Electricity and New Energy

Ni-MH Batteries

Courseware Sample

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By the staff of Festo Didactic

Internet: www.festo-didactic.com
e-mail: did@de.festo.com

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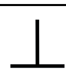
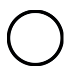
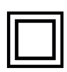
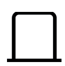
Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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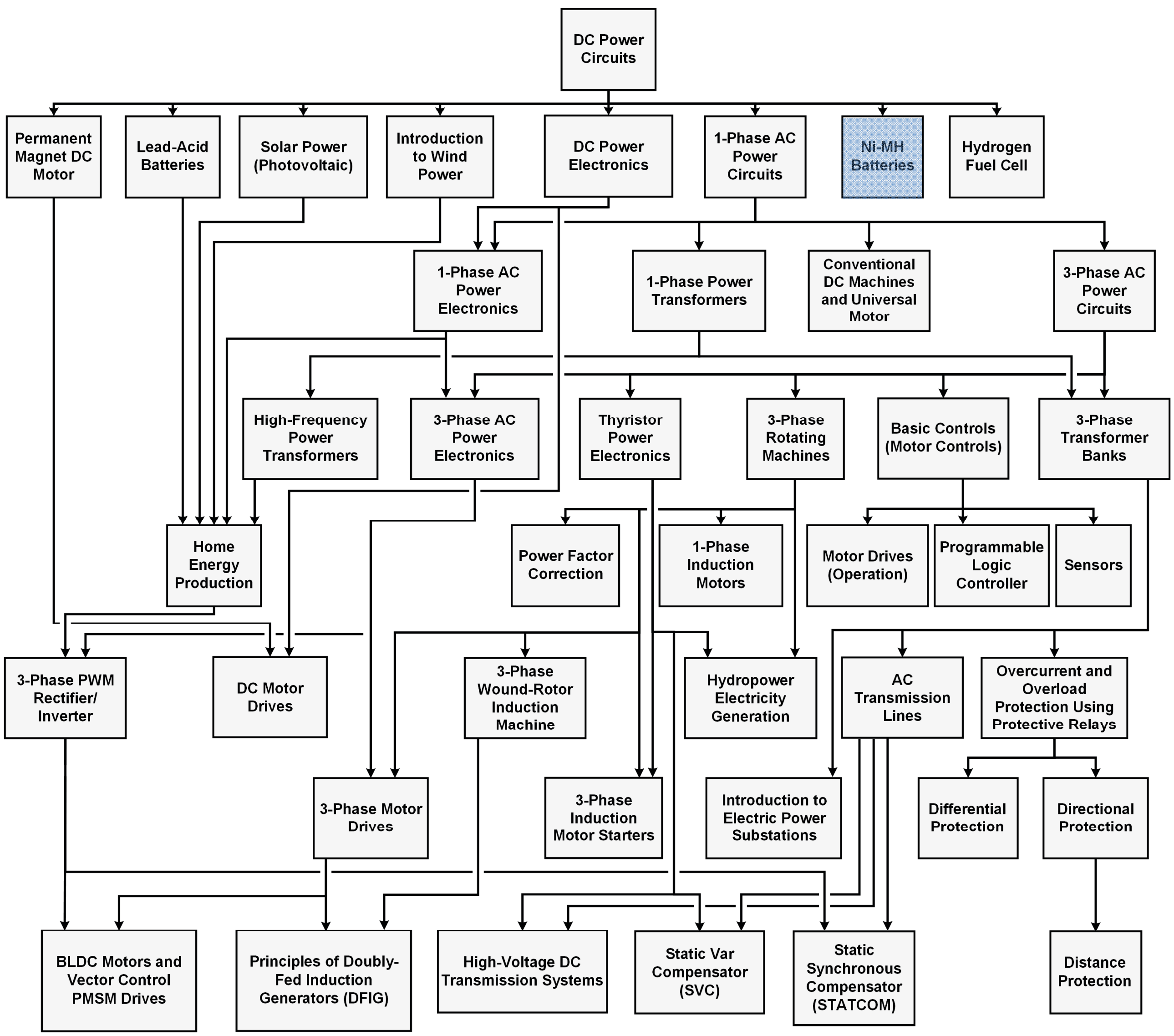
Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.



The Electric Power Technology Training Program.

Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

Batteries store electricity in a chemical form, inside a closed-energy system. Some batteries can be re-charged and re-used as a power source in small appliances, machinery, and remote locations. Advances in battery technology may one day help in achieving greater use of clean energy produced from renewable resources such as sunlight, wind, rain, tide, and others.

The Ni-MI Batteries course teaches the basic concepts of Ni-MI batteries. At the beginning of the course, students are introduced to the concepts of voltage regulation, internal resistance, capacity, depth of discharge, and cycle life of Ni-MI batteries. Students then learn about and experiment with both the discharge characteristics and the most common charging methods and charge-control techniques of Ni-MI batteries.

Figure 1. Typical commercially available Ni-MI batteries with corresponding Ni-MI battery charger.

About This Manual

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Prerequisite

As a prerequisite to this course, you should have read the manual titled *DC Power Circuits*, p.n. 86350.

Systems of units

Units are expressed using the International System of Units (SI) followed by the units expressed in the U.S. customary system of units (between parentheses).

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Electric Power Technology Training Equipment must have been properly installed, according to the instructions given in the user guide Electric Power Technology Training Equipment, part number 38486-E.

Sample Exercise

Extracted from

the Student Manual

and the Instructor Guide

Battery Capacity Versus Discharge Rate

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the effects of the discharge rate and battery temperature on the capacity and voltage of a Ni-MH battery. You will know how to calculate the energy supplied during a discharge cycle. You will also know what the specific energy and the energy density of a battery are, and how to determine these two parameters.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Battery cell voltage versus discharge rate
- Temperature versus available capacity
- Memory effect
- Energy supplied during a discharge cycle
- Specific energy and energy density

DISCUSSION

Battery cell voltage versus discharge rate

Figure 14 shows a family of discharge characteristic curves of a Ni-MH battery obtained at various discharge rates. Notice that these curves represent the voltage measured across each cell in the battery. The final voltage or cutoff voltage (1 V in the present case) does not vary as a function of the discharge rate. Also note that this family of curves is relative to the discharge characteristic curve obtained at a discharge rate of $0.2C_5$, i.e., the discharge rate commonly used to establish the nominal capacity of Ni-MH batteries.

