_2 = V \cdot I \cdot t$$

2. For how long could the current flow with an entire filling of H_2 (12 ml)?

6.5 The efficiency of a hydrogen fuel cell

Evaluation

3. Determine the efficiency of the reversible hydrogen fuel cell. The efficiency of the reversible fuel cell is given by:

$$\eta = \frac{W_2}{W_1}$$

(The lower fuel value of 2ml of H_2 is W_1= 22Ws)

1.

$$W_2 = V \cdot I \cdot t = 0.73V \cdot 0.138A \cdot 2 \cdot 60s = 12.1Ws$$

2.

$$t = 2min \cdot 6 = 12min$$

3.

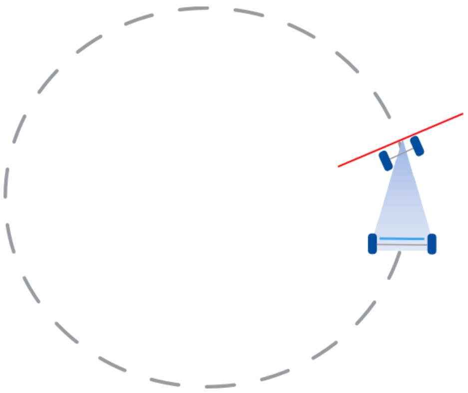
$$\eta = \frac{W_2}{W_1} = \frac{12.1Ws}{22Ws} = 55\%$$

7.1 Operation of the electric car with several battery modules

Task

Observe the driving behavior of the car with different battery modules and conclude the characteristics from it.

Setup



Equipment required

- Electric car with module plate
- 1 AV-Module
- lead battery module
- NiZn battery module
- NiMh battery module, single
- LiFePo battery module
- LiPo battery module
- capacitor module
- Stop watch

Preparation

For the experiment you need enough space (min. 2x2m). Tilt the front axle of the car to the left, so that the car drives a circular path. Mark the starting and the finishing line of the car on the circular path with adhesive tape or something like that. The battery modules should be fully loaded and the capacitor module should be loaded to 5V before starting the experiment.

Execution

Execute the instructions for every battery module:

1. Measure the open circuit voltage V_{OC} of the battery module and record your data in the table.
2. Plug the battery module onto the module plate and first connect only **one** cable.
3. Position the car at the starting line and connect the second cable shortly before putting down the car.
4. Measure the time that the car needs for 4 rounds and repeat the measurement several times without stopping the car. Record your data in the table.
5. Let the car drive for 5 minutes and note your observations.
6. Calculate the difference to the previous round to determine the time for 4 rounds.

Advice: Pay attention to the car. It should not hit something, because the axles could get damaged. Hold the car shortly before starting it, because it could tip otherwise.

Advice for the teacher: The car drives not safe on smoothy ground withe the LiPo module because the velocity is too high and the car could tip. If possible the experiment should be done on carpet floor.

7.1 Operation of the electric car with several battery modules

Evaluation

1. Compare the different battry modules and give reasons for the differences. Which properties of the respective module can you conclude from the differences?
2. Which parameters have influence on the measurement?
3. Which type of battery module would you classify as suitable for the use of an electric car?
4. Why should you load the capacitor to max. 5V to gain reasonable results?

Data

	4 rounds	8 rounds	12 rounds	16 rounds	20 rounds	Observation after 5min (resp.when the car stops)
Lead battery module V_0 = 2,05V						
time in s	13	26	39	52	65	constant velocity
time for 4 rounds	13	13	13	13	13	
NiZn battery module V_0 = 1,84V						
time in s	14	28	42	56	70	constant velocity
time for 4 rounds	14	14	14	14	14	
NiMH battery module V_0 = 1,38V						
time in s	18,6	38,6	58,9	79,6	100,6	light decrease of velocity, does not stop
time for 4 rounds	18,6	20	20,3	20,7	21	
LiFePo battery module V_0 = 3,23V						
time in s	8,6	17,3	26,1	34,8	43,7	decrease of velocity, does not stop
time for 4 rounds	8,6	8,7	8,8	8,7	8,9	
LiPo battery module V_0 = 3,83V						
time in s	0,9	0,8	0,72	0,70	0,66	constant velocity very fast
time for 4 rounds	8,2	8,1	8,2	8,3	8,2	
Capacitor module V_0 = 5V						
time in s	8,5	20,5	0	0	0	
time for 4 rounds	8,5	12	0	0	0	stops after 35s

7.1 Operation of the electric car with several battery modules

Evaluation

1.

