



**UNIVERSITÀ
DEGLI STUDI
DI TRIESTE**



Dipartimento di
**Ingegneria
e Architettura**

ELECTROCHEMICAL MEASUREMENTS

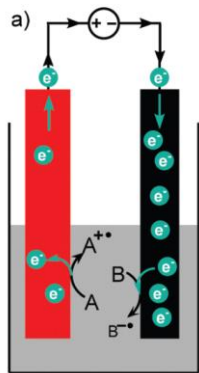
BASICS OF ELECTROCHEMISTRY, ELECTROCHEMICAL DEVICES, AND STANDARDS

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A.A. 2023-2024

ELECTROCHEMISTRY AND THE ELECTROCHEMICAL CELL

Electrochemistry is the science dealing with the interconversion of electrical and chemical energies. In particular, it deals with chemical reactions in which an electron transfer takes place in between two conductive electrodes, divided by an insulating and ionically conductive electrolyte.

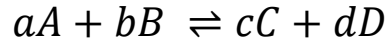


An electrochemical cell is a general device capable of converting chemical energy into electrical one. If current is generated during cell operation, the electrochemical cell is also known as Galvanic electrochemical cell.

In example, the electrochemical cell can be viewed as the fundamental brick constituting batteries.

REDOX (REDUCTION-OXIDATION) REACTIONS

Redox, is a term used to describe a couple of specular electrochemical reactions.



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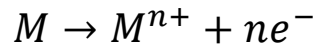
Reduction reaction

the oxidation number of a specimen is reducing (+ e⁻)



Oxidation reaction

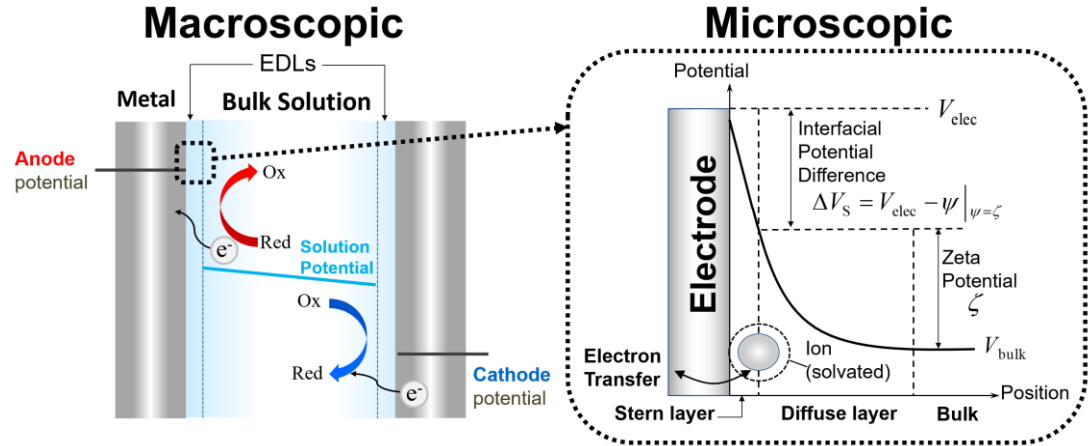
the oxidation number of a specimen is increasing (- e⁻)



PROCESSES AT THE ELECTRODE SURFACE

Processes involved in electrochemical reactions:

1. Transport by diffusion or migration of EC active species towards electrode surface
2. The EC active atom/ion has to adsorb at the electrode surface
3. Charge transfer (redox) has to take place
4. The reacted atom/ion has to desorb from the electrode surface
5. It migrates back in the electrolyte bulk



<https://nanolab.engineering.ucsb.edu/research/electrochemistry-nanoscale>

FUEL CELLS – A BRIEF RECALL

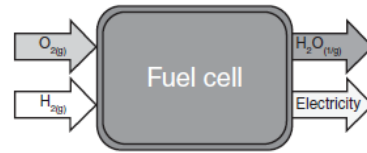
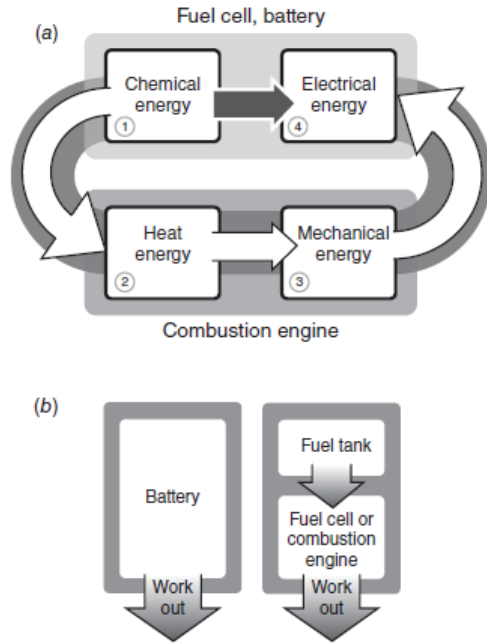
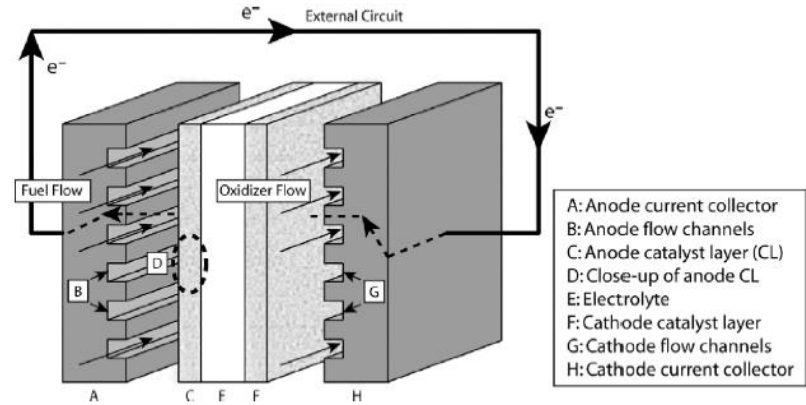
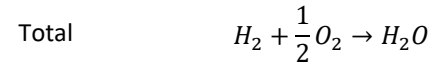
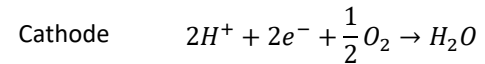


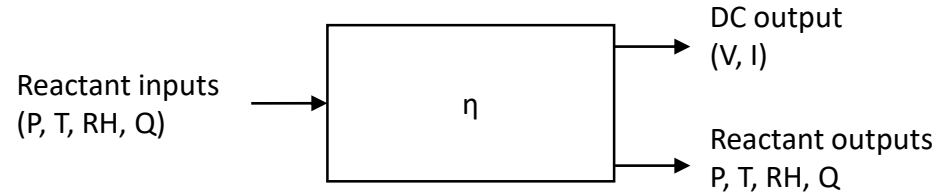
Figure 1.1. General concept of a (H₂-O₂) fuel cell.