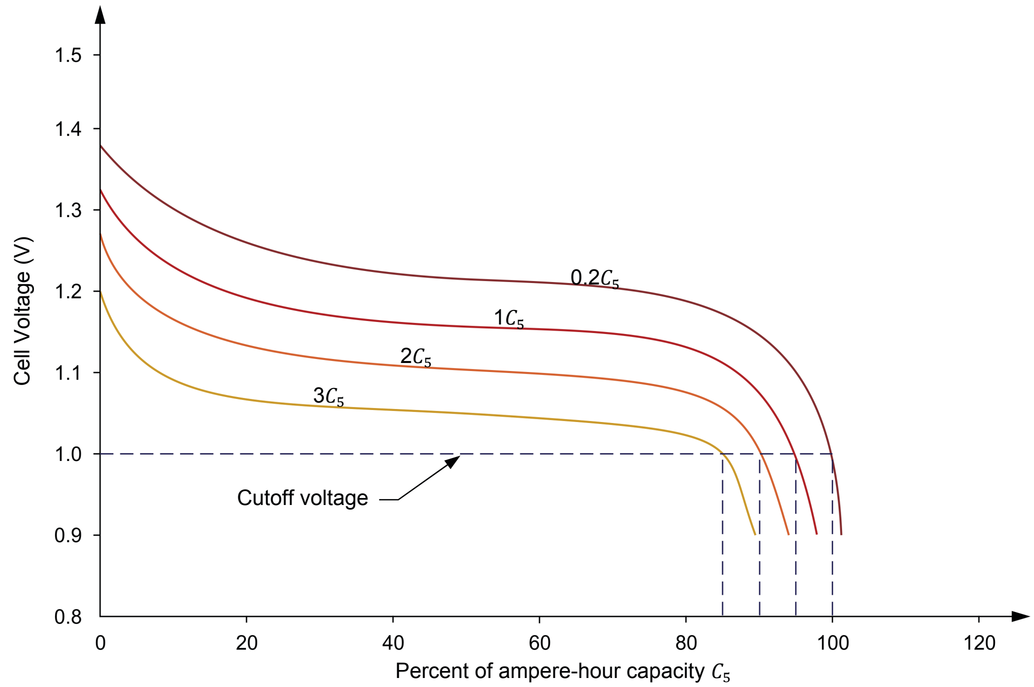


Figure 14. Family of discharge characteristic curves of a Ni-MH battery obtained at various discharge rates.

Table 3 shows the discharge time and relative battery capacity for each discharge characteristic curve in Figure 14. The capacity C of a Ni-MH battery decreases little as the discharge rate increases. In fact, even with a discharge rate of $3C_5$ (15 times the optimal discharge rate of $0.2C_5$), the relative battery capacity is still only 15% below its nominal capacity.

Table 3. Discharge time and relative battery capacity versus discharge rate.

Discharge rate	$0.2C_5$	$1C_5$	$2C_5$	$3C_5$
Discharge time (h)	5	0.95	0.45	0.28
Relative battery capacity (% of C_5)	100	95	90	85

Figure 15 shows a curve of the relative capacity of a Ni-MH battery as a function of the discharge rate. Notice that the relative capacity of the Ni-MH battery is still more than 80% of the nominal capacity even when the discharge rate is as high as $3C_5$. In comparison, the relative capacity of a lead-acid battery at a discharge rate of $3C_{20}$ is generally only 50% to 60% of the rated capacity.

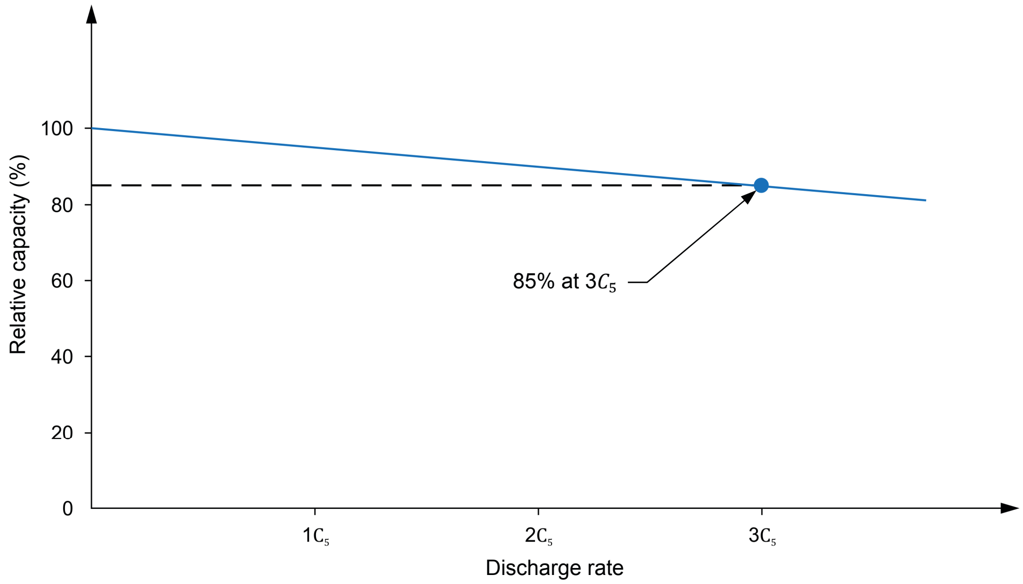


Figure 15. Relative capacity of a Ni-MH battery versus discharge rate.

Temperature versus available capacity

Figure 16 illustrates the effect of temperature on the available relative capacity of Ni-MH batteries at various discharge rates. As shown in the figure, Ni-MH batteries maintain their capacity over a wide range of discharge rates when operated at room temperature (20°C or 68°F and higher). However, the available capacity decreases fairly rapidly as the temperature goes below room temperature, especially at high discharge rates ($1C$ and higher). This is due to the progressively increasing internal resistance of Ni-MH batteries at lower temperatures.

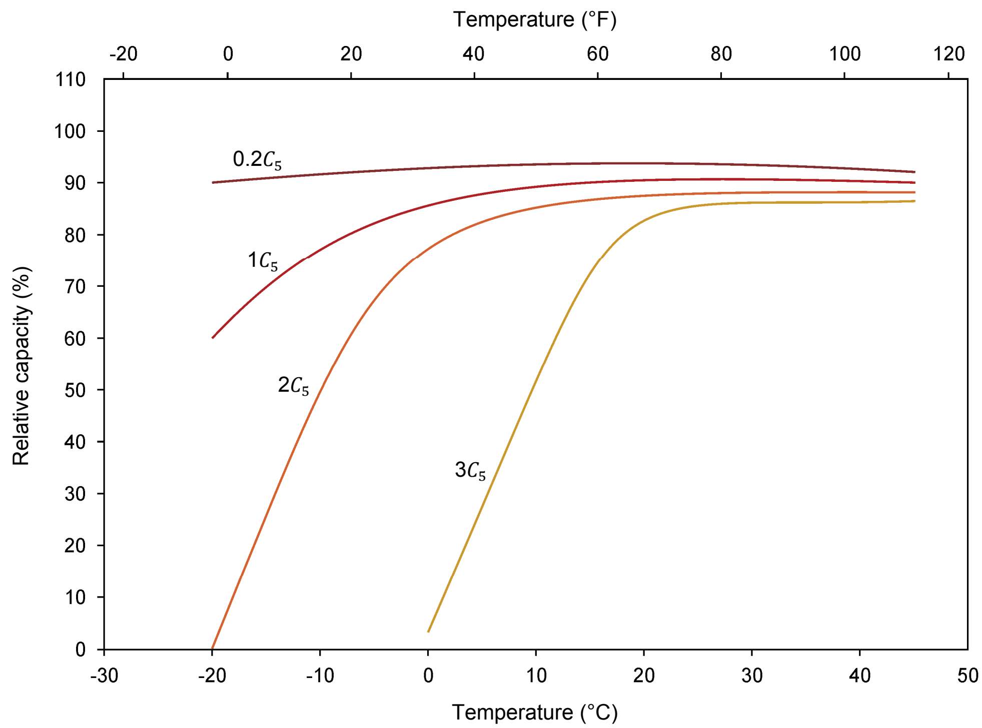


Figure 16. Relative capacity of a Ni-MH battery versus temperature at various discharge rates.

