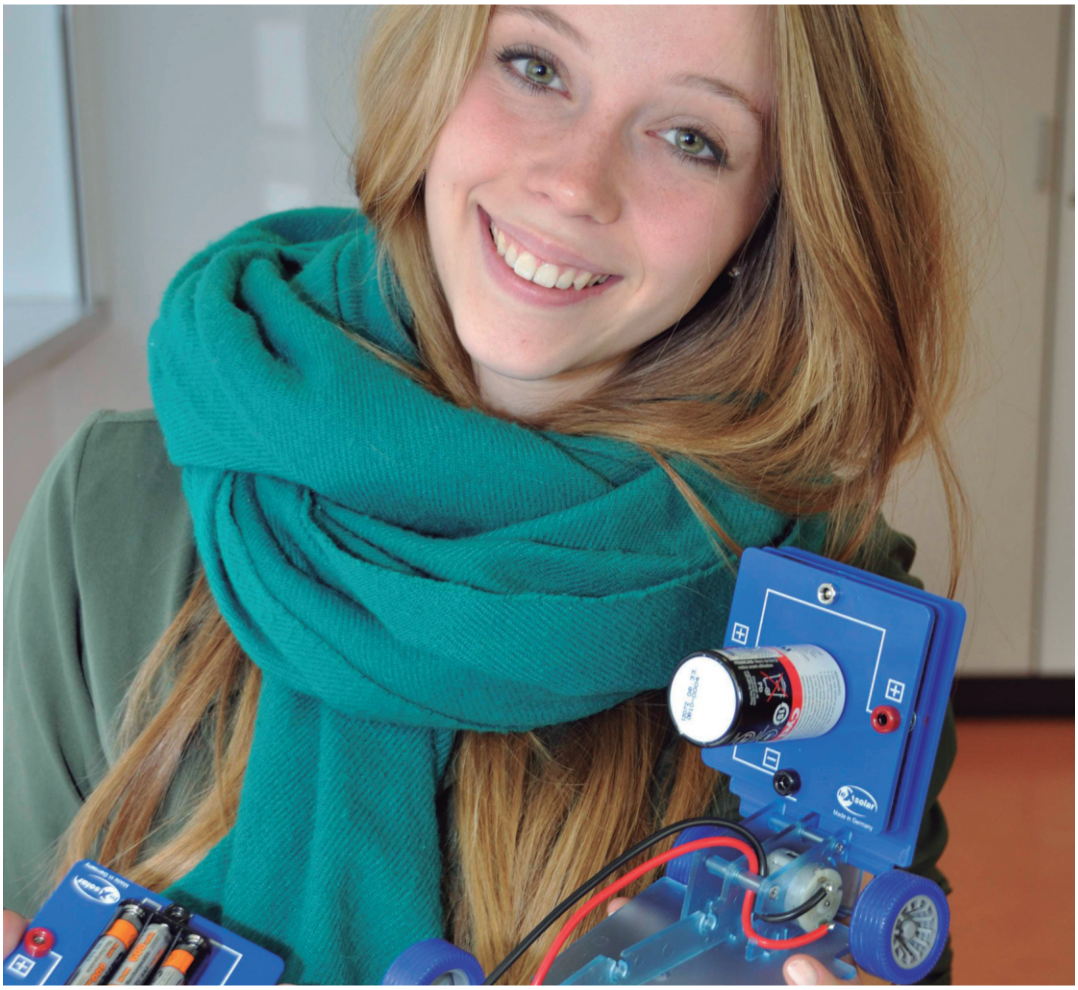
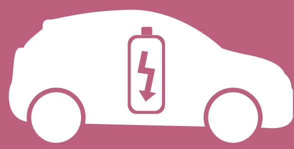
leXsolar-EMobility Ready-to-go





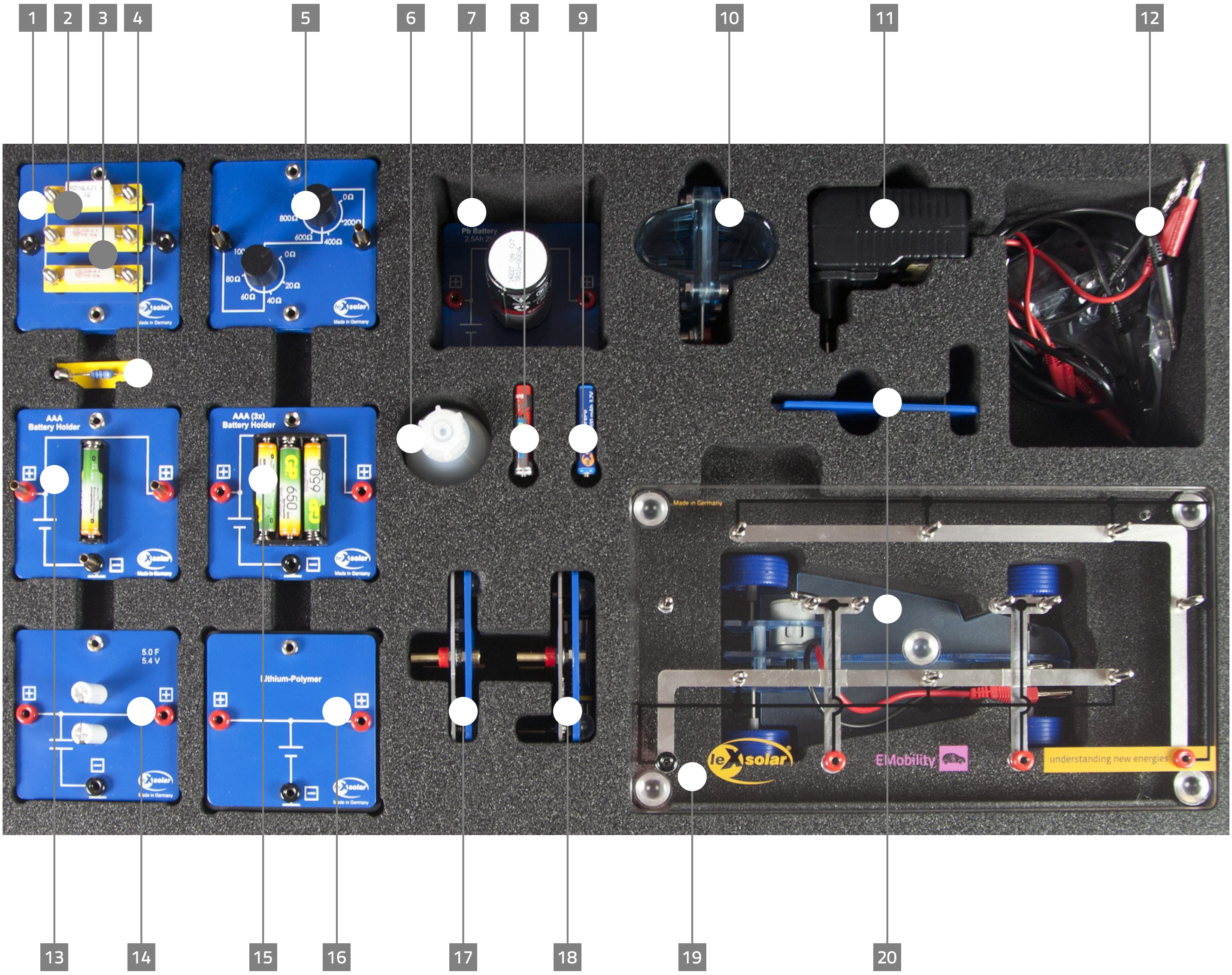
Instructions manual

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

Instructions manual

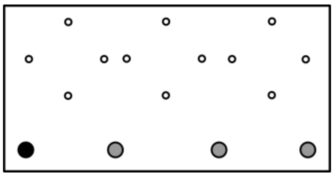
Content

I General Information

Components

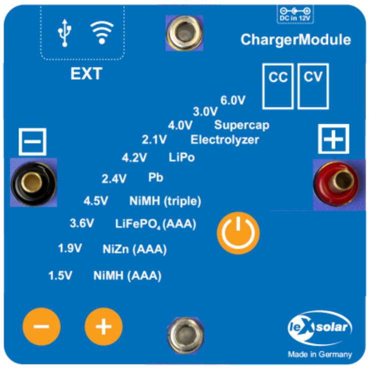
The following part contains information about the components of the experimental system. There is sketched a photograph and a small pictogram how the modules are displayed in the experimental setup. Furthermore you get information about the handling and the specifications of the components.

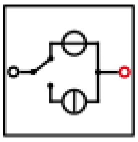
Base unit EMobility 1801-07



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

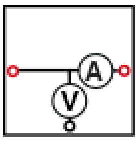
3V:

- Constant voltage of 3V

6V:

- Constant voltage of 6V

AV-Module 9100-03



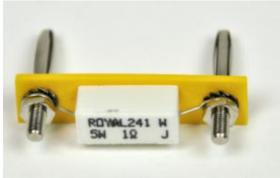
The AV-Module is a combined voltage and current meter. It holds 3 buttons, whose features are described in the display respectively. By pushing a random button the module will switch on. In the disabled state the display shows the leXsolar emblem. When the display does not show anything or the word „Bat“ 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.

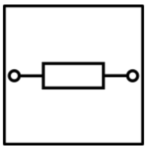
Specifications:

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

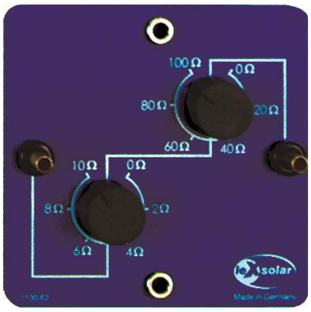


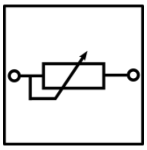


With the resistor plug module and the belonging resistor plug elements parallel connection and series connection of resistors are possible. For parallel connection use one resistor module (triple) with three slots. For series connection use two triple resistor modules. The following resistor plug elements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

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

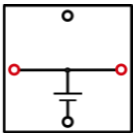
Potentiometer module 110Ohm Pro 1100-62





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

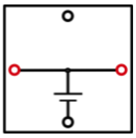


The capacitor module consists of 2 series-connected capacitors. Charging voltages for the capacitor should not exceed 5 V. It is possible to short-circuit the capacitor to discharge, because there are fuses to avoid damages.

Specifications:

Capacitance: 5 F
Maximum voltage: 5,4 V

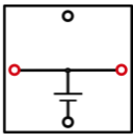
NiMH-battery module, single L2-04-021 with mount 1800-08



<u>Specifications:</u>

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

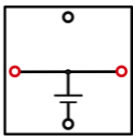
NiMH-battery module, triple 1118-09



<u>Specifications:</u>

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

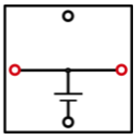
LiFePo-battery module 1801-06



<u>Specifications:</u>

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

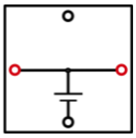
NiZn-battery module 1801-06



Specifications:

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

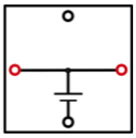
Lead-battery module 1800-13



Specifications:

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

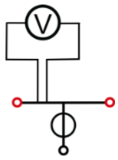
Lithium-Polymer-battery module 1800-07



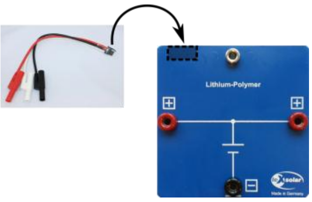
Specifications:

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**

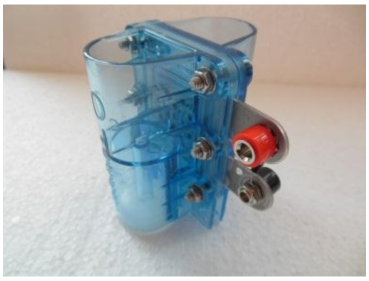


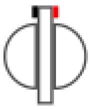
All battery modules are equipped with an additional connection for the four-point measurement. The adapter cable is connected with the black connector to this port:



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.

