

“abc” Course on BATTERY TESTING

Summary

The purpose of the course “*abc*” *Battery Testing* is to familiarise the students with the basic Nomenclature and Definitions of the *Electrochemical Energy Sources*. The course is designed primarily for beginners. It can be used also by PhD students and Post – Doc’s working in the fields of chemistry, electrochemistry and electrochemical power sources.

The course contains 6 lectures and a discussion:

1. Preliminaries: Electric Current, Voltage, Power, Energy, Resistance; Basic Electric Laws.
2. Batteries as Sources of Energy (Basic Knowledge): Nominal Voltage, Capacity, Specific Energy & Specific Power.
3. Modes of operation: Galvanostatic, Potentiostatic, Power-static, R-static.
4. Testing modes: Charge, Discharge, Life Cycling, Special Test Modes.
5. Load Characteristic. Discharge characteristics. Charge characteristics.
6. Life Performance. Specific Relations: Rate of Discharge, “Ragone” – dependence; State of Charge, State of Health.

D. Specific problems related to the Portable & Emergency Energy Sources.

The lectures are supplemented by practical exercises elucidating the material.

The lectures are presented in Bulgarian, following the classical lecturing routine; the English thesaurus is used, too.

The Tutor is supported by two assistants (highly-active students) preparing the notes of the course and the graphical material necessary for the building of the e – version of the course. The course finished with a test (in Bulgarian) and a conversation – in English.

abc Testing

The course "*abc*" *Testing* is prepared as general preliminary information for engineers and chemists, beginners in the field of battery testing and investigation. The course is part of the educational programme of the Project POEMES. The ensuing material represents the record of the presented during the course lectures delivered to POEMES Project's beginners in November 2003.

BATTERIES AS SYSTEMS UNDER STUDY

From system theory point of view the electrochemical power sources are large, non-linear, quasi-reversible and non-stationary systems with distributed parameters in macro- and micro- scale. During their operation, processes of mass and energy transfer take place on the electrodes. They change the electrochemical kinetics, the electrodes morphology and structure as well as the external battery behaviour and determine the strong dependence between the spaces of parameters and state. The batteries are systems with memory and could be presented as long Markov's chains.

Markov's chain: The term given by Markov has a wide application in statistics and in physical chemistry. For a system of this type, the probability for a given state is a function of a number of former states. The Markov's chains can be:

Short:

$$P_{n+1}(A) = f[P_n(B)];$$

Long:

$$P_{n+1}(A) = F[P_n(B), P_{n-k}(C_k)],$$
$$k=1,2,3\dots m.$$

1. PRELIMINARIES

1. **Electric Charge (q)**: Its unit is the Coulomb [C]. The elementary charge of the electron is a fundamental physical constant. It has the value of:

$$e_0 = 1.602\ 176\ 462(63) \times 10^{-19}\ \text{C}$$

2. **Electric current (I)** is any flow of charge, generally through a metal wire or some other electrical conductor. The SI unit of I is the Ampere [A]. The electric current can be directly measured with an ammeter, connected in series in the circuit. The large amperages can be measured by means of a shunt.

3. **Amount of charge (Q)**: The SI unit of Q is the Coulomb [C] and is defined in terms of the ampere-second: 1 coulomb is the amount of electric charge carried by a current of 1 ampere flowing for 1 second.

$$Q = I \cdot t$$

4. **Electric potential (E)**: It is a scalar field and it has a magnitude, but no direction, at every point in space. It determines (for a given system at a given point) the work needed to move a single charge to infinity. The electrical potential is measured in units of energy per unit of electric charge [J/C]=[V].

5. **Voltage (U)**: The potential difference between two points in the electric field. Its SI unit is volt [V]. The Electric Voltage can be directly measured with a voltmeter, connected in parallel to the measured object in the circuit.