PEMFC



FUEL CELLS – A BRIEF RECALL



The yield of the process is defined by the ratio between the produced electrical energy and the chemical energy brought by the reactants.

But:

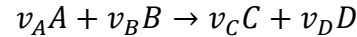
- While the electrical energy can be easily determined as: $V \cdot I \cdot t$
- The chemical energy brought by the reactants is related to the variation in the Gibbs free energy (over the reaction) and, to be estimated, a setpoint in terms of T and P has to be defined.

For the general fuel cells:

$$\eta = \frac{V \cdot I \cdot t}{\Delta G}$$
$$\Delta G = G(\text{products}) - G(\text{reactants})$$

FUEL CELLS – A BRIEF RECALL

Once gases are flowing across the cell, the so-called Open Circuit Potential (OCV) is formed, and it represents the maximum voltage which is characterizing a fuel cell disconnected from any load. For the general redox reaction:



The variation of the Gibbs free energy can be evaluated by means of the Nernst equation:

$$\Delta G = \Delta G^0(T) - RT \ln \left(\frac{a_A^{v_A} a_B^{v_B}}{a_C^{v_C} a_D^{v_D}} \right)$$

Here, by expressing the thermodynamic activity coefficients as $a_x = P_x/P^0$, the OCV can be expressed as:

$$E(P, T) = -\frac{\Delta G^0(T)}{nF} + \frac{RT}{nF} \ln \left(\frac{(P_A/P^0)^{v_A} (P_B/P^0)^{v_B}}{(P_C/P^0)^{v_C} (P_D/P^0)^{v_D}} \right)$$

Where ΔG^0 is the standard free energy variation of the redox reaction and a_x are the thermodynamic activity coefficients for the involved reacting species.

FUEL CELLS – A BRIEF RECALL

Partial pressure is then a crucial parameter to be monitored because it determines the internal relative humidity (RH) at which the redox reaction is taking place. This is strongly affecting the production of liquid water and the consequent water management issues

The gas pressure can be expressed as a sum of atmospheric partial pressure and a vapor partial one:

$$P_x = P_a + P_v$$

the RH is thus defined as:

$$RH(\%) = \frac{P_v}{P_{v,sat}}$$

Where $P_{v,sat}$ is the maximum vapor pressure at the thermodynamic equilibrium (from tabulated values; *e.g.* $P_{v,H_2O}(T)|_{T=100^\circ C} = P_{atm}$).

The rate of molar consumption or production of the x-specimen (\dot{n}_x) which is participating in current generation is then related to the produced current by the Faraday's second law:

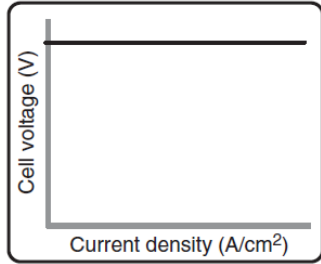
$$\dot{n}_x = \frac{jA}{nF} = \frac{I}{nF}$$

Where n is the equivalent number of electrons per mole of reactant involved in the redox reaction and F is the Faraday constant, which describes the charge carried per mole of equivalent electrons involved in the redox reaction.

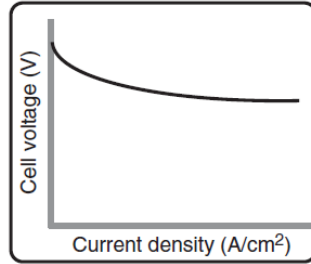
FUEL CELLS – A BRIEF RECALL

$$V = V_{THERMODYN} - \eta_{ACT} - \eta_{OHMIC} - \eta_{CONC}$$

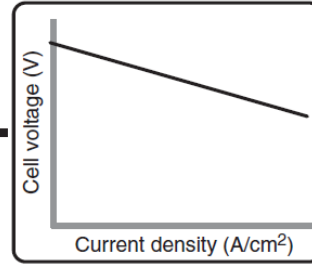
Reversible voltage (Chapter 2)



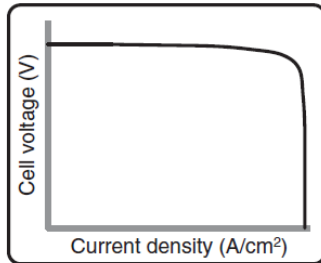
Activation loss (Chapter 3)



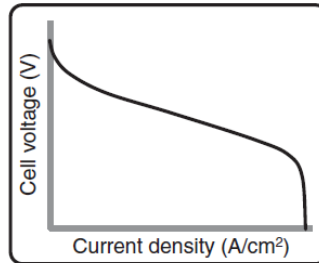
Ohmic loss (Chapter 4)



Concentration loss (Chapter 5)



Net fuel cell performance



$$\eta_{ACT} = a_A + b_A \ln j + a_C + b_C \ln j$$

(linearized Butler-Volmer equation)