Memory effect

The **memory effect** is a reversible drop in voltage and loss of capacity that may occur when a Ni-MH battery is repeatedly discharged partially and recharged without the benefit of a full discharge in between. This phenomenon is also called **voltage depression** and can be reversed by performing a few subsequent full-discharge cycles. Figure 17 shows the effect of partial-discharge cycles on the cell voltage and capacity of a Ni-MH battery, as well as the reversal of this effect through repetitive full-discharge cycles.

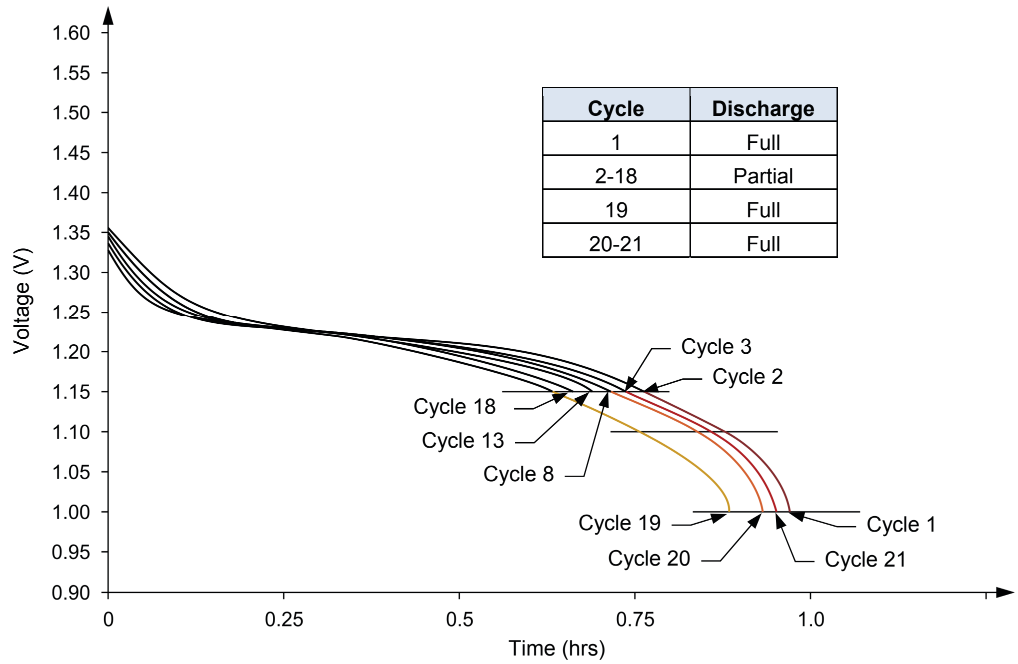


Figure 17. Voltage depression during partial cycling on a Ni-MH battery.

In Figure 17, after a full-discharge cycle (cycle 1), the Ni-MH battery went through a series of 18 partial-discharge cycles (cycles 2 to 18). On the subsequent full-discharge cycle (cycle 19), the observed voltage and capacity are significantly lower than those observed in cycle 1. However, after a few full-discharge cycles (cycles 20 and 21), the voltage and capacity of the battery are nearly restored to their initial values.

Energy supplied during a discharge cycle

A watt-hour (W·h) is a unit of energy, equal to the work done by a power of one watt (1 W) acting for one hour. Note that the symbol “Wh” is also widely used to represent the watt-hour.

Each discharge characteristic curve can be used to determine the amount of energy that a battery releases during a complete discharge. This is carried out by determining the average battery voltage during the complete discharge, multiplying this voltage by the discharge current to find the average power, and then multiplying the calculated average power by the discharge time. The released energy is expressed in **watt-hours** (W·h).

Example

Suppose a Ni-MH battery having a capacity C_5 of 50 Ah is discharged at a rate of 0.2C_5, i.e., a constant current of 10 A. Also suppose that the average voltage during the discharge is 12 V. In this case, the average power the battery delivers is equal to: 12 V × 10 A = 120 W. The energy supplied during the complete discharge cycle of 5 hours is thus equal to: 120 W × 5 h = 600 Wh.

Specific energy and energy density

The energy contained in a battery is often expressed as a ratio related to either the battery weight or volume. The ratio of battery energy to battery weight, called **specific energy**, is calculated by dividing the energy supplied by the battery during a complete discharge cycle by the battery's weight. The specific energy of Ni-MH batteries currently available does not exceed 80 Wh/kg (36.3 Wh/lb). This is about twice as much as lead-acid batteries (40 Wh/kg or 18.1 Wh/lb), but only half the specific energy of Li-ion batteries (160 Wh/kg or 75.6 Wh/lb).

The ratio of battery energy to battery volume, called **energy density**, is calculated by dividing the energy supplied by the battery during a complete discharge cycle by the battery's volume. The energy density of currently available Ni-MH batteries does not exceed 300 Wh/L (4.92 Wh/in^3). This is about four times the energy density of lead-acid batteries (75 Wh/L or 1.23 Wh/in^3), but about 80% of the energy density of Li-ion batteries (360 Wh/L or 5.90 Wh/in^3).

The specific energy and energy density of a battery usually depend on the discharge rate. In the case of Ni-MH batteries, both decrease only slightly as the discharge rate increases because the battery capacity decreases very little when the discharge rate increases. Ni-MH batteries thus generally offer better performances than lead-acid batteries at high discharge rates (more than 1C_5), i.e., in most deep-cycle applications such as electric bikes, mobility scooters, golf carts, and city cars.

Figure 18 shows the size comparison between a lead-acid battery (black) and a Ni-MH battery (green) having a similar battery capacity (2.3 Ah for the lead-acid battery and 2.0 Ah for the Ni-MH battery). The figure clearly demonstrates that, given a similar battery capacity, Ni-MH batteries occupy a much smaller volume than lead-acid batteries. Likewise, for a similar battery capacity, Ni-MH batteries have a much smaller weight compared to lead-acid batteries. For instance, in the picture below, the lead-acid battery weighs 950 g (2.10 lb), while the Ni-MH battery weighs 285 g (0.63 lb).