6. **Power (P)**: The power consumed by an electrical device is the product of the voltage and the current passing through the device. That is,

$$\mathbf{P = U \cdot I}$$

Power is the amount of work completed per unit of time. The SI unit of power is the Watt, which is equal to one Joule per Second.

$$[\mathbf{J/s}] = [\mathbf{A \cdot V}] = [\mathbf{W}]$$

7. **Energy (W)**: It could be defined by:

$$\mathbf{W = P \cdot t}$$

The SI unit of Energy is: $[\mathbf{J}] = [\mathbf{W \cdot sec}]$

$$\mathbf{W = U \cdot I \cdot t;}$$

$$\mathbf{W = U \cdot Q}$$

8. **Resistance (R)**: It is the ratio of the potential difference (i.e. voltage) across an electric component (such as a resistor) to the current passing through it. Its SI unit is Ohm $[\Omega]$

We can always find the equivalent resistance by repeated application of two simple rules. These rules relate to resistors connected in series and in parallel:

In series:

$$R_{\Sigma} = R_1 + R_2$$

In parallel:

$$R_{\Sigma}^{-1} = R_1^{-1} + R_2^{-1}$$

9. **Current density:** $j[\text{A/m}^2]$ is the current per unit (cross-sectional) area.

Basic Electric Laws

1. **Ohm's law** states that the voltage drop V across a resistor is proportional to the current I flowing through it:

$$R = U/I \text{ } [\Omega]$$

2. **Kirchoff's laws**

K1: Kirchoff's first law applies to *junction points* in circuits (*i.e.*, points at which three or more wires or elements come together). The junction rule is: The sum of all the currents entering any junction point is equal to the sum of all the currents leaving that junction point.

K2: Kirchoff's second law applies to *loops* in dc circuits. The loop rule is: The algebraic sum of the changes in electric potential encountered in a complete traversal of any closed loop is equal to zero.

2. THE BATTERIES AS ENERGY SOURCES

A battery is an electrochemical device that stores energy and typically consists of two or more cells. From a user's viewpoint, at least, batteries can be generally divided into two main types - rechargeable and non-rechargeable (disposable).

The disposable batteries are also labelled as primary cells and are intended to be used once, until the chemical changes that induce the electrical current supply are exhausted, at which point the battery is discharged. These are most commonly used in smaller, portable devices with either low current drain, only used intermittently, or well away from an alternative power source.

By contrast, the rechargeable batteries, or secondary cells, can be re-used after being drained. This latter is accomplished by applying externally supplied electrical current, which causes the chemical changes that occur to be reversed. Devices to supply the proper current are called chargers or re-chargers.

Battery Parameters

The batteries can be characterised by the following basic parameters:

1. **Nominal Voltage:** The voltage, which is displayed on the battery label.
2. **Nominal Capacity:** The quantity of electricity the battery can store. The practical unit of electrical capacity is Ampere-hour or Ah. Ah

designates the storage capacity of the battery. Amp-hour capacity will vary with temperature and with the rate of discharge.

3. **Weight G.**
4. **Volume V.**
5. **Specific capacity: Q/G [Ah/kg]; Q/V [Ah/l].**
6. **Specific energy: W/G [Wh/kg]; W/V [Wh/l].**

The other basic battery's parameters like U_{OCV} , Maximal Power, Internal Resistance and others can be illustrated by an important characteristic, designated:

Volt – Ampere characteristic (load characteristic): It gives the correlation between the current and the voltage:

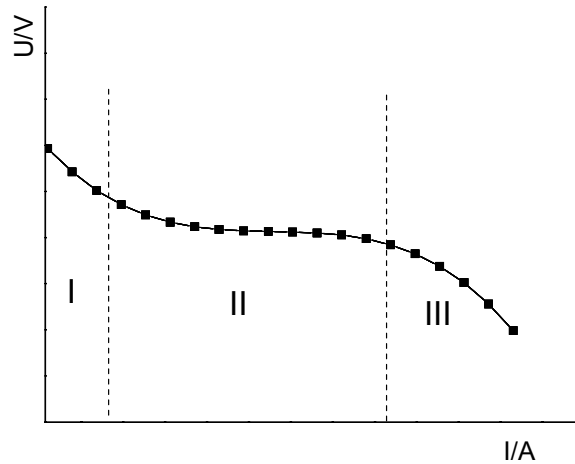


Fig.1. Typical discharge characteristic

The plot can be separated into three zones:

I: When the current values are small an electrochemical kinetics appears and the dependence is non-linear;

II: Here the dependence is quasi-linear and the basic processes are dominated by transport;

III: In this domain a new electrochemical reaction begins to dominate, the latter being generally destructive. This is the reason why this domain is undesirable and in contrast to the first two it is not a working region.