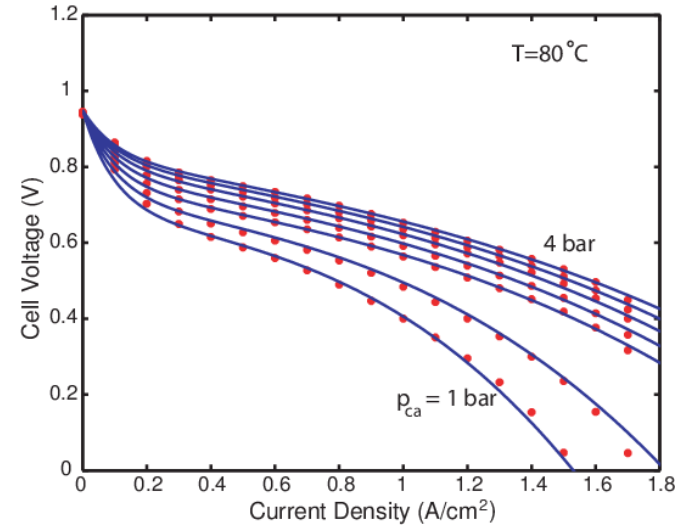
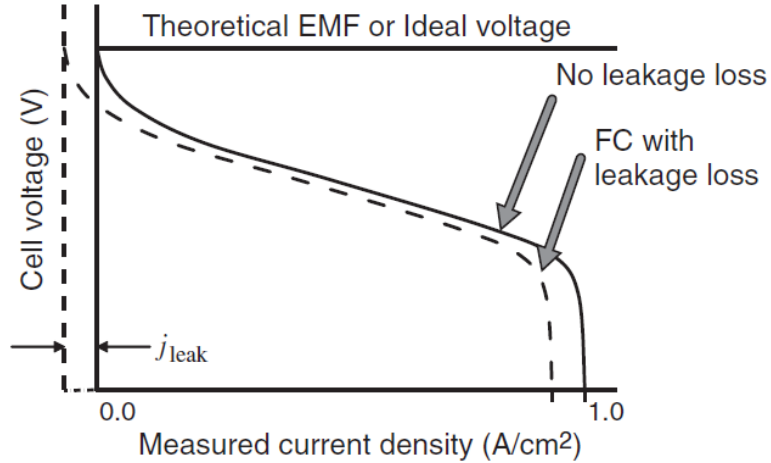
$$\eta_{OHMIC} = Rj$$

(ohm's equation)

$$\eta_{CONC} = c \ln \frac{j_L}{j_L - j}$$

j_L limiting current density (limit case for mass transport)

FUEL CELLS – A BRIEF RECALL

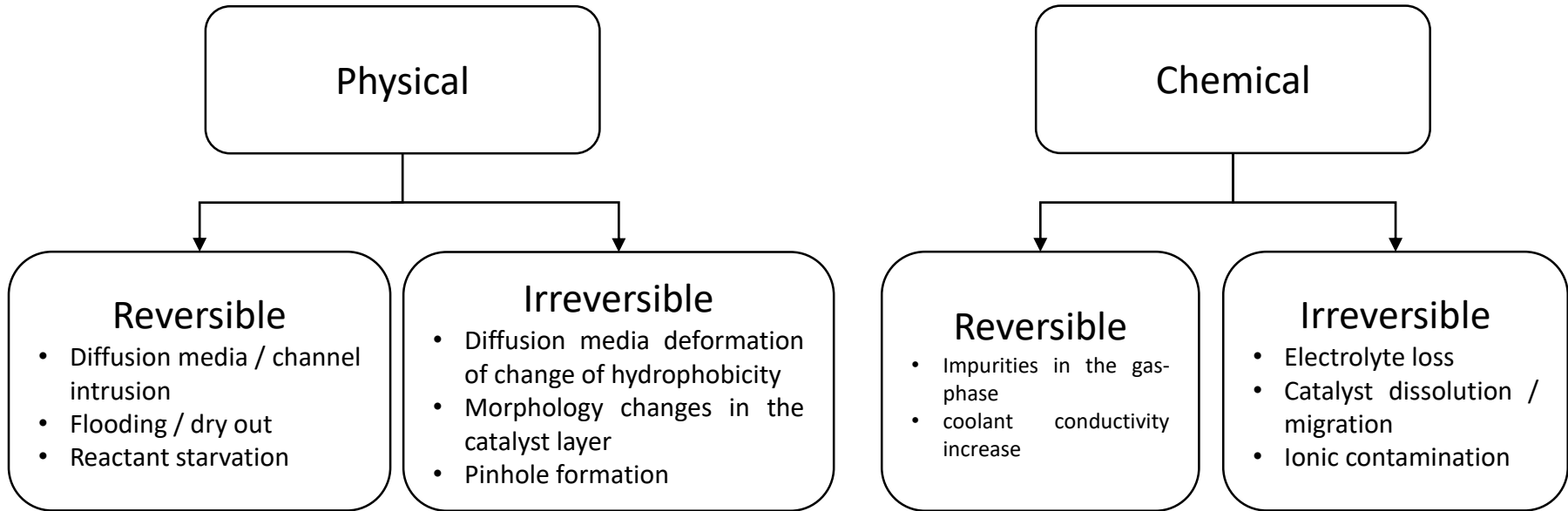


Pukrushpan, *Proceedings of the ASME 2002 International Mechanical Engineering Congress and Exposition. Dynamic Systems and Control*, 17–22, 2002. pp. 637-648.

FUEL CELLS – A BRIEF RECALL

System and electrochemical measurements are required to detect degradation mechanisms and improve cell design.

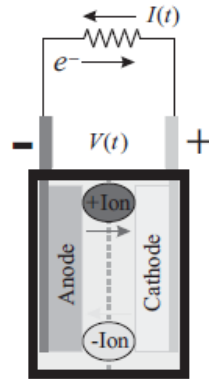
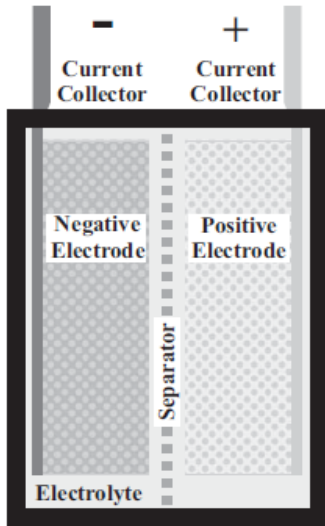
Due to the complex architecture of fuel cell systems, degradation mechanisms can be classified as:



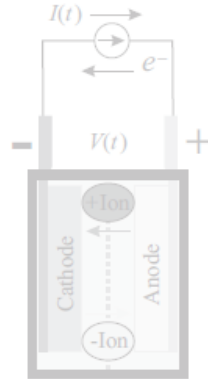
FUEL CELLS – THE NEED OF EXTENSIVE CHARACTERIZATION