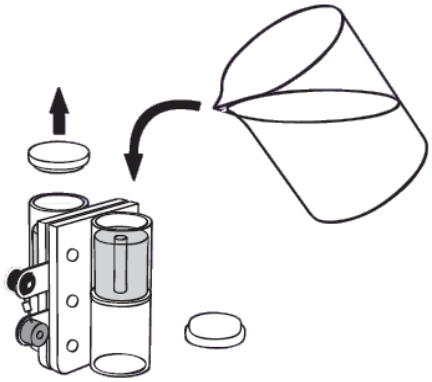
Reversible fuel cell (L2-06-067)





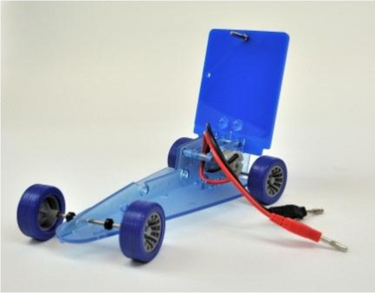
The reversible fuel cell consists of an electrolyzer and a fuel cell. To fill the reversible fuel cell you should proceed in the following way:

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



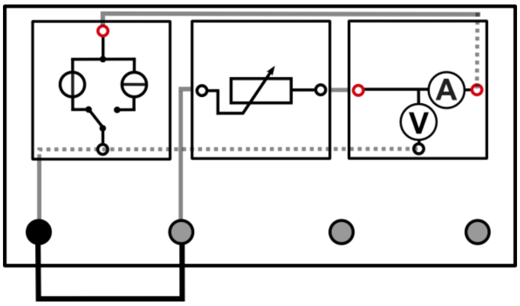
The electric model car can be used with the reversible fuel cell or the battery modules. The fuel cell can be plugged directly onto the car. The battery modules can be plugged with the adapter onto the car.
The car will move when both cables are connected with the voltage source. There will be a short 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)					
I (mA)					
V/I (Ω)					

Evaluation

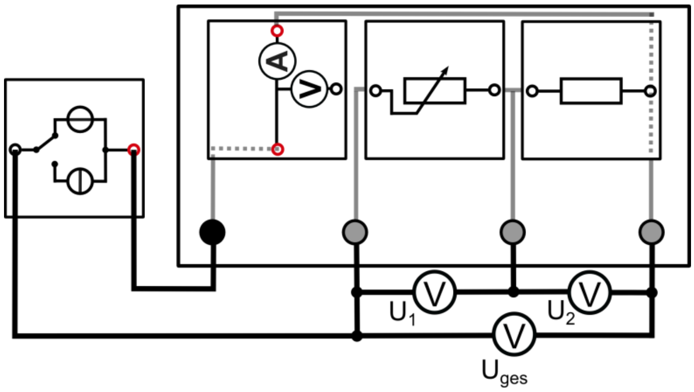
1. Calculate for each measuring point the ratio V/I and note your values in the table.
2. Which law reflects your findings? Illustrate these principles using data from the table.

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)					
V_2 (V)					
V_{tot} (V)					
I (mA)					
R_{ges}= V_{tot} /I (Ω)					

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		
R_{Pot} = 80Ω / R_S =100Ω		
R_{Pot} = 60Ω / R_S =100Ω		
R_{Pot} = 40Ω / R_S =100Ω		

3.

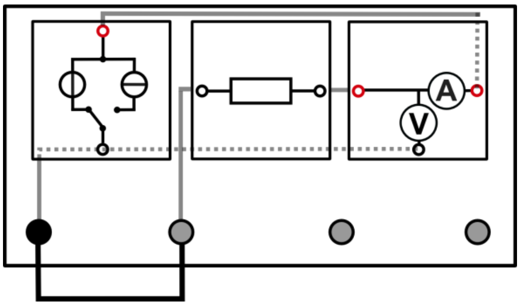
4.

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)				
I (mA)				
R_{ges}=V/I (Ω)				

Evaluation

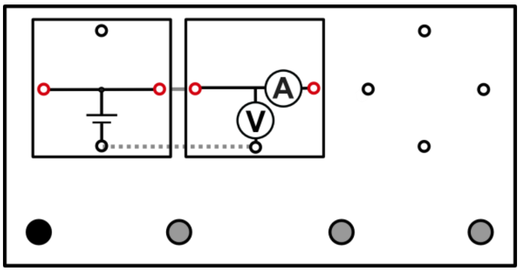
1. What is the influence of the resistance on the current I and the voltage V?
2. Formulate a law for the calculation of the total resistance in a parallel connection of resistances.

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		
NiZn		
LiFePo		
Pb		
LiPo		

2.1 Nominal voltage and capacity of voltage sources

Evaluation

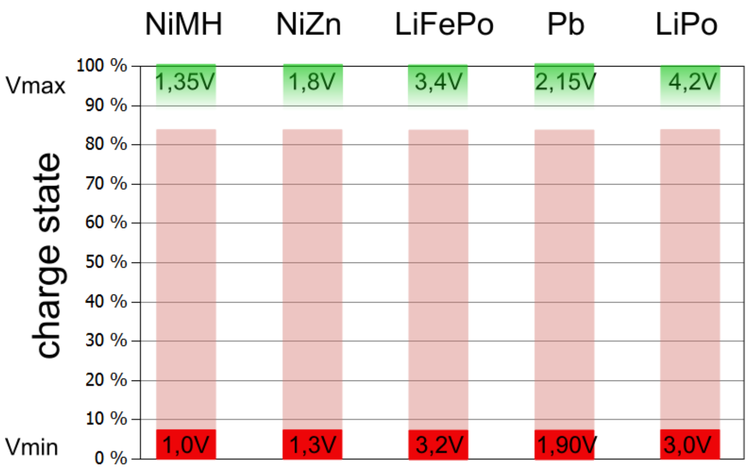


Diagram 2.1: Determination of the charge state

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

Table 2.1: Maximum capacity of the battery modules

2.

2.1 Nominal voltage and capacity of voltage sources

Evaluation

2.

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.*

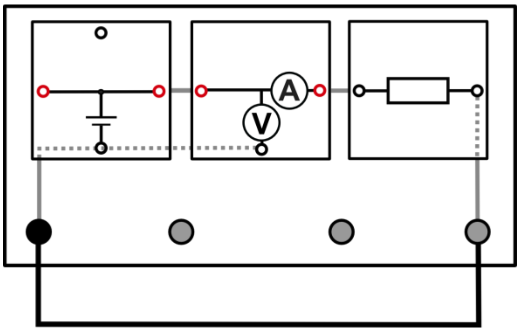
4.

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)					50
NiZn-battery module (R_{load} =5 Ω)					50
LiFePo-battery module (R_{load} =5 Ω)					50
Lead-battery module (R_{load} =5 Ω)					5
Lithium-polymer-battery module (R_{load} =10 Ω)					50
NiMH-battery module, triple (R_{load} =10 Ω)					220

Evaluation

1.

2.

2.2 Internal resistance of voltage sources

Evaluation

1.

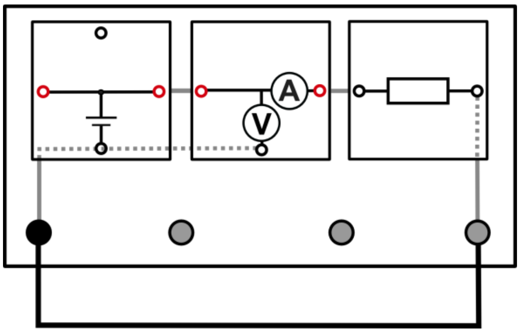
2.

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)			
2nd cell (R$_C$= 50 mΩ)			
3rd cell (R$_C$= 50 mΩ)			

Triple battery module:

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

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:

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

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.

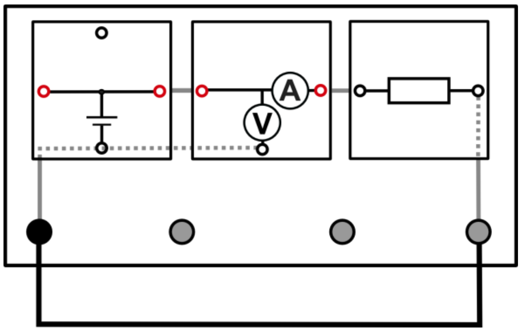
2.

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) = ______

t in min	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
V_{Load} in V																
I_{Load} in mA																

V_0 (2) = ______

2.4 The capacitance of a battery module

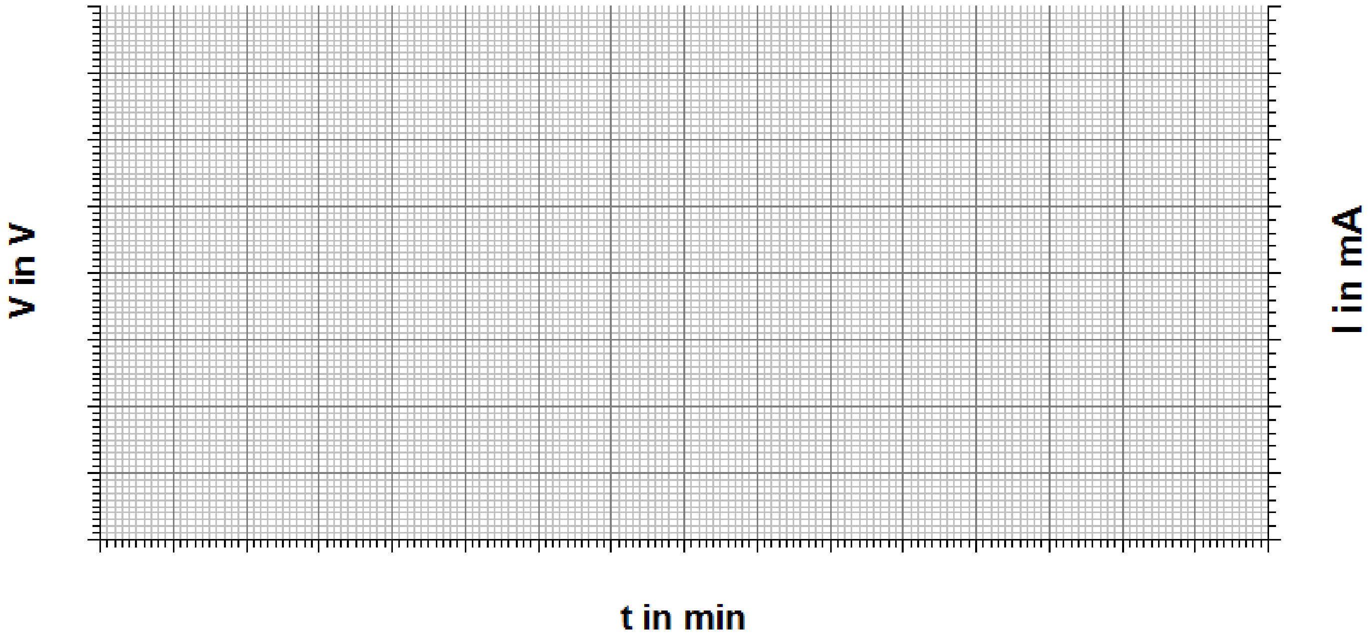
Evaluation

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.

3.

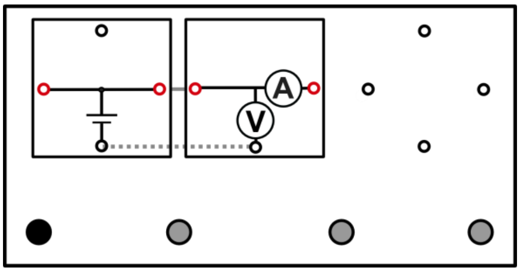
4.

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				
NiZn				
LiFePo				
Pb				
LiPo				

Evaluation

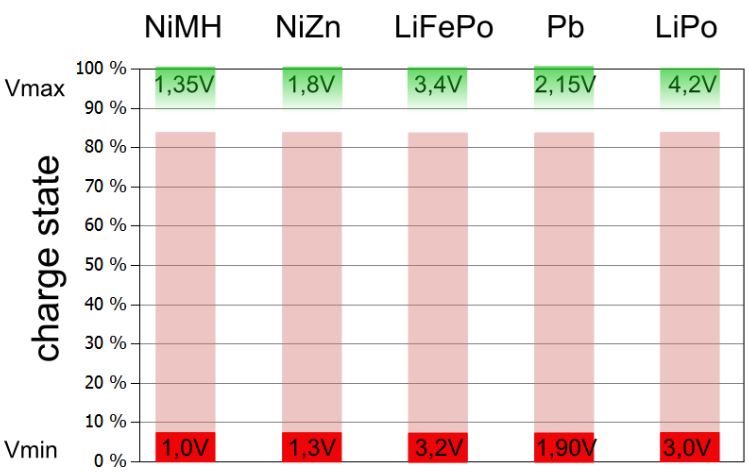


Diagram 2.6: Determination of charge state

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

2.5 The energy density of battery modules

Evaluation

2.

3.

2.5 The energy density of battery modules

Evaluation

3.

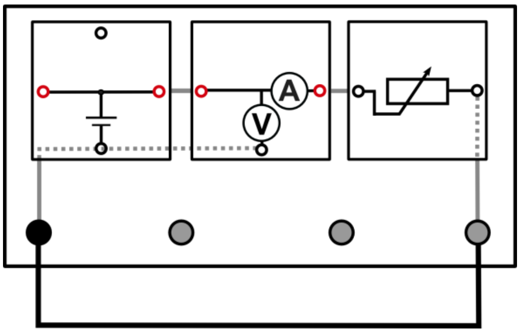
5.