From this characteristic plot some basic parameters can be derived:

1. $R_i = dU/dI$ - it can be determined within the second domain.
2. U_{ocv}^* - can be defined from the approximation of the linear domain to the abscise.
3. Maximal Power.

3. MODES OF OPERATION

The most common types of battery circuit connections are:

- **Two electrode cell (2-pole cell)** - a classical electrochemical cell circuit where the cell connection is by the two electrodes.
- **Three electrode (3-pole) connection.** An electrochemical cell containing a working electrode, a counter electrode and a reference electrode. The current flows between the working and the counter electrodes, while the potential of the working electrode is measured against the reference electrode.
- **Four electrode cell (4 pole).**
- **Five and six poles cells** are also used.

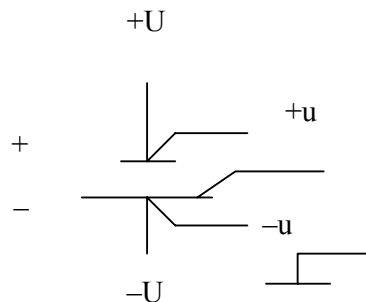


Fig.2. Circuit with three electrodes

Modes of operation:

1. **Galvanostatic mode** ($I=\text{const}$): An electrochemical measuring mode for electrochemical analysis or for the determination of the kinetics and mechanism of electrode reactions based on the control of the current flowing through the system. The control apparatus is called a galvanostat.

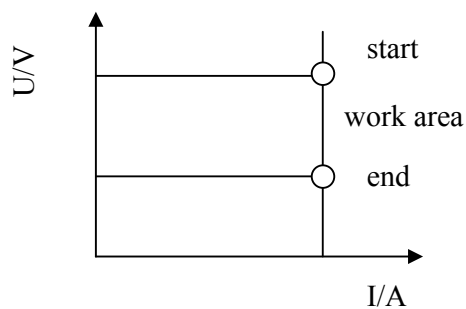


Fig.3. Operating diagram of a Galvanostat

2. **Potentiostatic** ($U=\text{const}$):

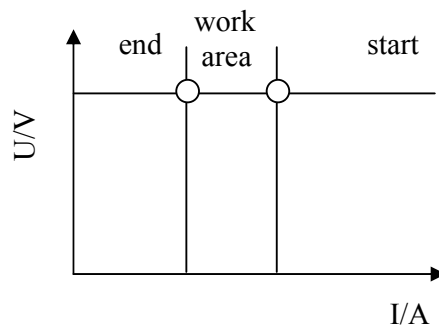


Fig.4. Operating diagram of a Potentiostat

3. **Potential-galvanostatic:** At the beginning of the measuring the mode is galvanostatic and in the special point (cross over point), when the voltage reaches a proper value the mode turns in potentiostatic.

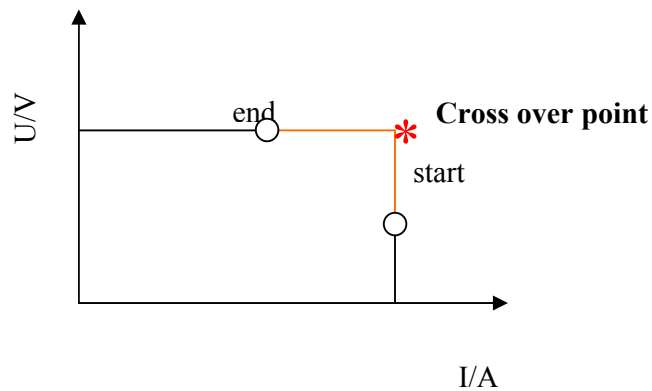


Fig.5. Operating diagram of a Potentio-Galvanostat

4. **Power-static** ($P=\text{const}$)