- Overall performance (j/V curve, power density)
- Kinetic properties (η_{act} , j_0 , α , Electrochemically Active Surface Area ECSA)
- Ohmic properties (R_{ohmic} , electrolyte conductivity, contact resistances, electrode resistances, interconnection resistances)
- Mass transport properties (j_L , D_{eff} , pressure losses, reactant/product homogeneity)
- Parasitic losses (j_{leak} , side reactions, fuel crossover)
- Electrode structure (porosity, tortuosity, conductivity)
- Catalyst structure (thickness, porosity, catalyst loading, particle size, ECSA, catalyst utilization, triple phase boundaries, ionic conductivity, electrical conductivity)
- Flow structure (pressure drop, gas distribution, conductivity)
- Heat generation/heat balance
- Lifetime issues (lifetime testing, degradation, cycling, start-up/shut-down, failure, corrosion, fatigue)

BATTERIES – A BRIEF RECALL



Discharge



Charge

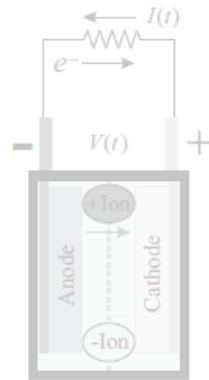
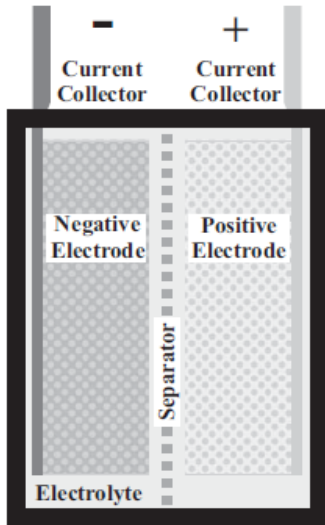
Discharge

The anode is the negative electrode, while the cathode is the positive one.

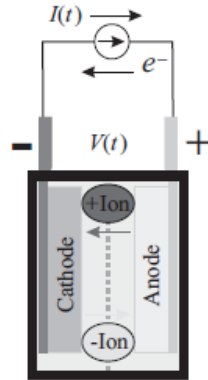
Oxidised positive ions (from oxidation reaction) move towards the cathode through the electrolyte. Negatively charged electrons flow through an external load from the anode to the cathode, creating a current in the opposite direction.

The cathode then is fed by electrons and reduction reaction hosts the positive ions within the cathode structure.

BATTERIES – A BRIEF RECALL



Discharge



Charge

Charge

Now the anode is the positive electrode, while the cathode is the negative one.

At the positive electrode oxidation takes place: a positive ion is dissolved in the electrolyte solution and an electron is freed and conveyed outside of the cell.

The negative electrode is fed by electrons and the positive ions migrating across the electrolyte under the applied difference of potential. Once at the electrode, ions are reduced at the electrode surface.

BATTERIES – A BRIEF RECALL

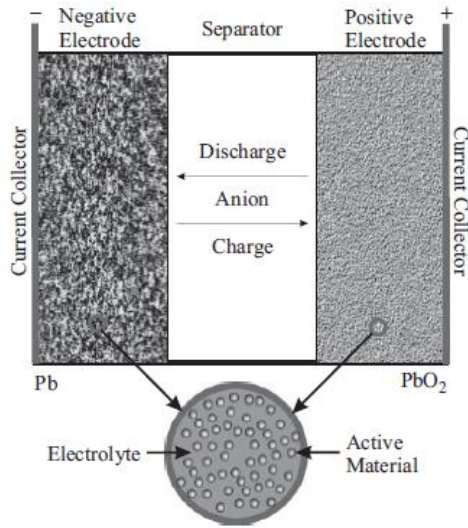


Figure 2.2 Schematic diagram of a Pb-acid cell

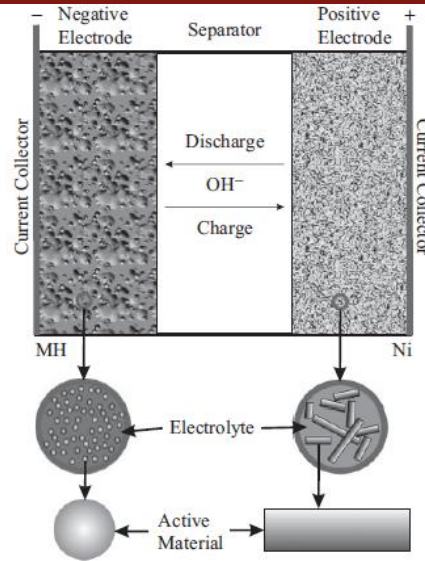
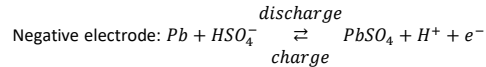
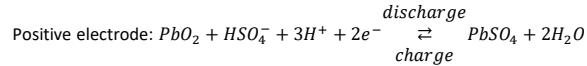


Figure 2.3 Schematic diagram of a Ni-MH cell

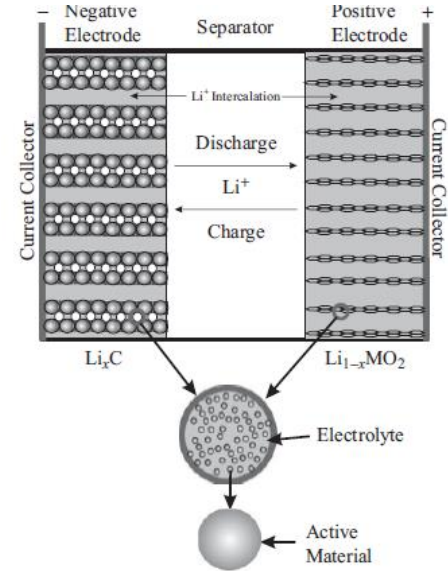
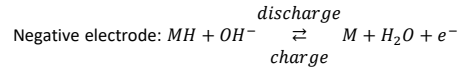
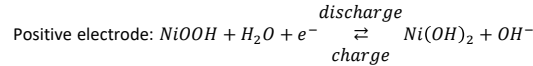
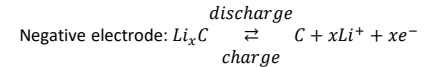
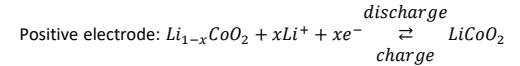
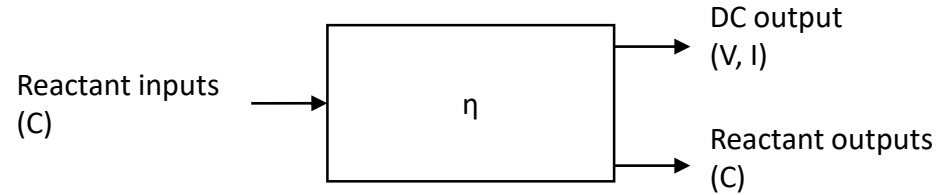