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:

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

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}.

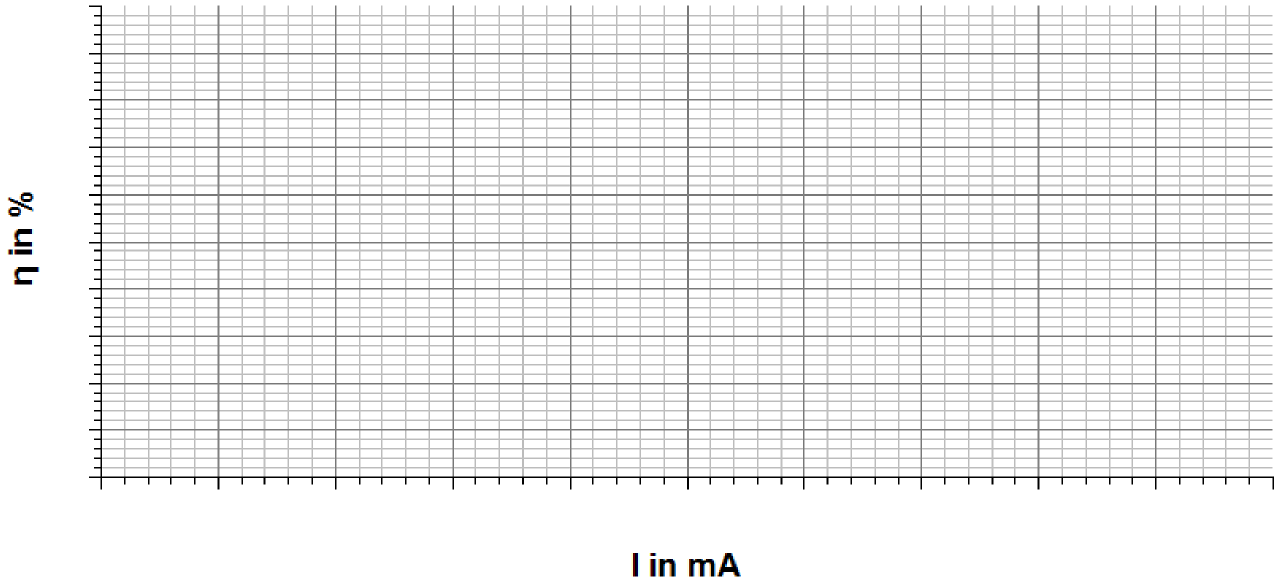
2.6 The R_i efficiency of a battery module

Measurement

V_0=__________

R_{Pot} in Ω									
V_{Load} in V									
I_{Load} in mA									
η in %									

Diagram



Evaluation

1.

2.6 The R_i efficiency of a battery module

Evaluation

3.

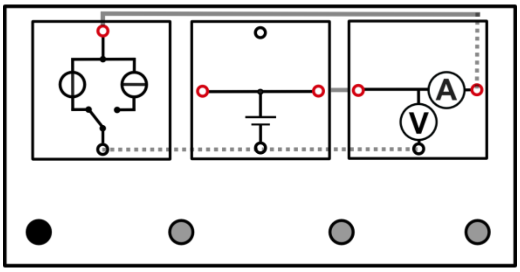
2.7 The total efficiency of a battery module

Task

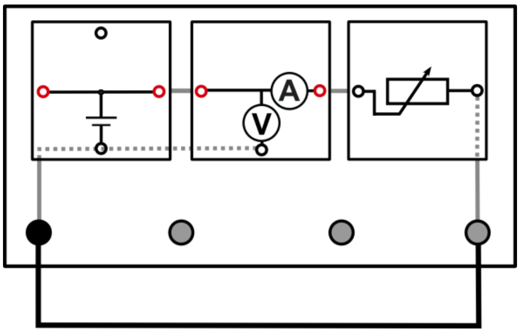
Determine the total efficiency of a battery module.

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) = ______

t in min	0	1	2	3	4	5	6	7	8	9	10
V in V											
I in mA											
W in J											

V_0 (2) = ______

Part 2: Discharging process

V_0 (1) = ______

t in min	0	1	2	3	4	5	6	7	8	9	10
V in V											
I in mA											
W in J											

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

t in min	0	1	2	3	4	5
$V_0(2)$ in V						

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.

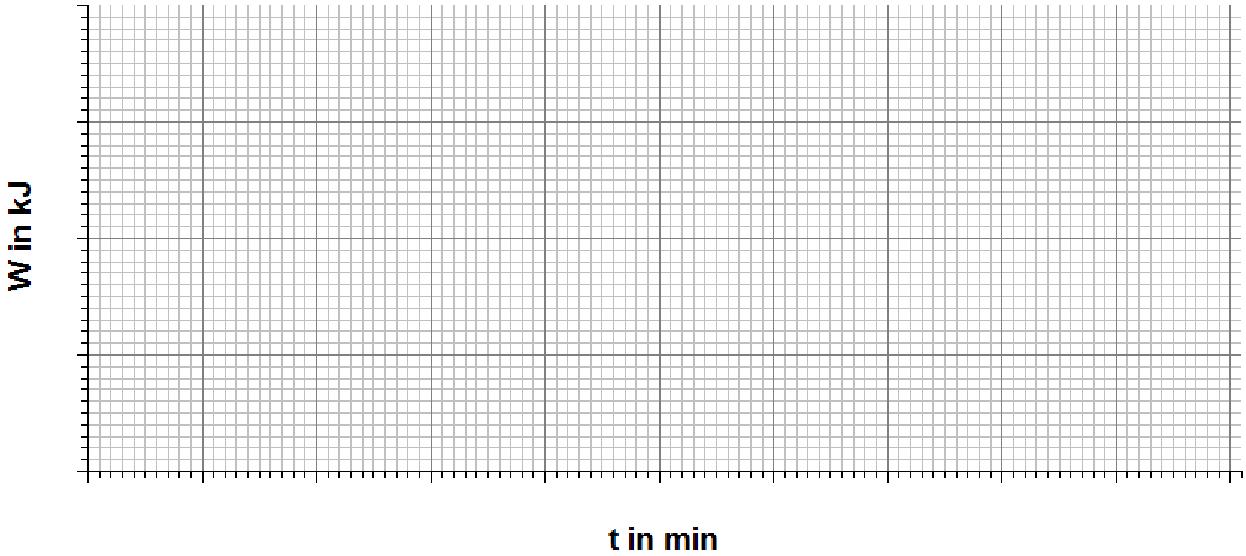
$$W = V \cdot I \cdot t$$

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.

2.7 The total efficiency of a battery module

Evaluation

3.

4.

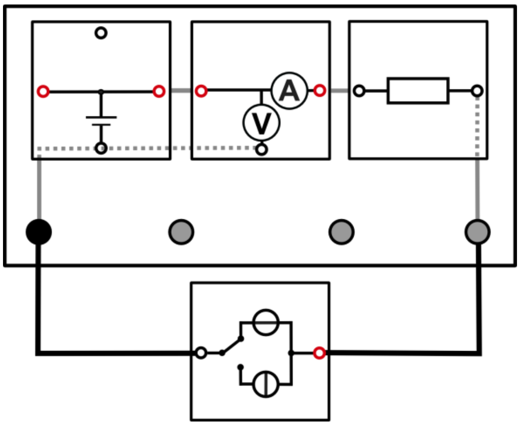
5.

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										
I_{Load} in mA										

R_1= 5Ω:

t in s	0	10	20	30	40	50	60	70	80	90
V_{Load} in V										
I_{Load} in mA										

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													
I_{Load} in mA													

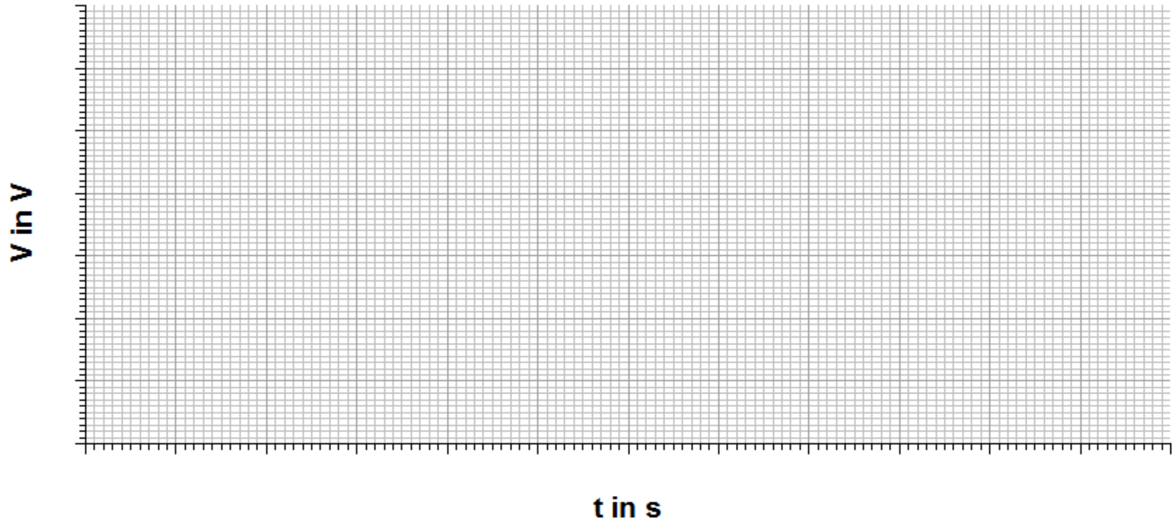
R_1= 5Ω:

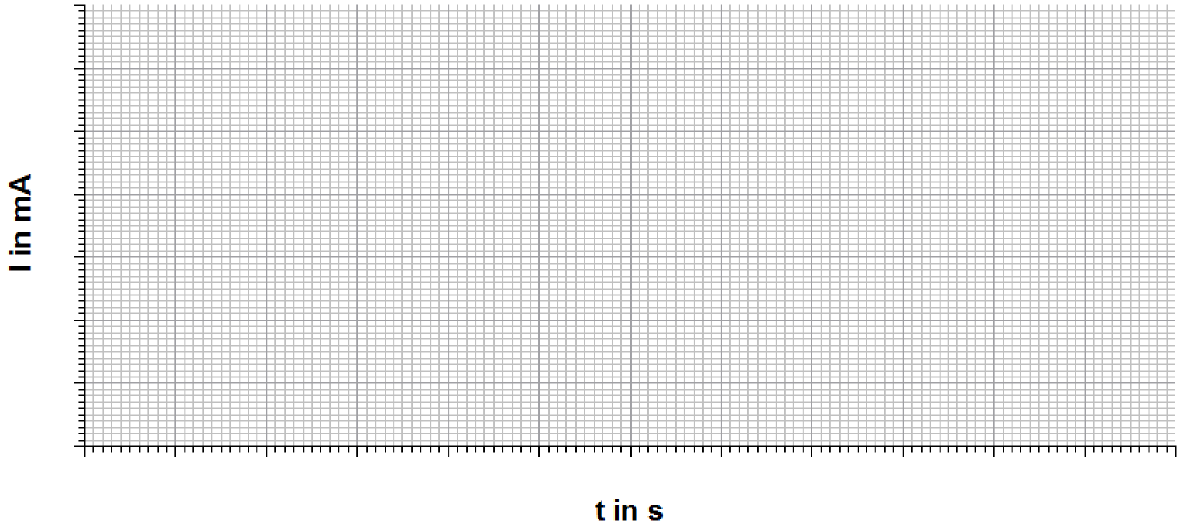
t in s	0	10	20	30	40	50	60	70	80	90	100	110	120
V_{Load} in V													
I_{Load} in mA													