5. **Resistance-static ($R=\text{const}$)**

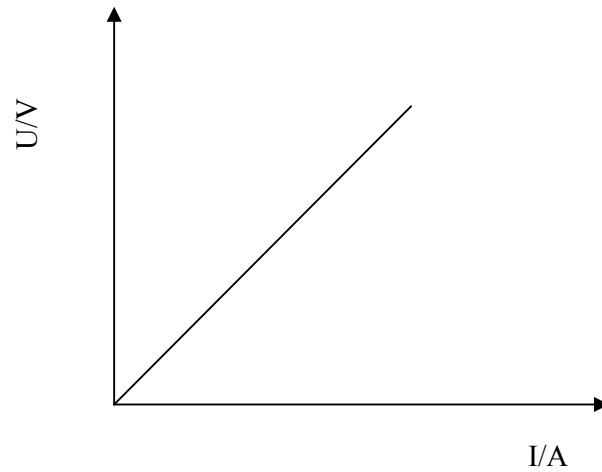


Fig.6. Operating diagram of a Resistance-static mode.

6. **Pulse modes:** The operational mode is typically galvanostatic and the load is pulsing. Different kinds of pulse shapes and number of cycles can be utilised:

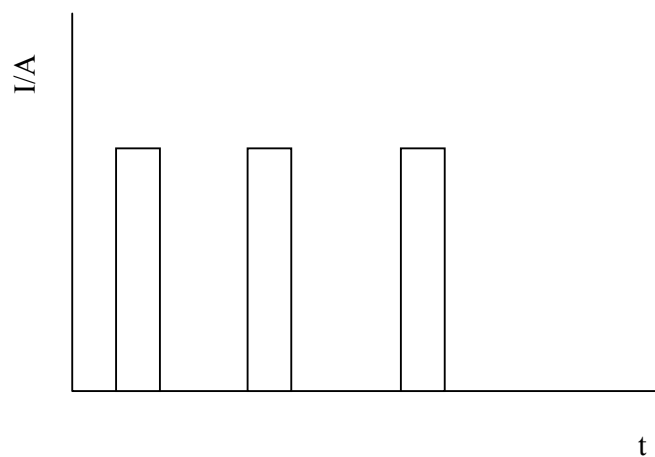
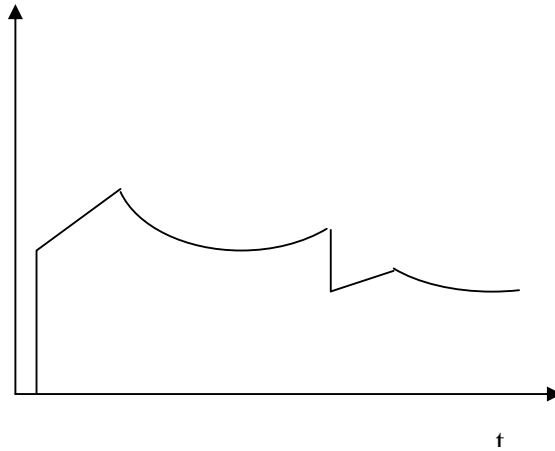


Fig.7. Typical pulse mode of operation.

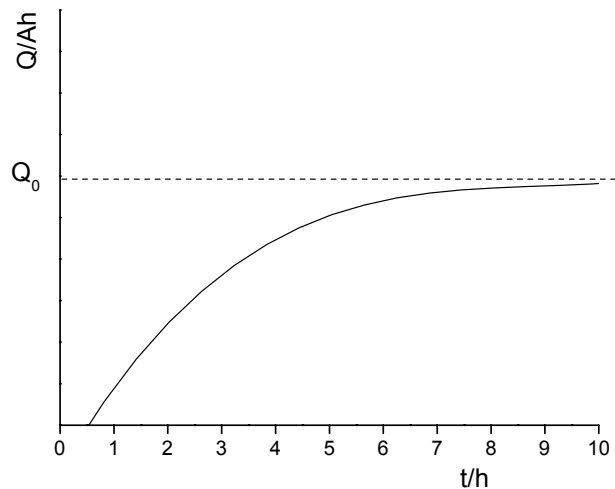
7. Functional mode.