Figure 18. Size comparison between a lead-acid battery (black) and a Ni-MH battery (green) having similar battery capacities (2.3 Ah and 2.0 Ah, respectively).

Procedure Outline

The Procedure is divided into the following sections:

- Set up and connections
- Battery voltage and energy supplied during a discharge at $1C_5$
- Battery voltage and energy supplied during a discharge at $2C_5$
- Battery capacity versus discharge rate
- Specific energy and energy density

Procedure

WARNING

High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

Set up and connections

In this section, you will set up and connect the equipment.

All exercises should ideally be performed at an ambient temperature between 20°C (68°F) and 25°C (77°F).

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform this exercise.

   Make sure that the serial number of the Ni-MH Batteries module you are using corresponds to the Ni-MH Batteries module serial number you noted in step 24 of Exercise 1. This ensures that the results you will obtain during the discharge cycles in this exercise are consistent with the results you obtained during the $0.5C_5$ discharge cycle in Exercise 1.

Install the required equipment in the Workstation.

2. Before you continue this section, make sure that both batteries in the Ni-MH Batteries module are fully charged by performing the "Battery state-of-charge evaluation" described in the procedure of Exercise 1.

3. Make sure the main power switch on the Four-Quadrant Dynamometer/ Power Supply is set to the O (off) position, then connect its *Power Input* to an ac power outlet.

4. Connect the USB port of the Four-Quadrant Dynamometer/ Power Supply to a USB port of the host computer.

5. Turn the Four-Quadrant Dynamometer/Power Supply on, then set the *Operating Mode* switch to *Power Supply*.

6. Turn the host computer on, then start the LVDAC-EMS software.

In the LVDAC-EMS Start-Up window, make sure the Four-Quadrant Dynamometer/Power Supply is detected. Select the network voltage and frequency that correspond to the voltage and frequency of the local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

7. Connect the battery of the Ni-MH Batteries module you used for the $0.5C_5$ discharge (see step 24 of Exercise 1) to the Four-Quadrant Dynamometer/Power Supply, as shown in Figure 19.

Connect the thermistor inputs of the Four-Quadrant Dynamometer/Power Supply to the thermistor of the Ni-MH battery to be discharged (without connecting the series resistor).

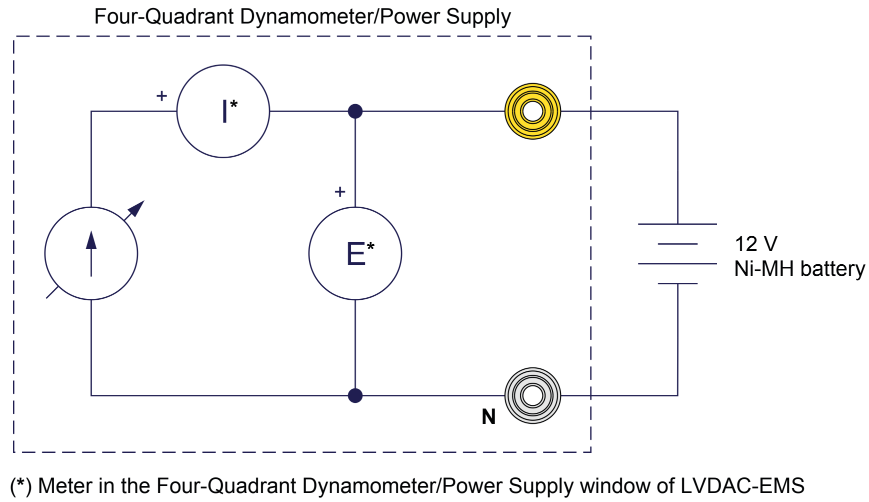


Figure 19. Ni-MH battery connected to the Four-Quadrant Dynamometer/Power Supply operating as a battery discharger.

Battery voltage and energy supplied during a discharge at $1C_5$

In this section, you will measure the battery voltage and energy supplied related to a Ni-MH battery during discharge at a rate of $1C_5$. You will use the obtained data to plot a battery discharge curve later in the exercise.

8. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:

   – Set the *Function* parameter to *Battery Discharger*.

   – Set the *Discharge Current* parameter to 2 A ($1C_5$).

   – Set the *Discharge Duration* parameter to 70 min.

   – Set the *Cutoff Voltage* parameter to 10.0 V (value recommended by the battery manufacturer).

   Also, reset the Energy Meter to make sure that the amount of energy discharged from the battery is currently equal to 0.00 Wh.

9. In LVDAC-EMS, open the Data Table window. Set the timer to make 140 records with an interval of 30 seconds between each record. This setting corresponds to a 70-minute period of observation.

   Set the Data Table to record the voltage, current, and energy indicated by the meters in the Four-Quadrant Dynamometer/Power Supply window, and the time associated with each record.

10. In the Four-Quadrant Dynamometer/Power Supply window, start the *Battery Discharger* then immediately start the timer in the Data Table window to begin recording data.

11. About 15 minutes after the battery discharge began, measure the battery voltage using an external multimeter. Compare the voltage measured with the multimeter with that indicated by the voltmeter on the Four-Quadrant Dynamometer/Power Supply. If the values differ, correct the cutoff voltage of the *Battery Discharger* accordingly. For example, if the module voltmeter underestimates the battery voltage by 0.3 V, reduce the cutoff voltage to 9.7 V to ensure the discharge terminates when the battery voltage is actually 10.0 V.

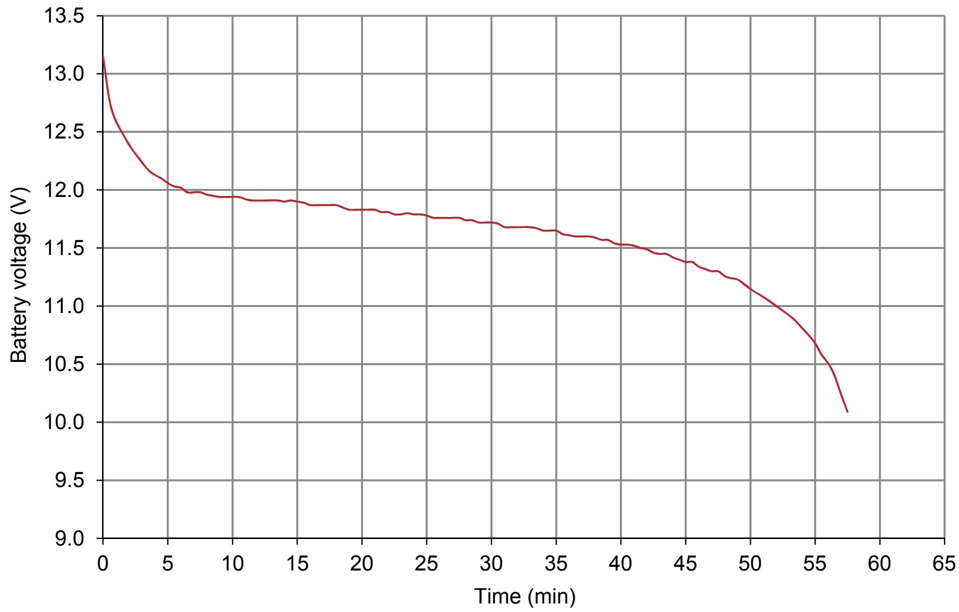
12. Once the *Battery Discharger* stops, stop the timer in the Data Table window to stop recording data, then save the recorded data.