3.1 The charging process of a capacitor

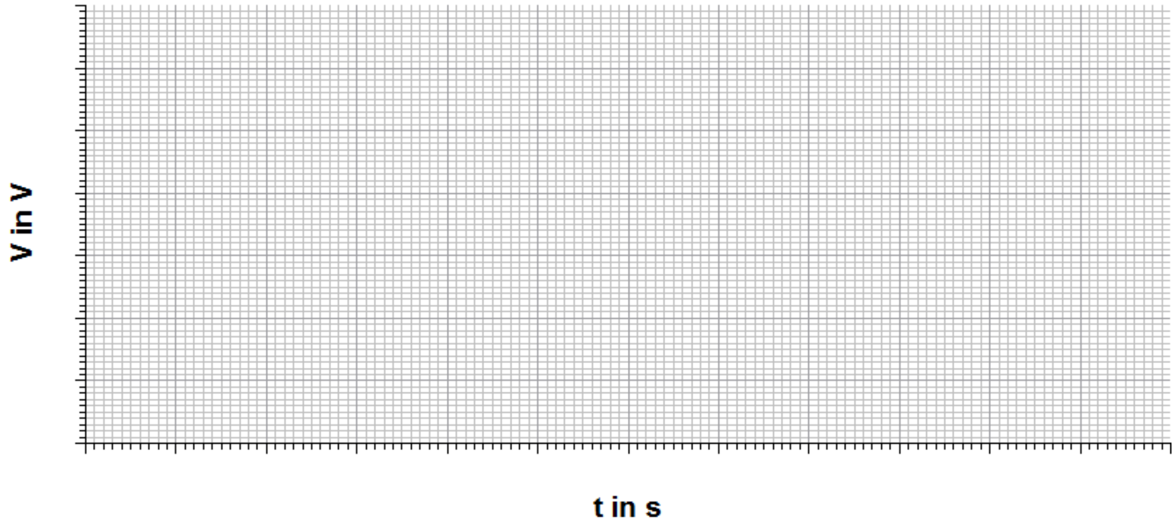
Diagrams

Part 1: Supercap-mode



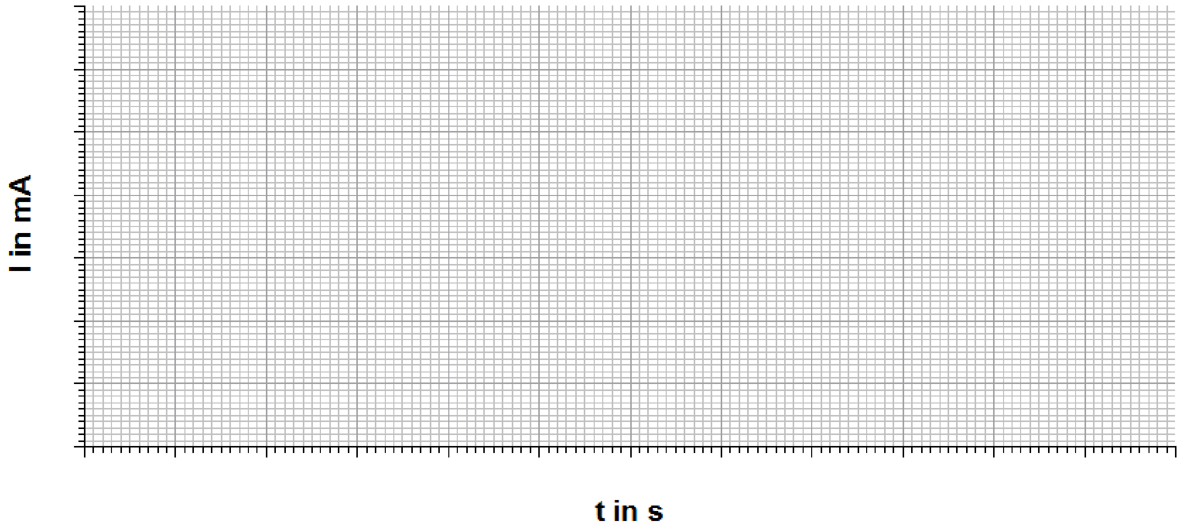


Part 2: Constant-voltage-mode



3.1 The charging process of a capacitor

Diagrams



Evaluation

2.

3.

R=10 Ω:

R=5 Ω:

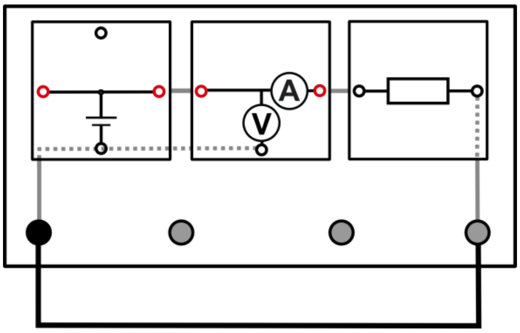
4.

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

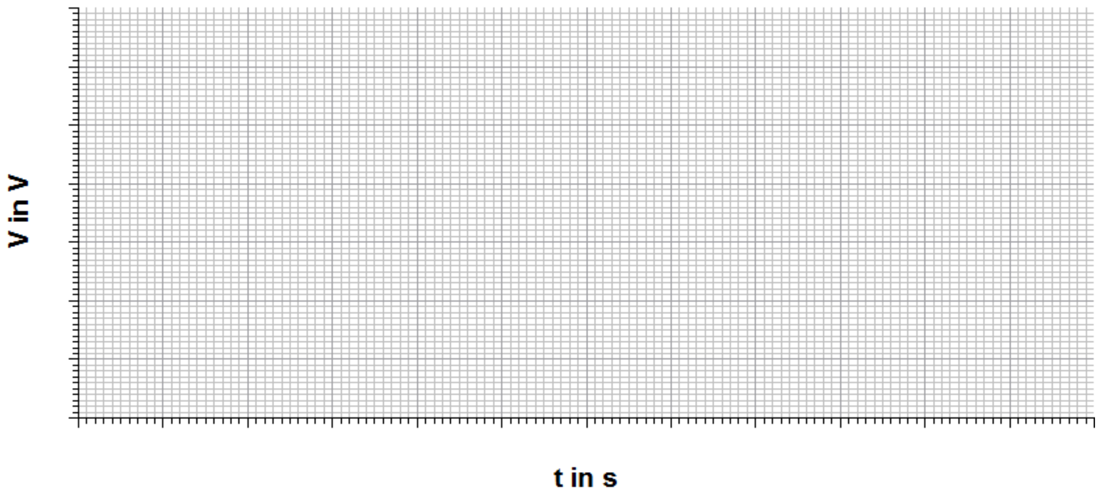
R_1= 10Ω:

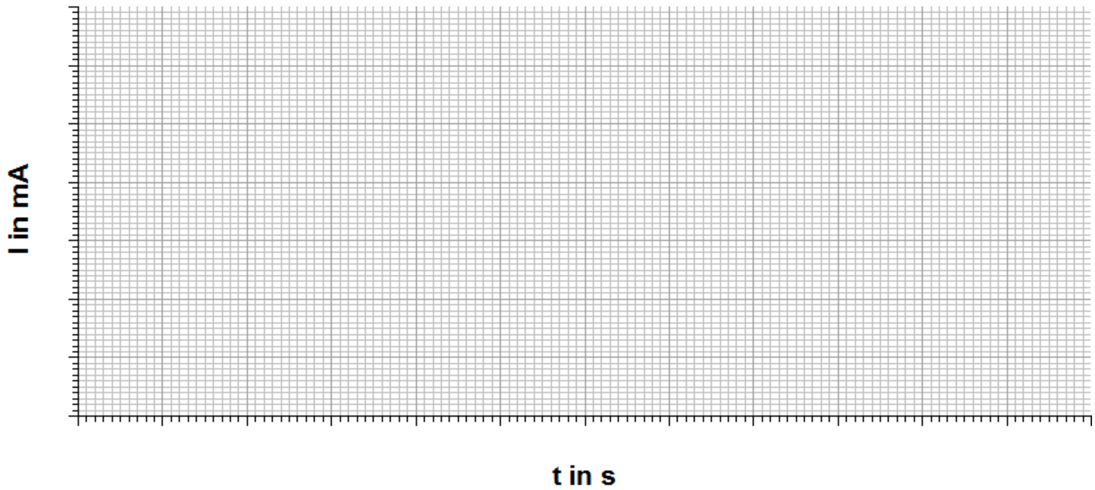
t in s	0	10	20	30	40	50	60	70	80	90
V in V										
I in mA										

R_2= 5Ω:

t in s	0	10	20	30	40	50	60	70	80	90
V in V										
I in mA										

Diagrams





3.2 The discharge process of a capacitor

Evaluation

2.

3.

4.

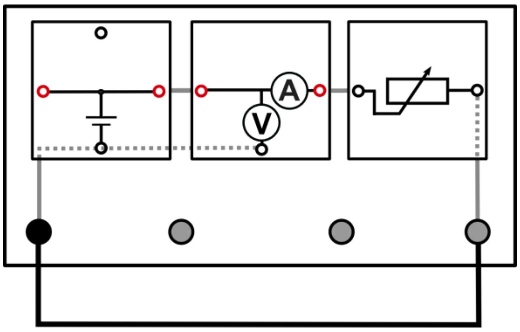
5.

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?

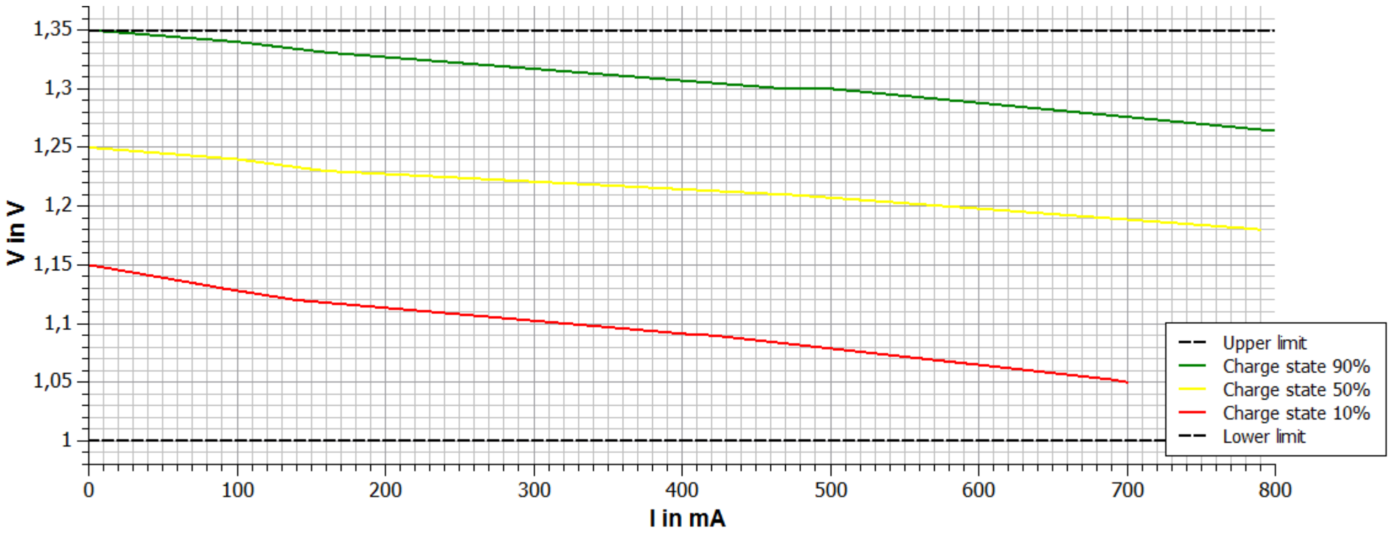
4.1 I-V characteristics of the single NiMH battery module

Measurements

V_0=__________

R_{Pot} in Ω												
V_{Load} in V												
I_{Load} in mA												

Diagram



Evaluation

2.

4.1 I-V characteristics of the single NiMH battery module

Evaluation

3.

4.

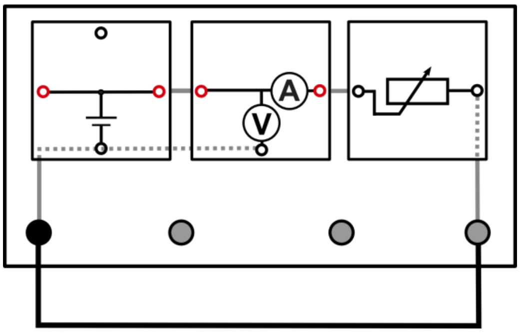
5.

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.

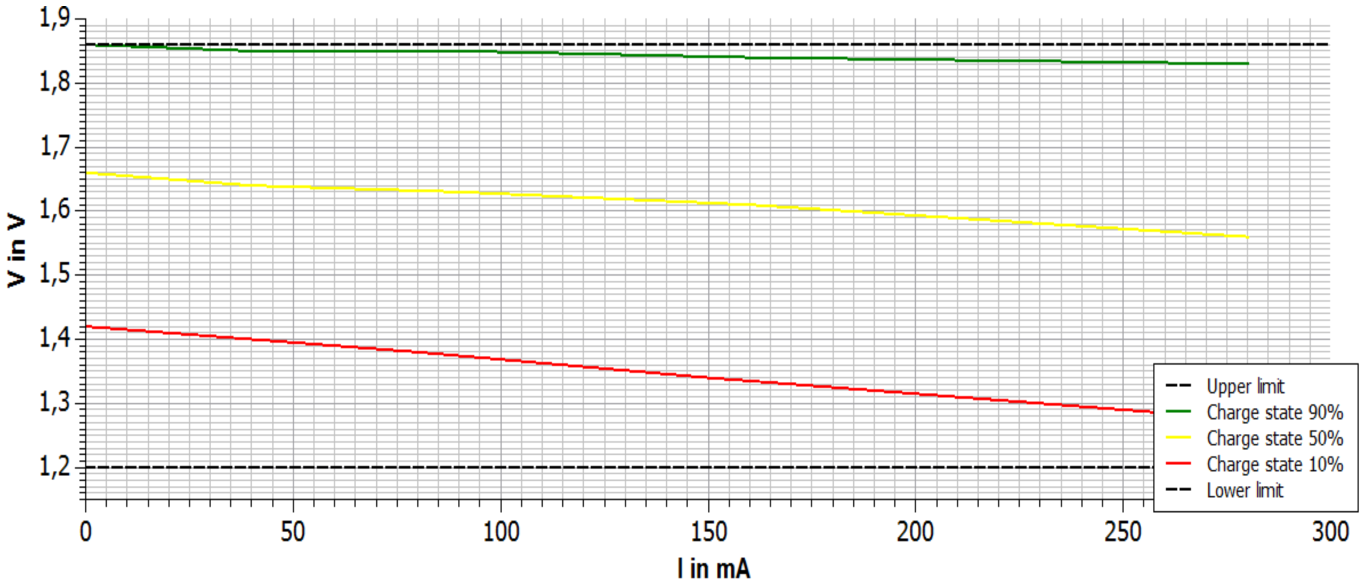
4.2 I-V characteristics of the NiZn battery module

Measurements

V_0= ________

R_{Pot} in Ω									
U_{Load} in V									
IL_{oad} in mA									

Diagram



Evaluation

2.