When the profile of the current is predetermined, the load diagram could be programmed:



4. TYPICAL TESTING MODES

Nominal Capacity (QT). It is used for the batteries capacity measurement. It consists of charge and discharge (QT: C, D_Q). The working regime is typically 20h, but in some cases it may be 10h. When this kind of test is executed, the battery under test must be at a definite state of charge, i.e. DSC. Classically this signifies a stationary state, which is defined by the stationarity of both voltage and electrolyte density.



With the decreasing of the working regime, Q also decreases. When the working regime is very short (<1h), Q decreases down to 50%.

Cycling Test (CT): This kind of test includes a large number of cycles(N), which are obtained by combination of charge and discharge.

T_1 is the time for charge and T_2 is the time for discharge. T is the period of the cycle and is equal to: $T = T_1 + T_2$.

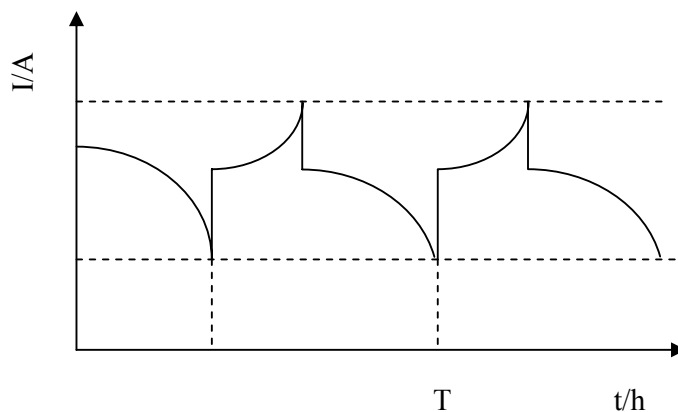
Every testing mode can be described by a number of test-vectors (TV) the sum of which is designated as a test-matrix:

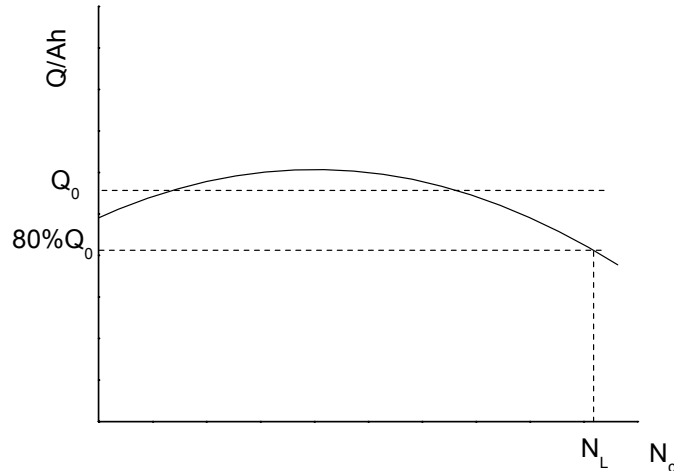
TV1: C: I/t, U, t^0 : 10; 6; 16; 45; 2

TV2: D: I/t, U: 20; 2; 10; 5; 3

TV3: END

Life cycling (Life Test - LT): The life test determines how many times a battery can be cycled before it reaches the point where it can deliver only (customarily) 80% of it's original capacity. This depends on how deep the battery is cycled.





Accelerated Tests: These are used for the approximate evaluation of the battery life.