The results are presented in the following table.

Time (s)	Volt (V)	Current (A)	Energy (Wh)
0	13.15	-1.850	-0.01
30	12.77	-2.008	-0.22
60	12.59	-2.008	-0.44
90	12.49	-2.008	-0.65
120	12.39	-2.008	-0.85
150	12.31	-2.008	-1.06
180	12.24	-2.008	-1.27
210	12.17	-2.008	-1.47
240	12.13	-2.008	-1.67
270	12.10	-2.008	-1.88
300	12.06	-2.008	-2.08
330	12.03	-2.008	-2.28
360	12.02	-2.008	-2.48
390	11.98	-2.008	-2.68
420	11.98	-2.008	-2.88
450	11.98	-2.008	-3.08
480	11.96	-2.008	-3.28
510	11.95	-2.008	-3.48
540	11.94	-2.008	-3.68
570	11.94	-2.008	-3.88
600	11.94	-2.009	-4.08
630	11.94	-2.008	-4.28
660	11.92	-2.008	-4.48
690	11.91	-2.008	-4.68
720	11.91	-2.008	-4.88
750	11.91	-2.008	-5.08
780	11.91	-2.008	-5.28
810	11.91	-2.008	-5.48
840	11.90	-2.007	-5.68
870	11.91	-2.008	-5.88
900	11.90	-2.007	-6.08
930	11.89	-2.008	-6.27
960	11.87	-2.007	-6.47
990	11.87	-2.008	-6.67
1020	11.87	-2.008	-6.87
1050	11.87	-2.008	-7.07
1080	11.87	-2.009	-7.26
1110	11.85	-2.008	-7.46
1140	11.83	-2.008	-7.66
1170	11.83	-2.008	-7.86
1200	11.83	-2.008	-8.06

Time (s)	Volt (V)	Current (A)	Energy (Wh)
1230	11.83	-2.008	-8.26
1260	11.83	-2.008	-8.45
1290	11.81	-2.007	-8.65
1320	11.81	-2.008	-8.85
1350	11.79	-2.008	-9.05
1380	11.79	-2.008	-9.24
1410	11.80	-2.008	-9.44
1440	11.79	-2.008	-9.64
1470	11.79	-2.009	-9.84
1500	11.78	-2.008	-10.03
1530	11.76	-2.009	-10.23
1560	11.76	-2.008	-10.43
1590	11.76	-2.007	-10.62
1620	11.76	-2.008	-10.82
1650	11.76	-2.007	-11.02
1680	11.74	-2.008	-11.21
1710	11.74	-2.008	-11.41
1740	11.72	-2.008	-11.61
1770	11.72	-2.006	-11.80
1800	11.72	-2.007	-12.00
1830	11.71	-2.007	-12.19
1860	11.68	-2.008	-12.39
1890	11.68	-2.009	-12.59
1920	11.68	-2.008	-12.78
1950	11.68	-2.008	-12.98
1980	11.68	-2.008	-13.17
2010	11.67	-2.008	-13.37
2040	11.65	-2.008	-13.56
2070	11.65	-2.008	-13.76
2100	11.65	-2.008	-13.95
2130	11.62	-2.008	-14.15
2160	11.61	-2.008	-14.34
2190	11.60	-2.008	-14.54
2220	11.60	-2.008	-14.73
2250	11.60	-2.007	-14.92
2280	11.59	-2.007	-15.12
2310	11.57	-2.007	-15.31
2340	11.57	-2.008	-15.51
2370	11.54	-2.008	-15.70
2400	11.53	-2.008	-15.89
2430	11.53	-2.008	-16.09
2460	11.52	-2.008	-16.28
2490	11.50	-2.008	-16.47
2520	11.49	-2.008	-16.66
2550	11.46	-2.007	-16.86
2580	11.45	-2.008	-17.05
2610	11.45	-2.007	-17.24
2640	11.42	-2.008	-17.43
2670	11.40	-2.008	-17.62
2700	11.38	-2.008	-17.81
2730	11.38	-2.008	-18.00
2760	11.34	-2.007	-18.19
2790	11.32	-2.007	-18.38
2820	11.30	-2.008	-18.57
2850	11.30	-2.008	-18.76
2880	11.26	-2.008	-18.95
2910	11.24	-2.007	-19.14
2940	11.23	-2.009	-19.33
2970	11.19	-2.008	-19.51
3000	11.15	-2.008	-19.70
3030	11.11	-2.008	-19.89
3060	11.08	-2.008	-20.07
3090	11.04	-2.008	-20.26
3120	11.00	-2.008	-20.44
3150	10.96	-2.008	-20.62
3180	10.92	-2.008	-20.81
3210	10.87	-2.008	-20.99

Time (s)	Volt (V)	Current (A)	Energy (Wh)
3240	10.81	-2.007	-21.17
3270	10.75	-2.008	-21.35
3300	10.68	-2.008	-21.53
3330	10.58	-2.008	-21.71
3360	10.51	-2.008	-21.89
3390	10.40	-2.009	-22.06
3420	10.24	-2.008	-22.23
3450	10.09	-2.008	-22.40
End of discharge			



Battery voltage versus time at a discharge rate of $1C_5$.

13. Record the duration of the discharge cycle at a rate of $1C_5$.

Discharge duration: _______ min

Discharge duration: 57.5 min (3450 s)

Battery voltage and energy supplied during a discharge at $2C_5$

In this section, you will measure the battery voltage and energy supplied related to a Ni-MH battery during discharge at a rate of $2C_5$. You will use the obtained data to plot a battery discharge curve later in the exercise.

14. Replace the battery connected to the Four-Quadrant Dynamometer/Power Supply by the other battery (fully charged) of the Ni-MH Batteries module.

Connect the thermistor inputs of the Four-Quadrant Dynamometer/Power Supply to the thermistor of the Ni-MH battery to be discharged (without connecting the series resistor).

15. In the Four-Quadrant Dynamometer/Power Supply window, make the following settings:

– Set the *Discharge Current* parameter to 4 A ($2C_5$).