- higher velocity → higher operation voltage
- LiPo with highest voltage V_{max} =4,2V and NiMH with lowest voltage V_{min}=1,35V
- capacitor discharges very fast → other modules have a higher capacity
- NiZn has also a lower capacity than other modules

2.

- surface conditions
- weight of the module (lead battery module is very heavy)
- air resistance
- car does not drive the same circular path every time

3.

- LiPo lasts very long and car drives very fast (high rated voltage)
- NiMH more slowly but continously

4.

When driving too fast (high voltage!) the car could tip and/or leave the circular path.

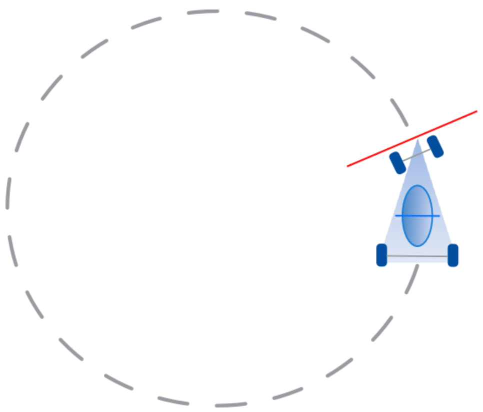
(overload of the capacitor)

7.2 Operation of the electric car with the reversible fuel cell

Task

Observe the driving behavior of the car with the fuel cell and conclude the characteristics from it.

Setup



Required devices

- 1 Electric car with module plate
- 1 reversible fuel cell with mount
- 1 Stop watch

Preparation

For the experiment you need enough space (min. 2x2m). Tilt the front axle of the car to the left, so that the car drives a circular path. Mark the starting and the finishing line of the car on the circular path with adhesive tape or something like that. Produce 12ml of H_2 with the fuel cell (see. exp.5.1).

Execution

1. Measure the open circuit voltage V_{OC} of the fuel cell after the production of 12ml H_2 and record your data in the table.
2. Plug the fuel cell module onto the car and first connect only **one** cable.
3. Position the car at the starting line and connect the second cable shortly before putting down the car.
4. Measure the time that the car needs for 4 rounds and repeat the measurement several times without stopping the car. Record your data in the table.
5. Let the car drive for 5 minutes and note your observations.
6. Calculate the difference to the previous round to determine the time for 4 rounds.

Advice: Pay attention to the car. It should not hit something, because the axles could get damaged. Hold the car shortly before starting it, because it could tip otherwise.

7.2 Operation of the electric car with the reversible fuel cell

Evaluation

1. Compare the operation of the electric car with the fuel cell to the operation with conventional accumulators like in the prior experiment.
2. Inform yourself about the application of fuel cells in the automotive industry. Which forms of storage of hydrogen are in use?

Data

	4 rounds	8 rounds	12 rounds	16 rounds	20 rounds	Observation after 5min (resp.when the car stops)
Fuel cell: V_0 = 1,4 V						
time in s	34	72	112	154	198	continuous decrease of speed stops after ca. 3:40 min
time for 4 rounds	34	38	40	42	44	

Evaluation

1.

- obviously much slower than with other accumulators. (lower operational voltage)

- lower storage capacity

- current is produced by reaction with hydrogen

2.

Used as hybrid drive in electric cars (for ex in combination with battery regeneration techniques).

compressed gaseous hydrogen storage, metal hydride hydrogen storage.

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