Figure 2.4 Schematic diagram of a Li-ion cell



BATTERIES – A BRIEF RECALL



The yield of the process is defined by the ratio between the charge (or the energy) stored during the charge and the charge (or the energy) drawn from the battery during its discharge. The coulombic efficiency is thus defined as:

$$\eta_c = \frac{\int_{discharge} I dt}{\int_{charge} I dt}$$

While the energy efficiency is defined as:

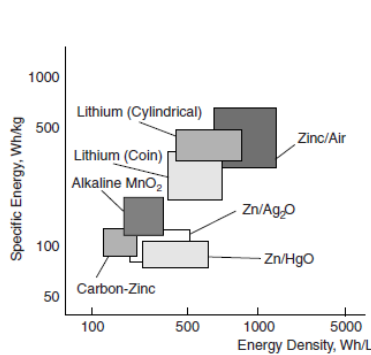
$$\eta = \frac{\int_{discharge} IV dt}{\int_{charge} IV dt}$$

BATTERIES – A BRIEF RECALL

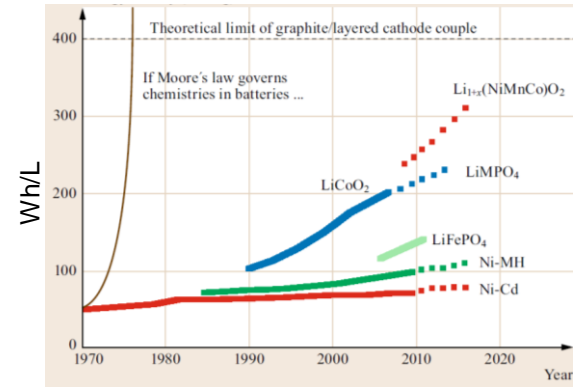
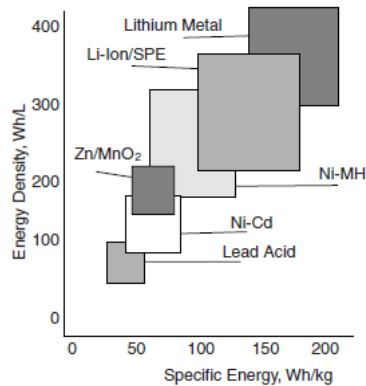
The maximum energy that can be delivered by an electrochemical system is based on the types and the amount of active materials that are used. Material type defines the battery voltage, material amounts, its capacity (Ah). Though, a divergence from the theoretical limit is always present and due to: the presence of the electrolyte (which adds mass and volume at the device) and to a reduced operative range (the battery does not charge at the theoretical voltage, nor is it discharged completely to zero). The specific energy and the energy density are two parameters which are commonly used for characterization and comparison of different battery system under different conditions of use.

The **specific energy** expresses the energy within the battery in function of the mass of the catalyst/battery system (Wh/kg), while the **energy density** expresses the energy with respect the volume (Wh/L)

For primary
batteries



For rechargeable
batteries



BATTERIES – A BRIEF RECALL

State of Charge The State of Charge (SOC) is defined as the percentage of the maximum possible charge that is present inside a battery. By defining the nominal capacity of a battery as the maximum amount of charge that can be drawn from the fully charged cell at room temperature and a C/30 rate, the SOC is expressed as:

$$SOC = \frac{C_r}{C} = 1 - \frac{1}{C} \int_0^t I(\tau) d\tau$$

Assuming that SOC = 100% at t=0. At this point it is assumed that the battery can provide C/30 A for 30h. A complementary parameter to the SOC is the Depth of Discharge (DOD) which defines the amount of charge which has been drawn from the battery.

$$DOD = 1 - SOC$$

SOC is not directly measurable in a battery, so it must be inferred from other measurements or estimated by the battery management system. Voltage, current, and sometimes temperature are measured for this purpose in the less intrusive way.

BATTERIES – A BRIEF RECALL

Also from batteries the Gibbs free energy is related to the useful work that can be done by the cell. From the Gibbs free energy it is possible to retrieve the standard cell potential (tabulated at standard conditions – 25°C, 1 bar):

$$E^0 = -\frac{\Delta G}{nF}$$

The intrinsic voltage of a battery (for the generic redox reaction $aA + bB \rightleftharpoons cC + dD$) can be expressed via the Nernst equation:

$$E = E^0 - \frac{RT}{nF} \ln \left(\frac{a_C^c a_D^d}{a_A^a a_B^b} \right)$$

where a_X are the activities of the specimens involved.