4.2 I-V characteristics of the NiZn battery module

Evaluation

3.

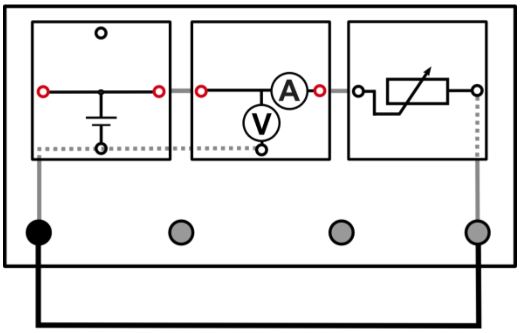
4.

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?

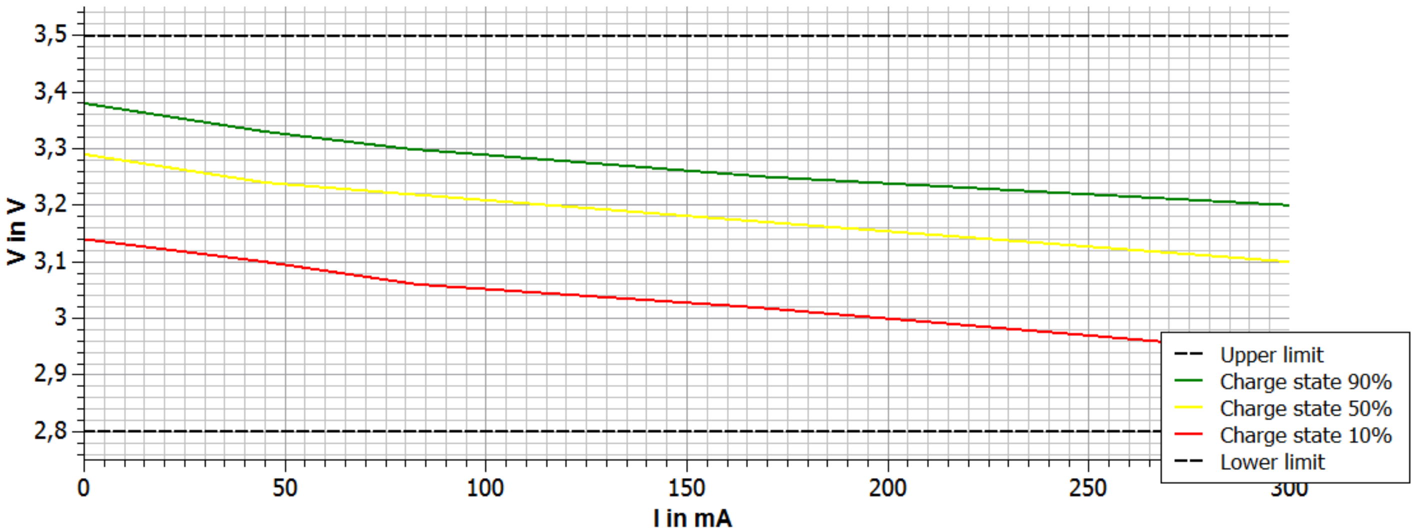
4.3 I-V characteristics of the LiFePo battery module

Measurements

V_0= ________

R_{Pot} in Ω									
V_{Load} in V									
I_{Load} in mA									

Diagram



Evaluation

2.

4.3 I-V characteristics of the LiFePo battery module

Evaluation

3.

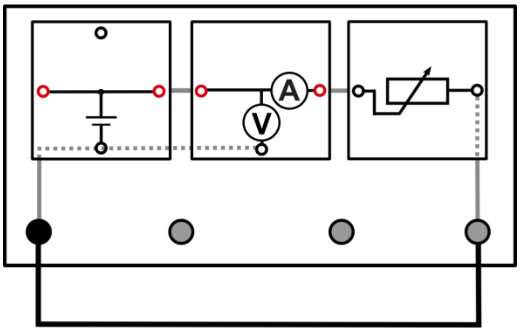
4.

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?

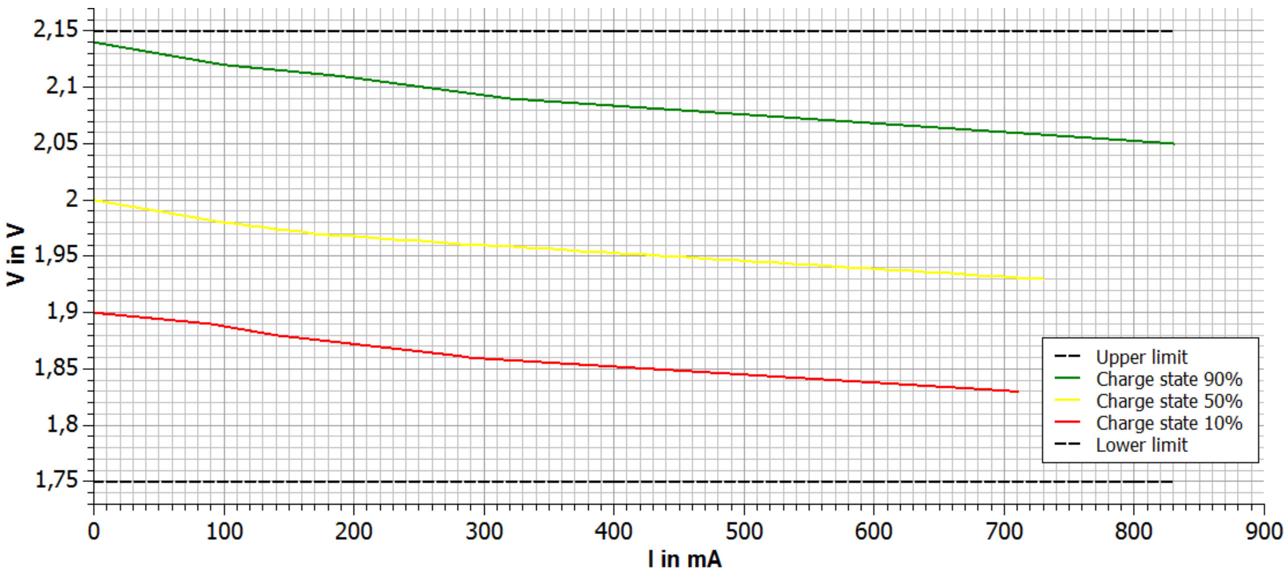
4.4 I-V characteristics of the lead battery module

Measurements

V_0=__________

R_{Pot} in Ω										
V_{Load} in V										
I_{Load} in mA										

Diagram



Evaluation

2.

4.4 I-V characteristics of the lead battery module

Evaluation

3.

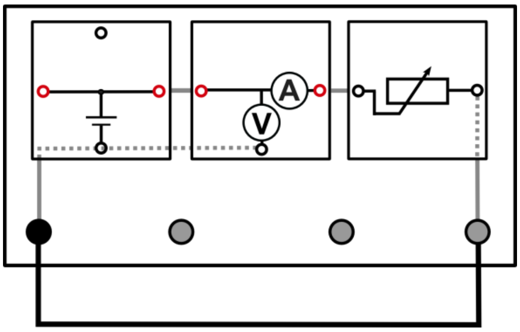
4.

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?

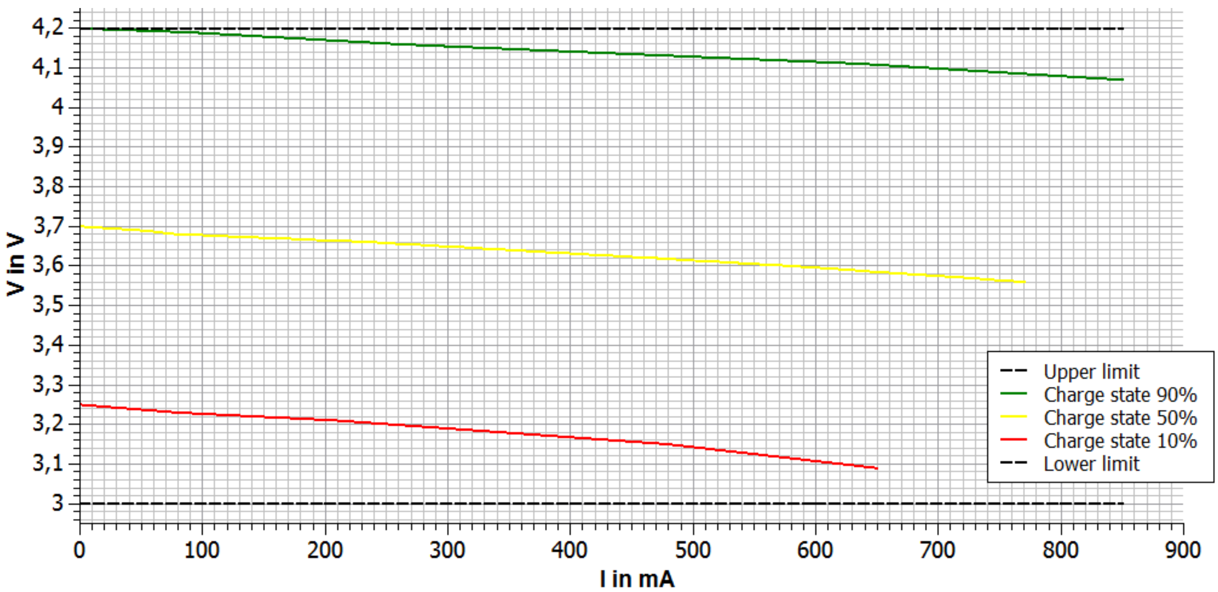
4.5 I-V charachteristics of the lithium-polymer battery module

Measurements

V_0=__________

R_{Pot} in Ω									
V_{Load} in V									
I_{Load} in mA									

Diagram



Evaluation

2.

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

Evaluation

3.

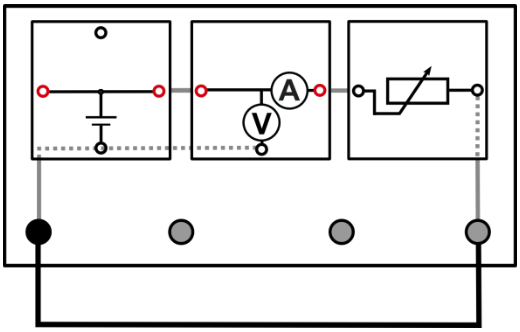
4.

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.