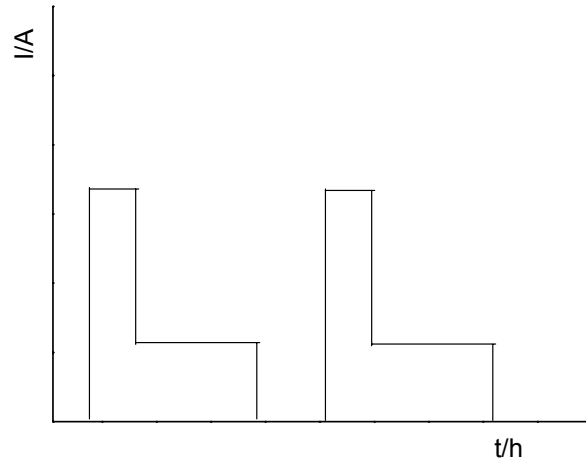
Basic approaches: Temperature rising and heavy pulse testing. An example: Edison's cycle: slow charge and heavy discharge ($5Q_0$).

Self-Discharge Test (SDT): All batteries will "self-discharge" if left with no load. The rate of self-discharge can vary considerably both with the battery type and age. The basic procedure for SDT is:

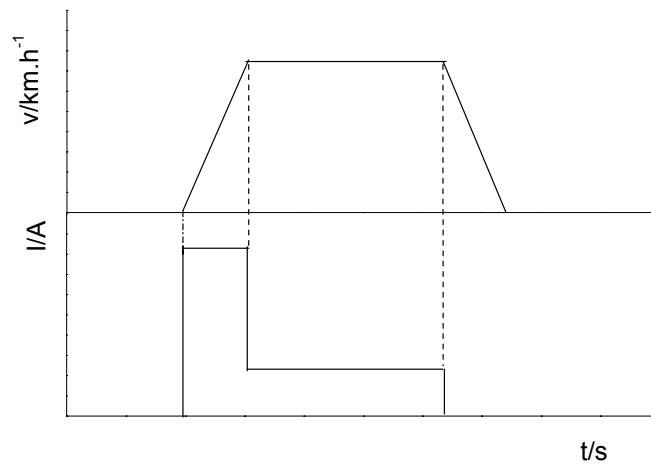
1. DSC; 2. $(QT)_1$; 3. DSC; 4. Shelf Pause; 5. $(QT)_2$

Special Test Modes

GSM-T: The GSM Batteries must meet some special requirements. Unlike analogue equipment that draws a steady current, the digital phone loads the battery with very short and heavy current spikes.



EVT is designed for tests of batteries for electric vehicles. It consists of discharge steps with programmed current (or power) and pause. The test consists of repetition of the test profile (cycling) and registration of the measured data. This kind of the load profile is shown in the following diagram:

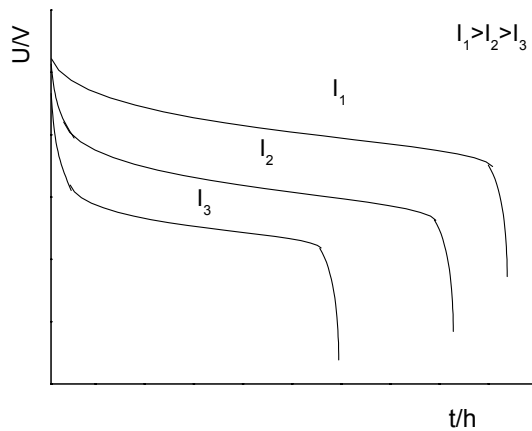
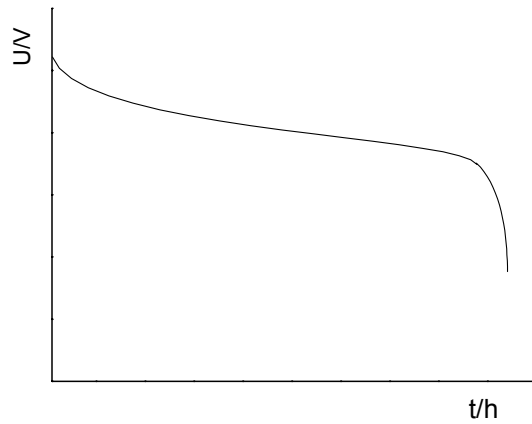


5. LOAD CHARACTERISTIC

Discharge

Discharging is the process of utilising the delivered by the battery power. Depending on the purpose the battery is used for, the energy that a battery