Electrode reaction	E^0 , V	Electrode reaction	E^0 , V
$\text{Li}^+ + e \rightleftharpoons \text{Li}$	-3.01	$\text{Tl}^+ + e \rightleftharpoons \text{Tl}$	-0.34
$\text{Rb}^+ + e \rightleftharpoons \text{Rb}$	-2.98	$\text{Co}^{2+} + 2e \rightleftharpoons \text{Co}$	-0.27
$\text{Cs}^+ + e \rightleftharpoons \text{Cs}$	-2.92	$\text{Ni}^{2+} + 2e \rightleftharpoons \text{Ni}$	-0.23
$\text{K}^+ + e \rightleftharpoons \text{K}$	-2.92	$\text{Sn}^{2+} + 2e \rightleftharpoons \text{Sn}$	-0.14
$\text{Ba}^{2+} + 2e \rightleftharpoons \text{Ba}$	-2.92	$\text{Pb}^{2+} + 2e \rightleftharpoons \text{Pb}$	-0.13
$\text{Sr}^{2+} + 2e \rightleftharpoons \text{Sr}$	-2.89	$\text{D}^+ + e \rightleftharpoons \frac{1}{2}\text{D}_2$	-0.003
$\text{Ca}^{2+} + 2e \rightleftharpoons \text{Ca}$	-2.84	$\text{H}^+ + e \rightleftharpoons \frac{1}{2}\text{H}_2$	0.000
$\text{Na}^+ + e \rightleftharpoons \text{Na}$	-2.71	$\text{Cu}^{2+} + 2e \rightleftharpoons \text{Cu}$	0.34
$\text{Mg}^{2+} + 2e \rightleftharpoons \text{Mg}$	-2.38	$\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2e \rightleftharpoons 2\text{OH}^-$	0.40
$\text{Ti}^+ + 2e \rightleftharpoons \text{Ti}$	-1.75	$\text{Cu}^+ + e \rightleftharpoons \text{Cu}$	0.52
$\text{Be}^{2+} + 2e \rightleftharpoons \text{Be}$	-1.70	$\text{Hg}^{2+} + 2e \rightleftharpoons 2\text{Hg}$	0.80
$\text{Al}^{3+} + 3e \rightleftharpoons \text{Al}$	-1.66	$\text{Ag}^+ + e \rightleftharpoons \text{Ag}$	0.80
$\text{Mn}^{2+} + 2e \rightleftharpoons \text{Mn}$	-1.05	$\text{Pd}^{2+} + 2e \rightleftharpoons \text{Pd}$	0.83
$\text{Zn}^{2+} + 2e \rightleftharpoons \text{Zn}$	-0.76	$\text{Ir}^{3+} + 3e \rightleftharpoons \text{Ir}$	1.00
$\text{Ga}^{3+} + 3e \rightleftharpoons \text{Ga}$	-0.52	$\text{Br}_2 + 2e \rightleftharpoons 2\text{Br}^-$	1.07
$\text{Fe}^{2+} + 2e \rightleftharpoons \text{Fe}$	-0.44	$\text{O}_2 + 4\text{H}^+ + 4e \rightleftharpoons 2\text{H}_2\text{O}$	1.23
$\text{Cd}^{2+} + 2e \rightleftharpoons \text{Cd}$	-0.40	$\text{Cl}_2 + 2e \rightleftharpoons 2\text{Cl}^-$	1.36
$\text{In}^{3+} + 3e \rightleftharpoons \text{In}$	-0.34	$\text{F}_2 + 2e \rightleftharpoons 2\text{F}^-$	2.87

BATTERIES – A BRIEF RECALL

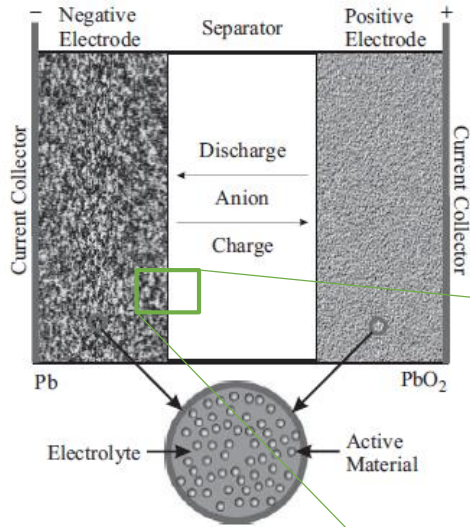
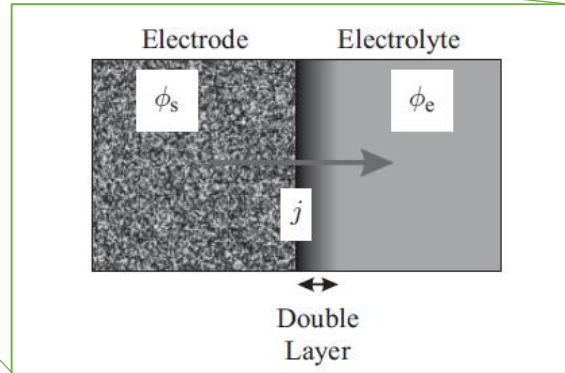


Figure 2.2 Schematic diagram of a Pb-acid cell

Batteries have porous, solid-phase electrodes that are saturated with liquid-/gel-phase electrolyte that transports ions from one electrode to the other. The electrons involved in the electrode reactions must pass through the electrode–electrolyte interface. This interface resists the flow of electrons, creating an overpotential (η) that must be overcome to allow charge transfer.



$$\eta = R_{ch.tr} j$$

For anodic or oxidation reactions, current flows from the electrode to the electrolyte and $\eta > 0$.
 For cathodic or reduction reactions, current flows from the electrolyte to the electrode and $\eta < 0$.

BATTERIES – A BRIEF RECALL

Electrode kinetics are described by means of the Butler-Volmer equation:

$$j = j_0 [e^{\eta\alpha_a F/RT} - e^{\eta\alpha_c F/RT}]$$

Here j_0 is the exchange current density, and α_x are the anodic and cathodic exchange coefficients.

The exchange current density is a measure of the rate of exchange of charge between oxidized and reduced species at any equilibrium potential without net overall change. At equilibrium, its value equals the value of both the redox-induced anodic and the cathodic currents ($i_0 = i_a = i_c$). It defines a background for the net current which is recorded during battery operation and it depends on the concentrations of the reactants and products, on temperature, and on the nature of the solid-electrolyte interface:

$$j_0 = \frac{i_0}{A} = nFkC_0^{(1-\alpha)}C_R^\alpha$$

Where k is the rate of the redox reaction, C_x defines the concentration at the electrode surface and α is a parameter related to the potential energy of reaction.