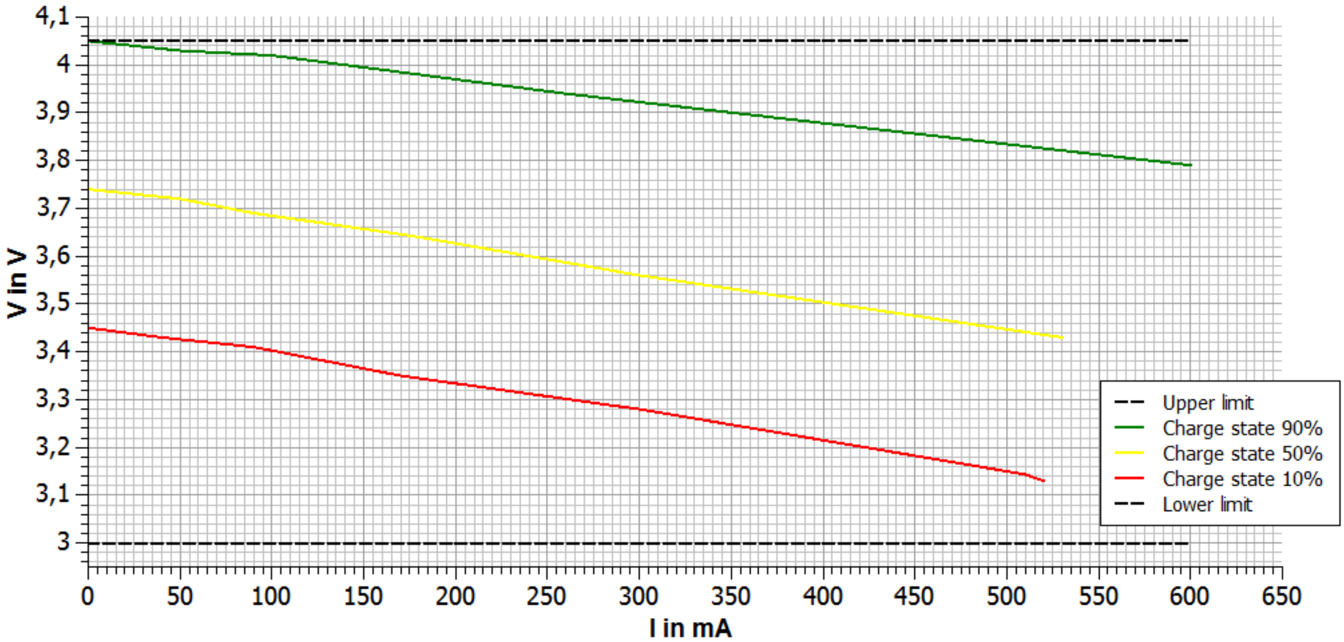
4.6 I-V characteristics of the triple NiMH battery module

Measurements

V_0=__________

R_{Pot} in Ω										
V_{Load} in V										
I_{Load} in mA										

Diagram



Evaluation

2.

4.6 I-V characteristics of the triple NiMH battery module

Evaluation

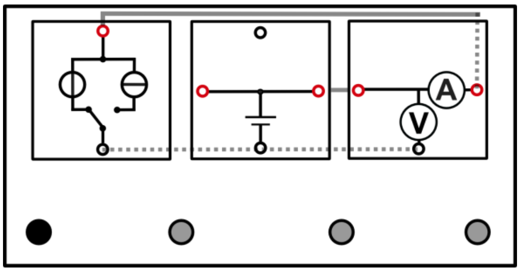
3.

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

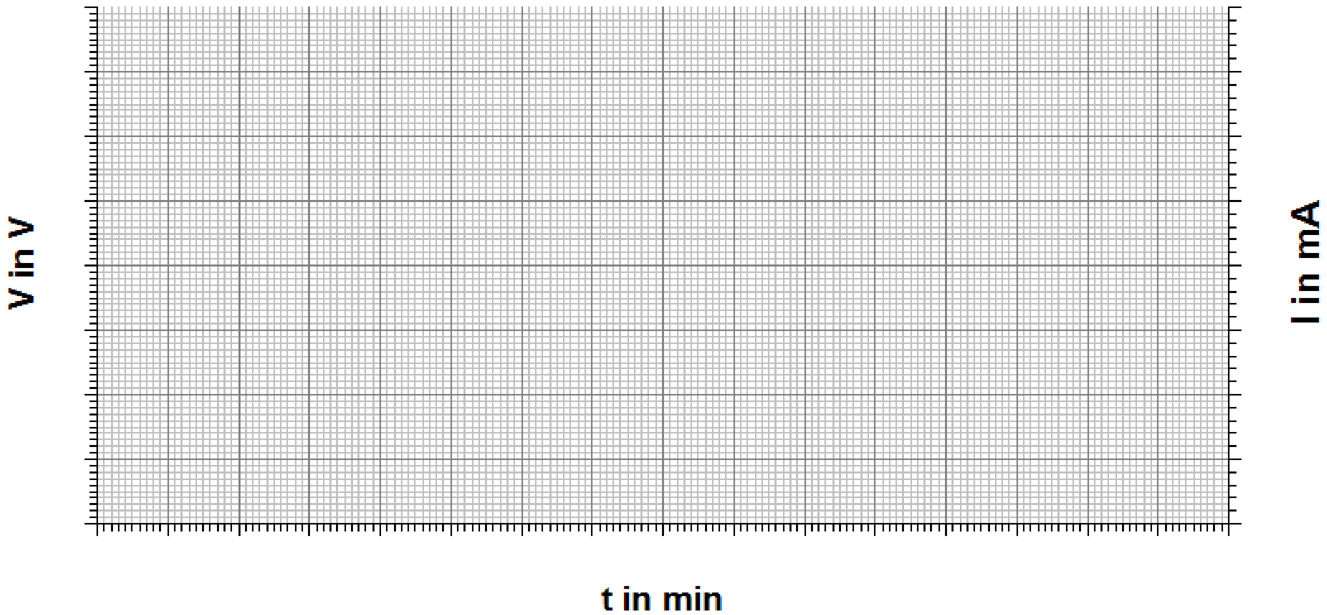
$V_0(1)$ = ______

t in min													
V in V													
I in mA													

t in min												
V in V												
I in mA												

t in min												
V in V												
I in mA												

Diagram



5.1 The charging process of the NiMH battery

Evaluation

2.

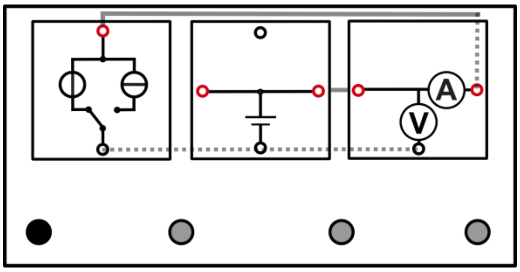
3.

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)?

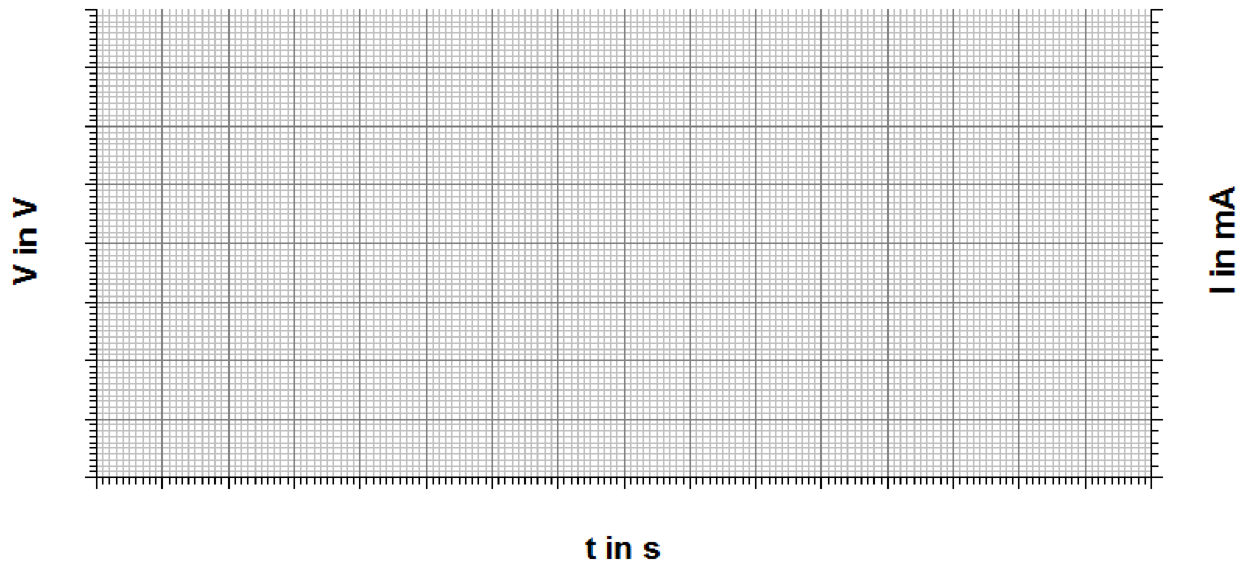
Measurements

$V_0(1)$ = ______

t in s													
V in V													
I in mA													

5.2 The charging process of the NiZn battery

Diagram



Evaluation

2.

3.

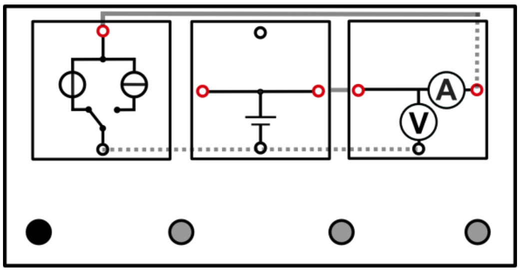
4.

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

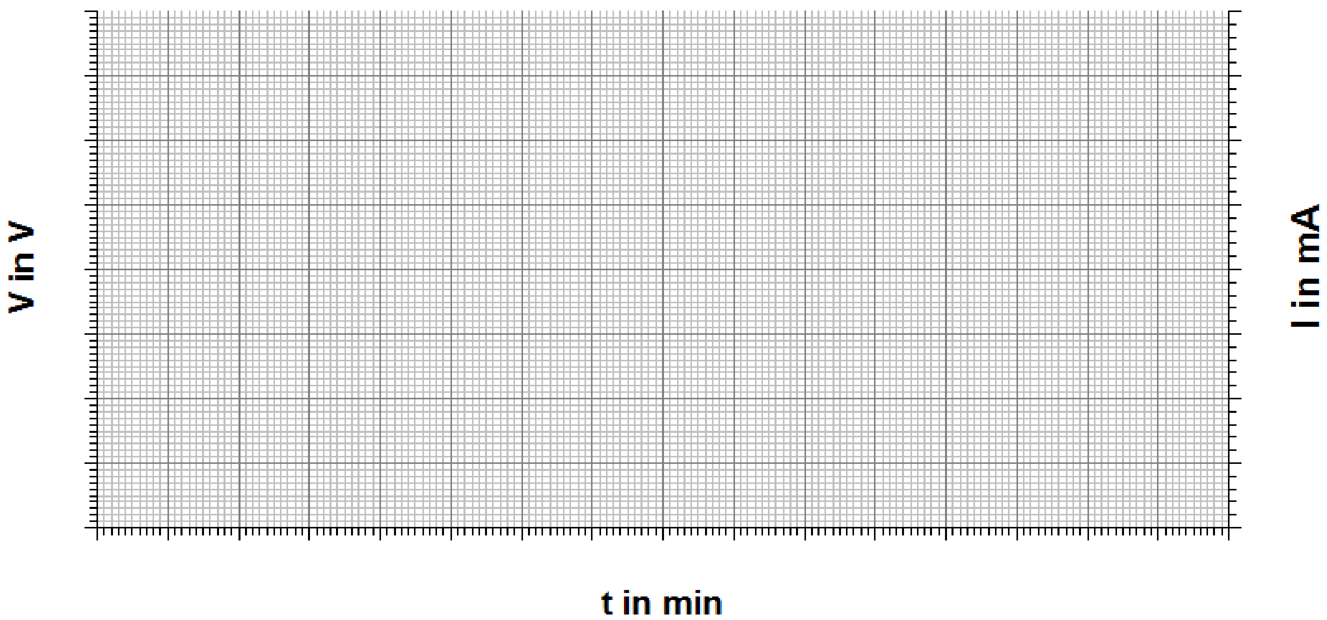
$V_0(1)$ = ______

t in min												
V in V												
I in mA												

t in min												
V in V												
I in mA												

t in min												
V in V												
I in mA												

Diagram



5.3 The charging process of the LiFePo battery

Evaluation

2.

3.

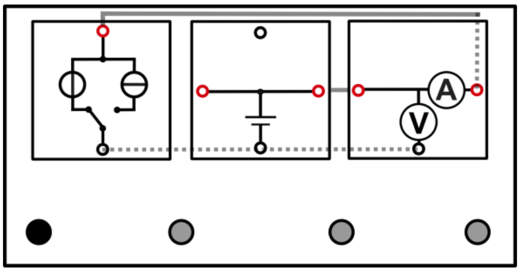
4.