– Set the *Discharge Duration* parameter to 40 min.

– Set the *Cutoff Voltage* parameter to 10.0 V (value recommended by the battery manufacturer).

Also, reset the Energy Meter to make sure that the amount of energy discharged from the battery is currently equal to 0.00 Wh.

16. Open a new data table in the Data Table window and set the timer to make 160 records with an interval of 15 seconds between each record. This setting corresponds to a 40-minute period of observation.

Set the Data Table to record the voltage, current, and energy indicated by the meters in the Four-Quadrant Dynamometer/Power Supply window, and the time associated with each record.

In the Four-Quadrant Dynamometer/Power Supply window, start the *Battery Discharger* then immediately start the timer in the Data Table window to begin recording data.

17. About 15 minutes after the battery discharge began, measure the battery voltage using an external multimeter. Compare the voltage measured with the multimeter with that indicated by the voltmeter on the *Four-Quadrant Dynamometer/Power Supply*. If the values differ, correct the cutoff voltage of the *Battery Discharger* accordingly. For example, if the module voltmeter underestimates the battery voltage by 0.3 V, reduce the cutoff voltage to 9.7 V to ensure the discharge terminates when the battery voltage is actually 10.0 V.

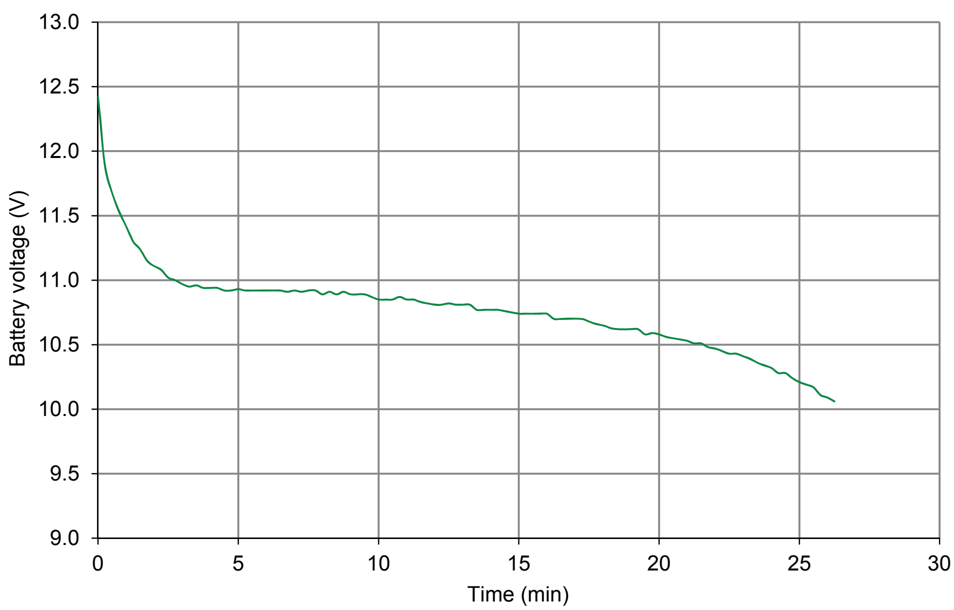
18. Once the *Battery Discharger* stops, stop the timer in the Data Table window to stop recording data, then save the recorded data.

The results are presented in the following table.

Time (s)	Volt (V)	Current (A)	Energy (Wh)
0	12.42	-3.781	0.00
15	11.88	-4.007	-0.20
30	11.68	-4.008	-0.39
45	11.53	-4.007	-0.59
60	11.42	-4.007	-0.78
75	11.30	-4.007	-0.97
90	11.24	-4.006	-1.16

Time (s)	Volt (V)	Current (A)	Energy (Wh)
105	11.15	-4.005	-1.34
120	11.11	-4.006	-1.53
135	11.08	-4.001	-1.72
150	11.02	-4.008	-1.90
165	11.00	-4.005	-2.08
180	10.97	-4.007	-2.27
195	10.95	-4.010	-2.45
210	10.96	-4.006	-2.63
225	10.94	-4.006	-2.82
240	10.94	-4.006	-3.00
255	10.94	-4.008	-3.18
270	10.92	-4.009	-3.36
285	10.92	-4.004	-3.55
300	10.93	-4.004	-3.73
315	10.92	-4.006	-3.91
330	10.92	-4.002	-4.09
345	10.92	-4.005	-4.28
360	10.92	-4.004	-4.46
375	10.92	-4.006	-4.64
390	10.92	-4.006	-4.82
405	10.91	-4.009	-5.00
420	10.92	-4.007	-5.19
435	10.91	-4.006	-5.37
450	10.92	-4.009	-5.55
465	10.92	-4.005	-5.73
480	10.89	-4.009	-5.92
495	10.91	-4.006	-6.10
510	10.89	-4.005	-6.28
525	10.91	-4.006	-6.46
540	10.89	-4.008	-6.64
555	10.89	-4.003	-6.82
570	10.89	-4.009	-7.01
585	10.87	-4.006	-7.19
600	10.85	-4.007	-7.37
615	10.85	-4.006	-7.55
630	10.85	-4.006	-7.73
645	10.87	-4.008	-7.91
660	10.85	-4.005	-8.09
675	10.85	-4.007	-8.28
690	10.83	-4.007	-8.46
705	10.82	-4.007	-8.64
720	10.81	-4.007	-8.82
735	10.81	-4.005	-9.00
750	10.82	-4.005	-9.18
765	10.81	-4.008	-9.36
780	10.81	-4.008	-9.54
795	10.81	-4.005	-9.72
810	10.77	-4.008	-9.90
825	10.77	-4.006	-10.08
840	10.77	-4.006	-10.26
855	10.77	-4.006	-10.44
870	10.76	-4.007	-10.62
885	10.75	-4.006	-10.80
900	10.74	-4.007	-10.98
915	10.74	-4.007	-11.16
930	10.74	-4.008	-11.34
945	10.74	-4.005	-11.52
960	10.74	-4.008	-11.70
975	10.70	-4.006	-11.87
990	10.70	-4.007	-12.05
1005	10.70	-4.007	-12.23
1020	10.70	-4.006	-12.41
1035	10.70	-4.007	-12.59
1050	10.68	-4.007	-12.77
1065	10.66	-4.007	-12.95
1080	10.65	-4.005	-13.12
1095	10.63	-4.007	-13.30