The exchange coefficients are related to the number of electrons involved in the redox reactions (n):

$$\alpha_a + \alpha_c = n$$

And they are usually equal to $n/2$

BATTERIES – A BRIEF RECALL

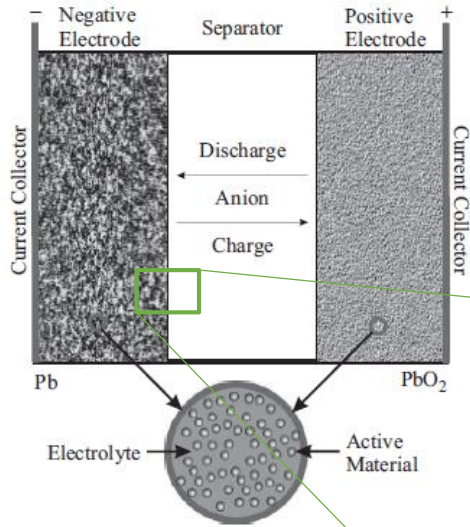
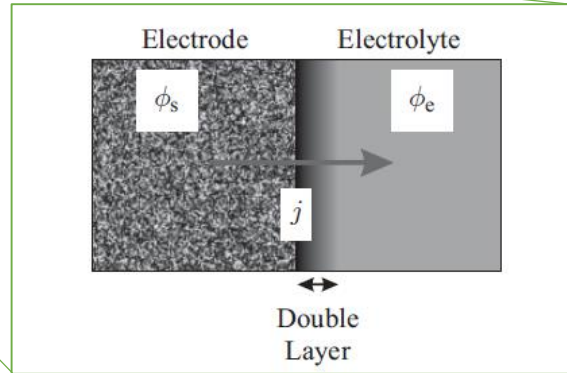


Figure 2.2 Schematic diagram of a Pb-acid cell



At the electrode-electrolyte interface the double layer is hosting specimens prone to be reduced or oxidized.

This charge accumulation induces the formation of a capacitance, called as Double Layer Capacitance:

$$i_{dl} = C_{dl} \frac{\partial \eta}{\partial t}$$

Which has to be taken into account in modelling battery systems.

BATTERIES – A BRIEF RECALL

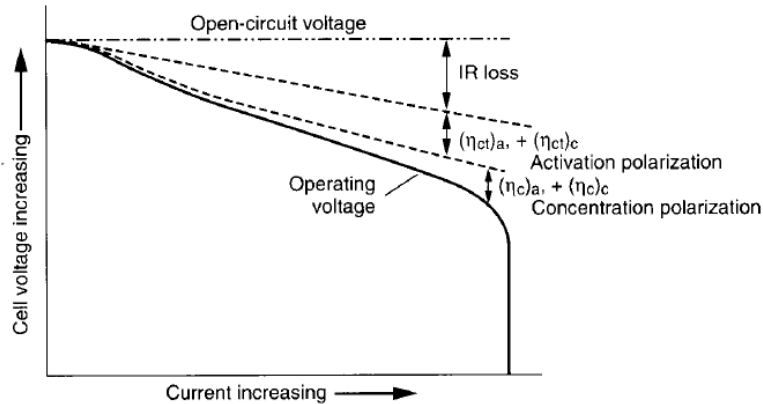


FIGURE 2.1 Cell polarization as a function of operating current.

By considering the whole battery system, there are several phenomena which are concurring in defining battery voltage:

$$V = V_{OCV} - [(\eta_{ct})_a + (\eta_c)_a] - [(\eta_{ct})_c + (\eta_c)_c] - iR_i = iR$$

Where :

V_{OCV} is the open circuit voltage

$(\eta_{ct})_x$ describe the so called activation polarization losses due to the formation of the overpotential at the electrode-electrolyte interface

$(\eta_c)_x$ describe the so called concentration polarization losses due to the formation of the overpotential arising from the concentration of the reactants and products.

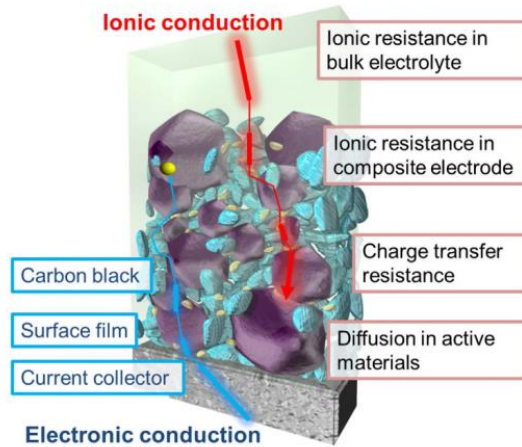
iR_i are the ohmic losses due to the product of the current drawn from the battery and the battery internal resistance.

All of them can be recognized in the polarization curve (V/I)