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

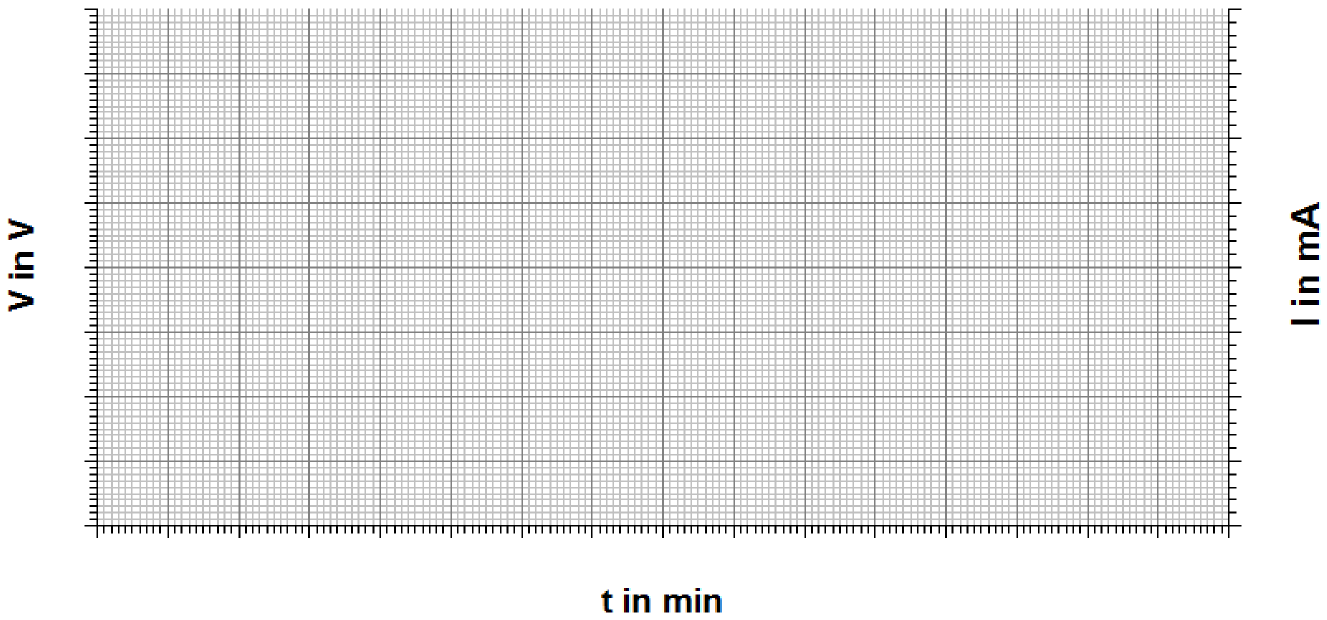
$V_0(1)$ = ______

t in min													
V in V													
I in mA													

t in min													
V in V													
I in mA													

t in min													
V in V													
I in mA													

Diagram



5.4 The charging process of the lead battery

Evaluation

2.

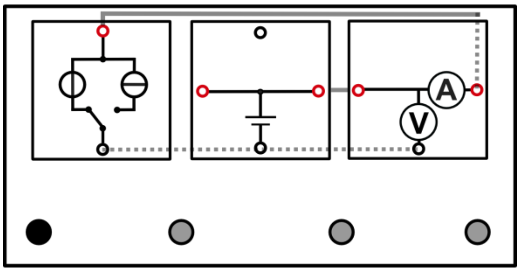
3.

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

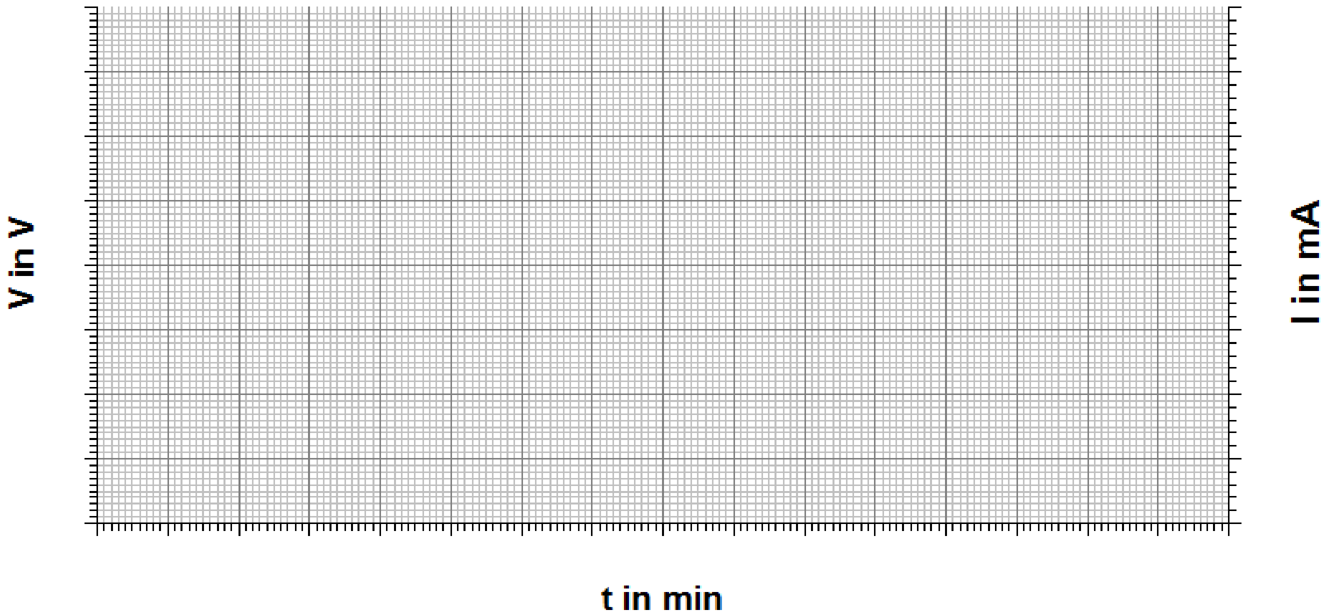
$V_0(1)$ =______

t in min														
V in V														
I in mA														

t in min														
V in V														
I in mA														

t in min														
V in V														
I in mA														

Diagram



5.5 The charging process of the lithium-polymer battery

Evaluation

2.

3.

4.

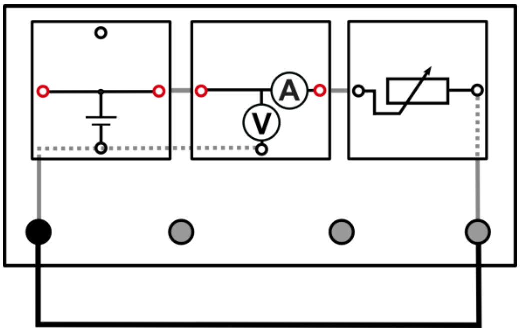
5.

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) = ______ V_0 (2) = ______

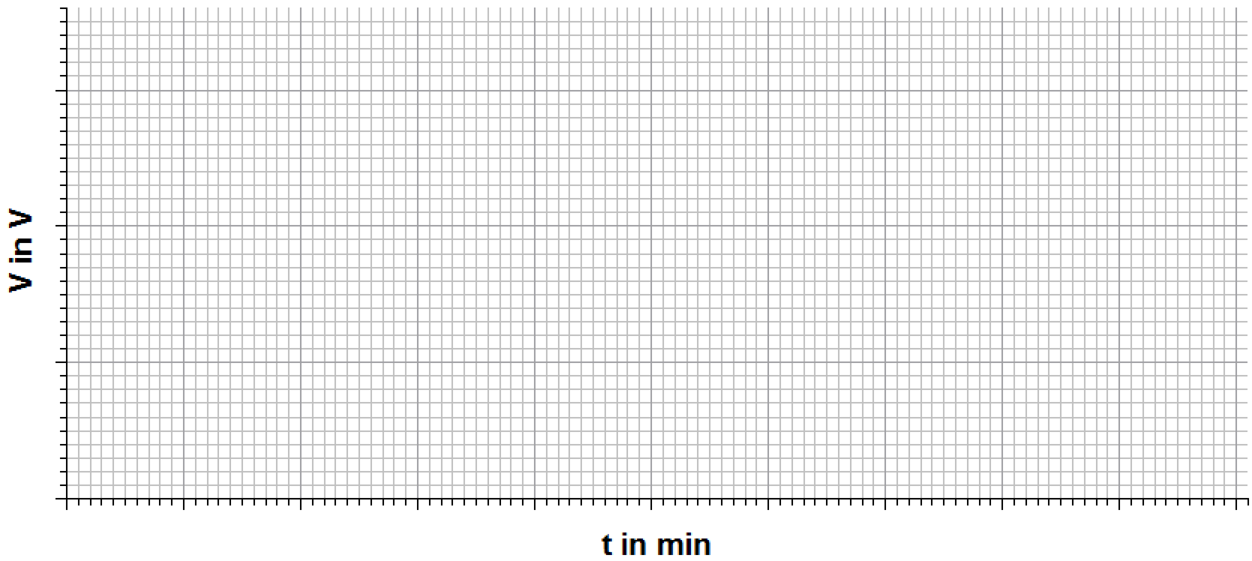
t in min	0	1	2	3	4	5	6	7	8	9	10
V in V											

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.

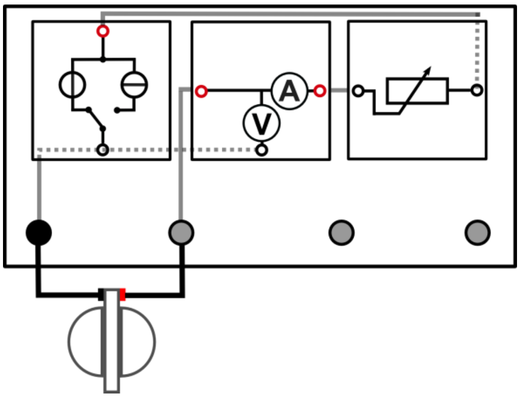
3.

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

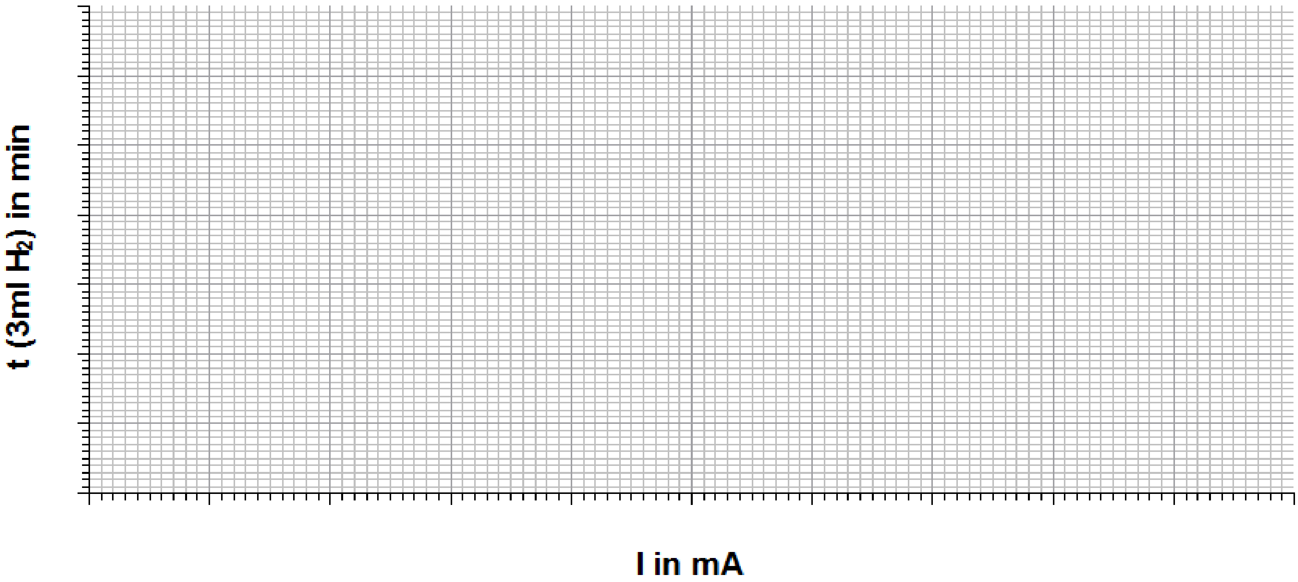
1. 1. Enter your values in the diagram.
2. How does the oxygen production rate cohere with the current of a fuel cell?
3. Explain the behavior of voltage and current in dependence from the resistance.

Data

R in Ω	2	4	6	8
V in V				
I in mA				
t (3ml H_2) in min				

6.1 Hydrogen production in the reversible hydrogen fuel cell

Diagram



Evaluation

2.

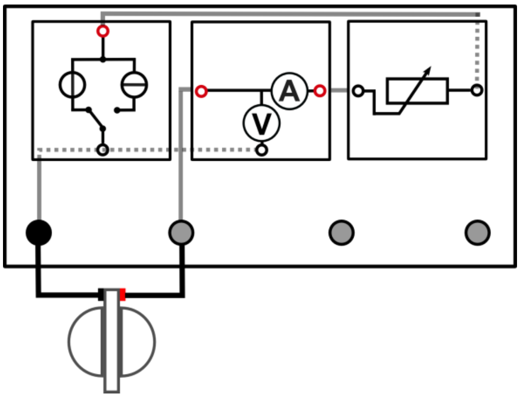
3.