Time (s)	Volt (V)	Current (A)	Energy (Wh)
1110	10.62	-4.007	-13.48
1125	10.62	-4.007	-13.66
1140	10.62	-4.006	-13.83
1155	10.62	-4.007	-14.01
1170	10.58	-4.006	-14.19
1185	10.59	-4.007	-14.36
1200	10.58	-4.007	-14.54
1215	10.56	-4.007	-14.72
1230	10.55	-4.006	-14.89
1245	10.54	-4.006	-15.07
1260	10.53	-4.008	-15.25
1275	10.51	-4.006	-15.42
1290	10.51	-4.008	-15.60
1305	10.48	-4.006	-15.77
1320	10.47	-4.007	-15.95
1335	10.45	-4.006	-16.12
1350	10.43	-4.007	-16.30
1365	10.43	-4.006	-16.47
1380	10.41	-4.007	-16.64
1395	10.39	-4.007	-16.82
1410	10.36	-4.007	-16.99
1425	10.34	-4.006	-17.16
1440	10.32	-4.006	-17.34
1455	10.28	-4.007	-17.51
1470	10.28	-4.007	-17.68
1485	10.24	-4.006	-17.85
1500	10.21	-4.006	-18.02
1515	10.19	-4.007	-18.19
1530	10.17	-4.006	-18.36
1545	10.11	-4.007	-18.53
1560	10.09	-4.006	-18.70
1575	10.06	-4.007	-18.87
1590	9.98	-4.006	-19.04
End of discharge			



Battery voltage versus time at a discharge rate of 2C_5.

19. Record the duration of the discharge cycle at a rate of $2C_5$.

Discharge duration: _______ min

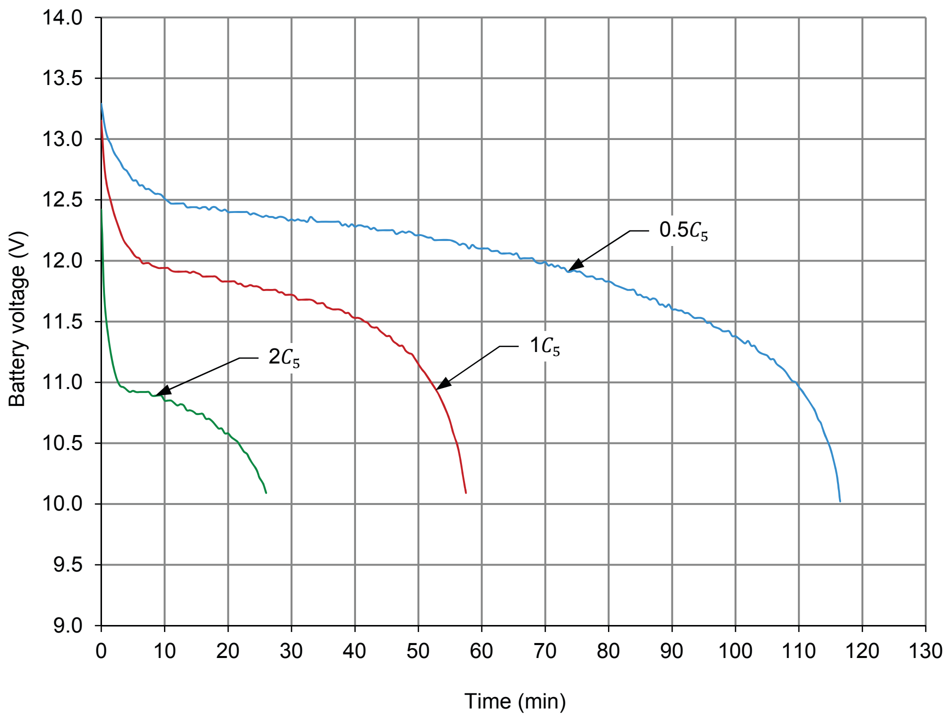
Discharge duration: 26.5 min (1590 s)

Battery capacity versus discharge rate

In this section, you will plot the discharge curves of a Ni-MH battery using the data recorded during the discharge tests at rates of $0.5C_5$, $1C_5$, and $2C_5$. You will also determine the battery capacity at various discharge rates and plot the graph of the battery capacity versus discharge rate.

20. Export your data recorded at discharge rates of $0.5C_5$ (obtained in Exercise 1), $1C_5$, and $2C_5$ to a spreadsheet application. Using the data measured until the voltage cutoff is reached during each discharge, plot the battery discharge curves at $0.5C_5$, $1C_5$, and $2C_5$ (battery voltage versus time).

The results are shown in the following figure.



Battery discharge curves at $0.5C_5$, $1C_5$, and $2C_5$.

21. From the curves you plotted in the previous step, determine the discharge time to the specified cutoff voltage, expressed in hours, for each discharge rate ($0.5C_5$, $1C_5$, and $2C_5$). Record your results in the appropriate cells of Table 4.

The discharge time, capacity in Ah, and capacity in % for a discharge rate of $0.2C_5$ are already provided in Table 4.

22. Calculate the capacity of the battery at $0.5C_5$, $1C_5$, and $2C_5$ from the curves you plotted in the previous step. Use the following suggested equation: capacity = discharge current × discharge time to the specified cutoff voltage. Record your results (expressed in Ah) in the appropriate cells of Table 4.

23. Express your calculated capacity values as a percentage of the nominal capacity C_5 of the battery. Record your results in the appropriate cells of Table 4.

Table 4. Capacity and discharge time of a Ni-MH battery in relation to the discharge current.

Discharge rate	Discharge current (A)	Discharge time (min)	Capacity (Ah)	Capacity (%)
$0.2C_5$	0.40	305	2.03	102
$0.5C_5$	1.00			
$1C_5$	2.00			
$2C_5$	4.00			

The results are presented in the following table.

Capacity and discharge time of a Ni-MH battery in relation to the discharge current.

Discharge rate	Discharge current (A)	Discharge time (min)	Capacity (Ah)	Capacity (%)
$0.2C_5$	0.40	305	2.03	102
$0.5C_5$	1.00	117	1.94	97.0
$1C_5$	2.00	57.5	1.92	96.0
$2C_5$	4.00	26.5	1.77	88.5

24. Using the data in Table 4, plot a graph of the battery capacity expressed as a percentage of the nominal capacity C_5 versus the discharge rate.