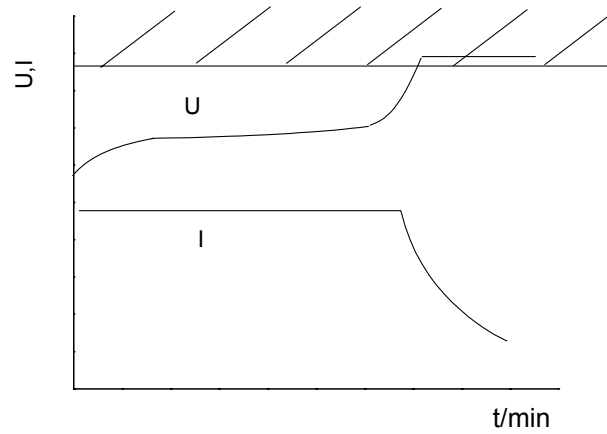
delivers can be specified in different ways. Typical discharge characteristics are illustrated below:



Charge

The limited efficiency of the chemical process within the battery signifies that the energy supplied must be larger than the useful energy output from the battery. It is important that the batteries should be exactly fully charged. All the lead sulphate must be processed into lead oxide in order that the electrodes do not sulphate, which is what happens if the battery is under-charged. If the battery is overcharged, water is lost through gassing, which will cause corrosion of the electrodes. Overcharging can also cause the

temperature inside the battery to rise above the admissible level and damage the battery as a result.

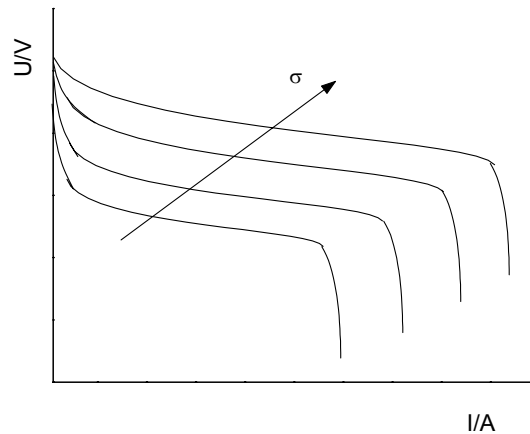


The shape of the curves depends on the mode of operation and the electrochemical nature of the object.

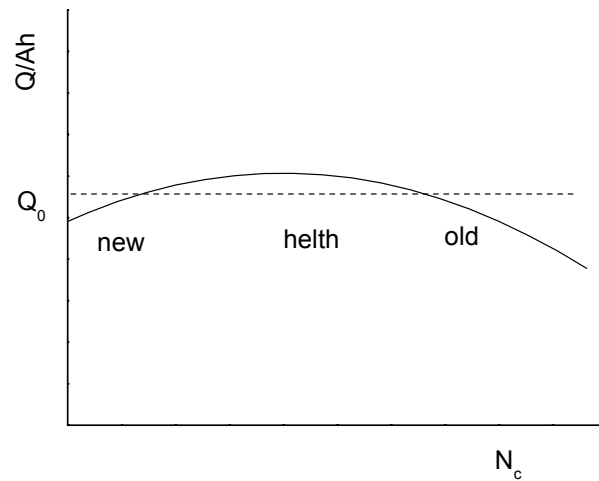
6. LIFE PERFORMANCE

DOD - Depth of Discharge: How much of the available charge has been used compared to the full 100% charge.

SOC (σ) - State of Charge is similar to DOD - it is how much charge is left.



SOH (α) - State of Health: As a battery ages, the maximum amount of charge it can hold will gradually decrease; which is known as a degradation. The status of battery degradation can be referred to as its “state of health”; for example, a battery with a state of health at 70% can only hold a maximum of 70% of its original capacity.



The energy of the system E is a function of the following parameters: nominal voltage, nominal capacity, time, temperature, state of health, depth of discharge, testing regime:

$$E (U_0, Q_0, t, t^0, \alpha, DOD, h).$$