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 distilled 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									
I in mA									

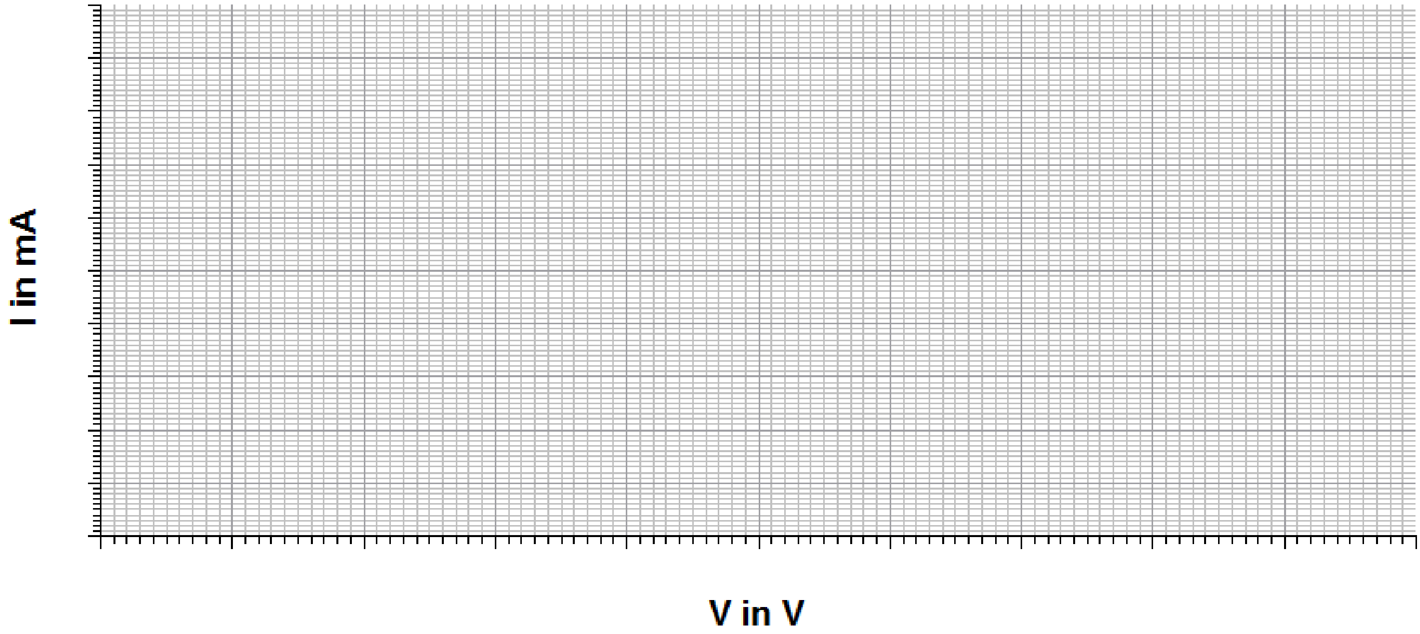
V in V									
I in mA									

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

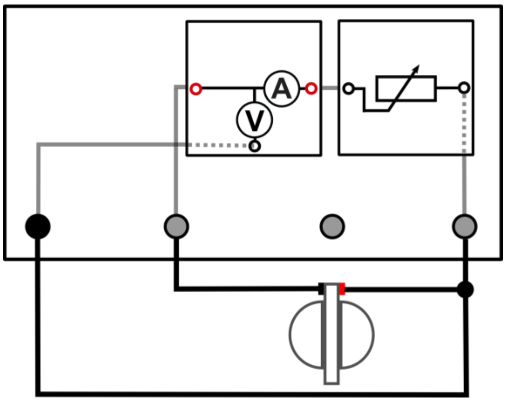
2.

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					
I in mA					
H_2 in ml					

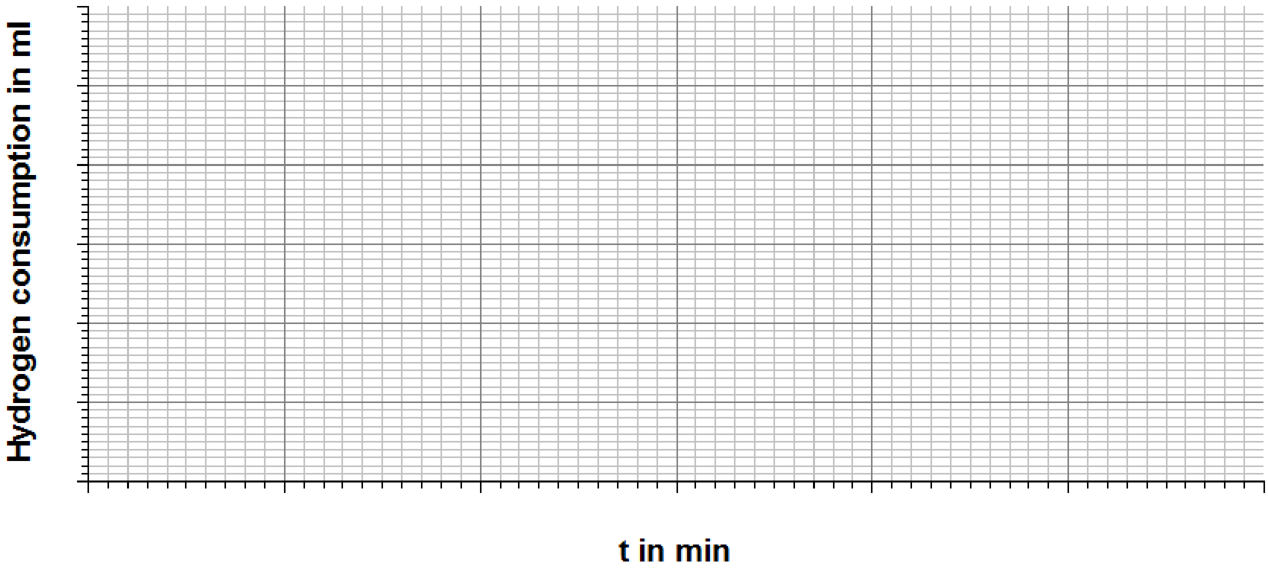
6.3 Hydrogen consumption of a fuel cell

Measurements

R=2.0Ω

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

Diagram



Evaluation

1.

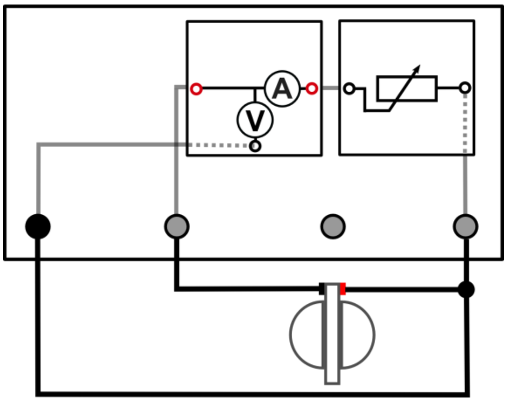
3.

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.

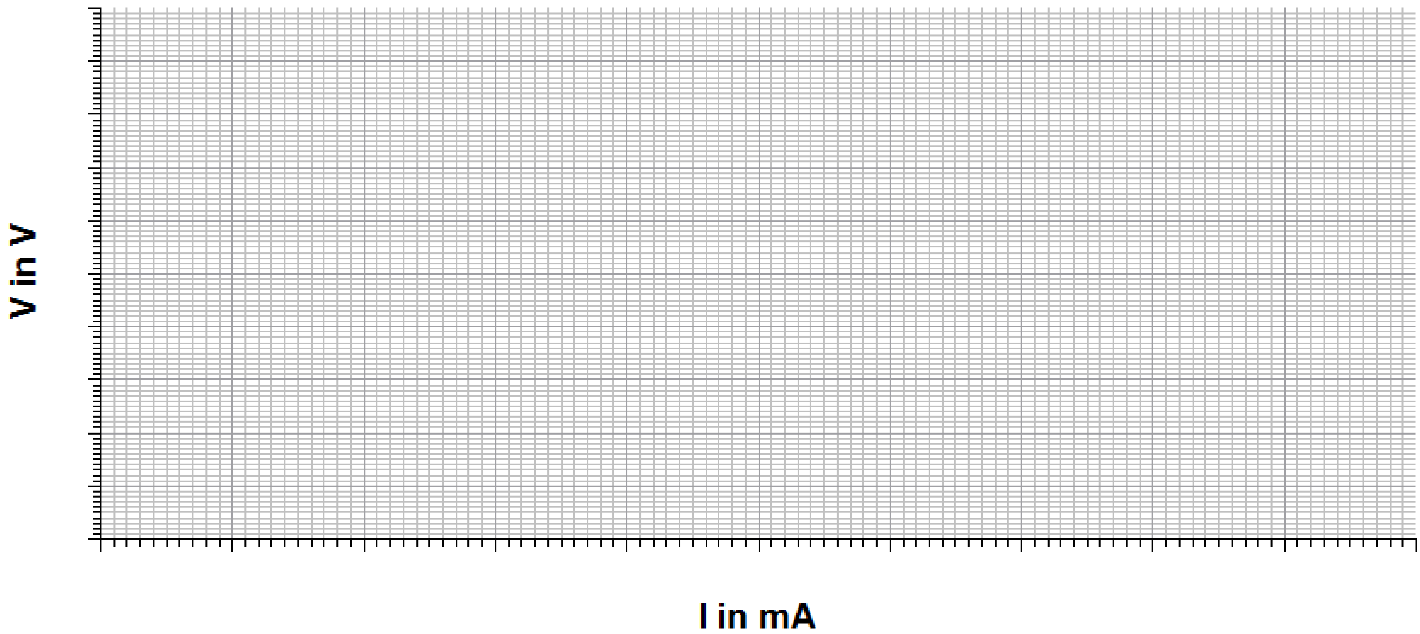
6.4 Characteristic curve of the fuel cell

Measurements

V in V														
I in mA														

V in V														
I in mA														

Diagram



Evaluation

2.

6.4 Characteristic curve of the fuel cell

Evaluation

3.

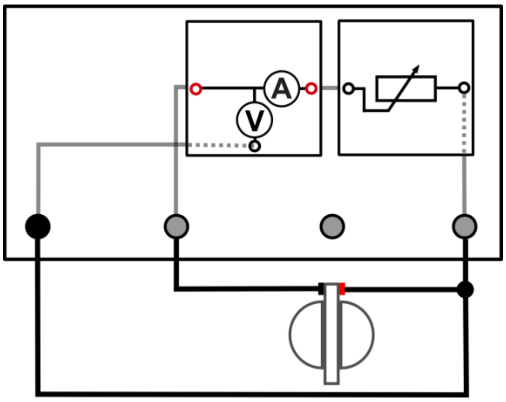
4.

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=__________ I=___________ t=___________

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:

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

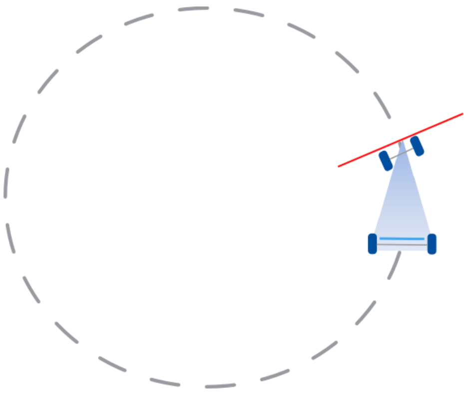
(The lower fuel value of 2ml of H_2 is W_1= 22Ws)

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.

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 = ______						
time in s						
time for 4 rounds						
NiZn battery module V_0 = ______						
time in s						
time for 4 rounds						
NiMH battery module V_0 = ______						
time in s						
time for 4 rounds						
LiFePo battery module V_0 = ______						
time in s						
time for 4 rounds						
LiPo battery module V_0 = ______						
time in s						
time for 4 rounds						
Capacitor module V_0 = ______						
time in s						
time for 4 rounds						

7.1 Operation of the electric car with several battery modules

Evaluation

1.

2.

3.

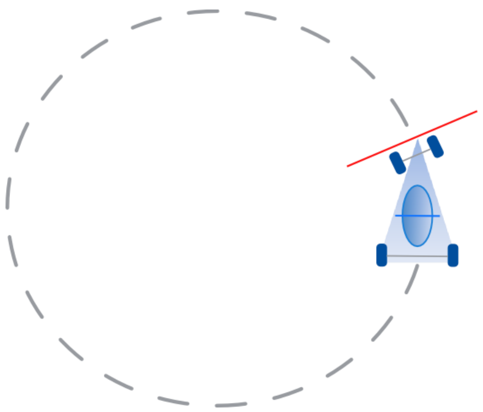
4.

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 = ______						
time in s						
time for 4 rounds						

Evaluation

1.

2.

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