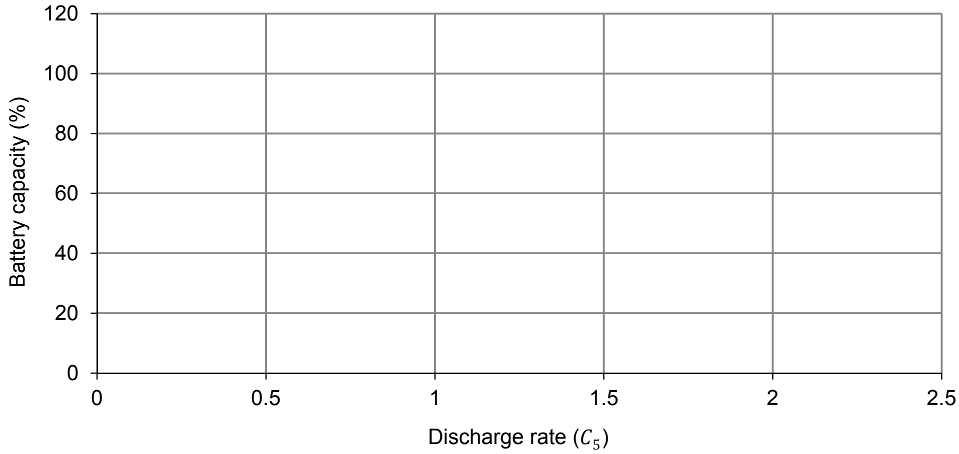
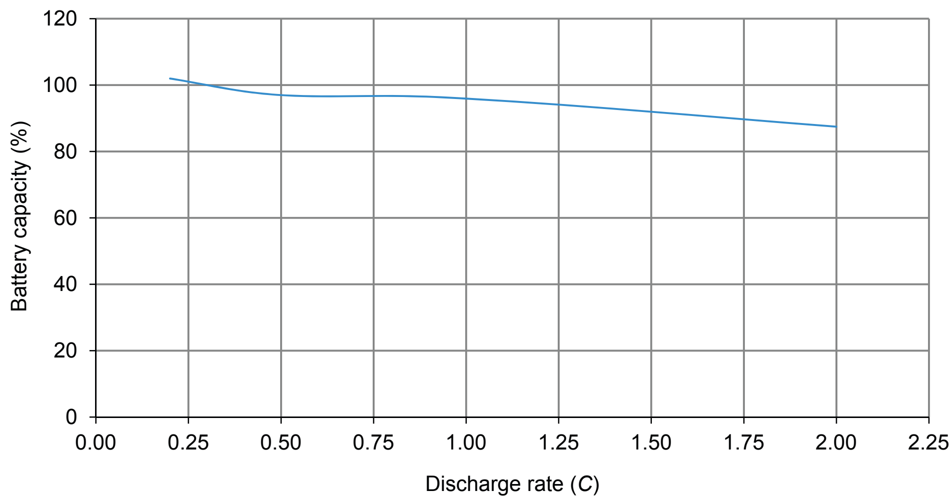


Figure 20. Battery capacity versus discharge rate related to the C_5 capacity.

The results are shown in the following figure.



Battery capacity versus discharge rate related to the C_5 capacity.

25. How does the battery capacity vary as the discharge rate increases?

The battery capacity decreases slightly as the discharge rate increases.

Specific energy and energy density

In this section, you will determine the specific energy and energy density of the Ni-MH batteries. You will then observe how the specific energy and energy density related to the Ni-MH batteries vary with the discharge rate.

26. Record the amount of energy supplied (in Wh) for each discharge rate ($0.5C_5$, $1C_5$, and $2C_5$) in the second column of Table 5. Then, calculate the specific energy of the Ni-MH batteries for each discharge rate using the measured released energy values, and record your results in the third column of Table 5. Assume that the weight of each battery in the Ni-MH Batteries module is 0.285 kg (0.628 lb).

Calculate the energy density of the Ni-MH batteries for each discharge rate ($0.5C_5$, $1C_5$, and $2C_5$) using the measured released energy values, and record your results in the fourth column of Table 5. Assume that the volume of each battery in the Ni-MH Batteries module is 0.0762 L (4.65 in^3).

Table 5. Specific energy and energy density of the Ni-MH batteries at discharge rates of $0.5C_5$, $1C_5$, and $2C_5$.

Discharge rate	Released energy (Wh)	Specific energy (Wh/kg or Wh/lb)	Energy density (Wh/L or Wh/in^3)
$0.5C_5$			
$1C_5$			
$2C_5$			

The results are presented in the following tables.

Specific energy and energy density of the Ni-MH batteries at discharge rates of $0.5C_5$, $1C_5$, and $2C_5$.

Discharge rate	Released energy (Wh)	Specific energy [Wh/kg (Wh/lb)]	Energy density [Wh/L (Wh/in^3)]
$0.5C_5$	23.4	82.1 (37.3)	307 (5.03)
$1C_5$	22.4	78.6 (35.7)	294 (4.82)
$2C_5$	19.0	66.7 (30.3)	249 (4.09)

27. How do the specific energy and energy density vary when the discharge rate increases?

Both the specific energy and energy density decrease slightly as the discharge rate increases.

28. Close LVDAC-EMS, then turn off all the equipment. Disconnect all leads and return them to their storage location.

Conclusion

In this exercise, you became familiar with the effects of the discharge rate and battery temperature on the capacity and voltage of a Ni-MH battery. You learned how to calculate the energy supplied during a discharge cycle. You also learned what the specific energy and the energy density of a battery are, and how to determine these two parameters.

Review Questions

1. When a Ni-MH battery discharges at a high current rate ($1C_5$ and more), what happens to the voltage measured across the battery and to its relative battery capacity?

   The higher the current rate, the lower the measured voltage across the battery. Similarly, the higher the current rate, the less available relative battery capacity during the discharge cycle.

2. What is the effect of ambient temperature on the relative capacity of a Ni-MH battery at low discharge rates (about $0.2C_5$)? At high discharge rates (about $3C_5$)?

   At low discharge rates, ambient temperature does not significantly reduce the relative capacity of a Ni-MH battery, even at very low temperatures (-20°C or -4°F). When discharging a Ni-MH battery at high current rates, however, the relative battery capacity begins to drop rapidly when the ambient temperature falls below 10°C (50°F).

3. What is the memory effect and how is it possible to cancel its effect?

   The memory effect is a reversible drop in battery voltage that may occur when a battery is repetitively partially discharged and recharged. It is possible to cancel its effect by making the battery go through successive full discharge cycles.

4. Suppose a Ni-MH battery having a capacity C_5 of 15 Ah is discharged at a rate of $0.2C_5$, i.e., a constant current of 3 A. Also suppose that the average voltage during the discharge is 10 V. Calculate the amount of energy supplied by the battery during the complete discharge cycle of 5 hours.

   The average power the battery delivers is equal to: 10 V · 3 A = 30 W. The energy supplied by the battery during the complete discharge cycle of 5 hours is thus equal to: 30 W · 5 h = 150 Wh.

5. Suppose that a 12 V Ni-MH battery releases a total of 12 Wh during a full-discharge cycle. If it has a weight of 0.18 kg (0.40 lb) and a volume of 0.05 L (3.05 in^3), what are its specific energy and energy density?

The specific energy of the battery is 66.7 Wh/kg (12 Wh ÷ 0.18 kg) or 30 Wh/lb (12 Wh ÷ 0.40 lb). The energy density of the battery is 240 Wh/L (12 Wh ÷ 0.05 L) or 3.93 Wh/in^3 (12 Wh ÷ 3.05 in^3).

Bibliography

Linden, David, and Reddy, Thomas B., *Handbook of Batteries*, 3d ed. New York: McGraw-Hill, 2002, ISBN 0-07-135978-8.