BATTERIES – A BRIEF RECALL

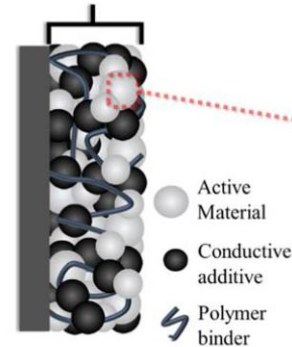
$$R_i = \sum R_e + \sum R_i$$

$$\sum R_x = R_{electrolyte}^x + R_{electrodes}^x + R_{c.t.,cat/sup}^x$$

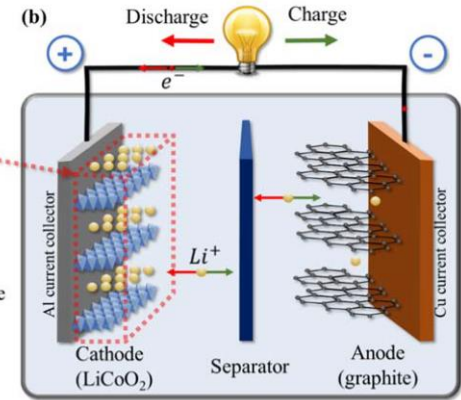


Orikasa, *Sci Rep* 6, 26382 (2016). <https://doi.org/10.1038/srep26382>

(a) Composite electrode

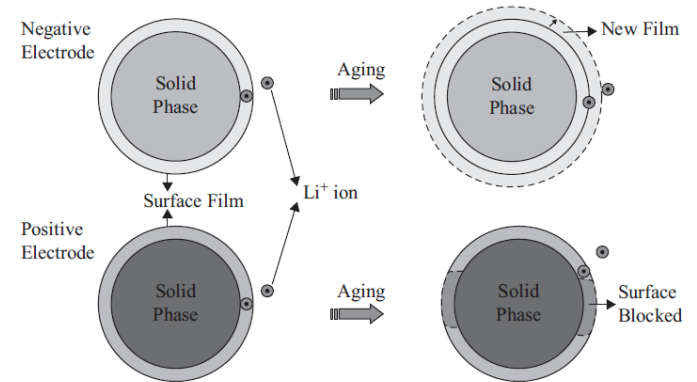
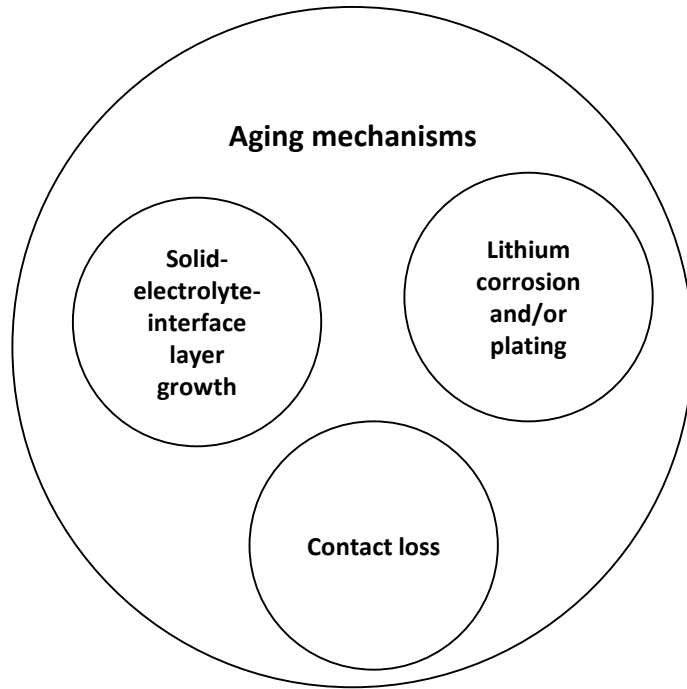


(b)

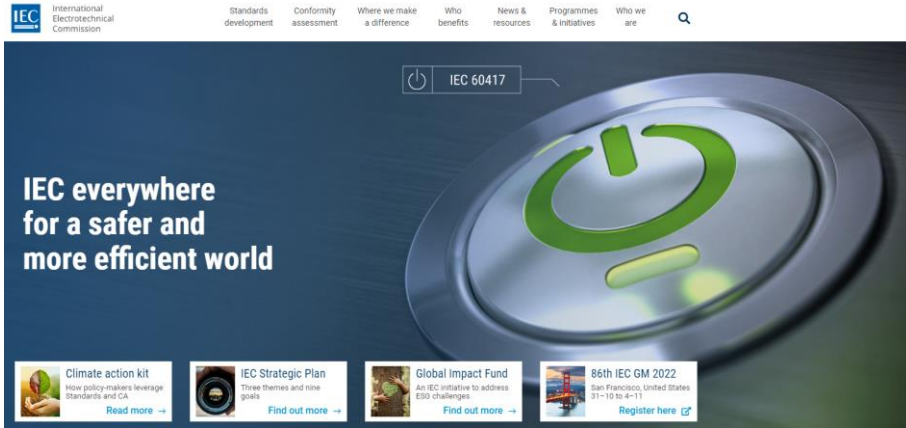


Cholewinski, *Polymers* 2021, 13(4), 631; <https://doi.org/10.3390/polym13040631>

BATTERIES – A BRIEF RECALL



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Hydrogen and Fuel Cell Technologies Office

Fuel Cell Tech Team Accelerated Stress Test and Polarization Curve Protocols for PEM Fuel Cells

AUGUST 18, 2015



[Hydrogen and Fuel Cell Technologies Office »](#)

[Fuel Cell Tech Team Accelerated Stress Test and Polarization Curve Protocols for PEM Fuel Cells](#)

Accelerated stress test and polarization curve protocols developed by the U.S. DRIVE Fuel Cell Technical Team for polymer electrolyte membrane (PEM) fuel cells, revised January 14, 2013.

[Fuel Cell Tech Team Accelerated Stress Test and Polarization Curve Protocols for PEM Fuel Cells](#)

Table A 1. Electrocatalyst Cycle and Metrics

Table revised March 2, 2010

Cycle	Triangle sweep cycle: 50 mV/s between 0.6 V and 1.0 V. Single cell 25–50 cm ²	
Number	30,000 cycles	
Cycle time	16 seconds	
Temperature	80°C	
Relative humidity	Anode/cathode 100/100%	
Fuel/oxidant	Hydrogen/N ₂ (H ₂ at 200 sccm and N ₂ at 75 sccm for a 50 cm ² cell)	
Pressure	Atmospheric pressure	
Metric	Frequency	Target
Catalytic mass activity*	At beginning and end of test minimum	≤40% loss of initial catalytic activity
Polarization curve from 0 to ≥1.5 A/cm ²	After 0, 1k, 5k, 10k, and 30k cycles	≤30 mV loss at 0.8 A/cm ²
ECSA/cyclic voltammetry***	After 10, 100, 1k, 3k, 10k, 20k, and 30k cycles	≤40% loss of initial area

* Mass activity in A/mg @ 150 kPa abs, backpressure at 857 mV iR-corrected on 6% H₂ (bal N₂)/O₂ (or equivalent thermodynamic potential), 100% RH, 80°C normalized to initial mass of catalyst and measured before and after test.

** Polarization curve per Fuel Cell Tech Team Polarization Protocol in Table A-5.

*** Sweep from 0.05 to 0.60 V at 20 mV/s, 80°C, and 100% RH.

REFERENCE INSTITUTION AND STANDARDS FOR ELECTROCHEMICAL MEASUREMENTS (APPLIED TO FUEL CELLS, ELECTROLYSERS, AND BATTERIES)



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European Partnership for Hydrogen Technologies

The Clean Hydrogen Partnership's main objective is to contribute to EU Green Deal and Hydrogen Strategy through optimised funding of R&I activities. The Clean Hydrogen Partnership is the successor of the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) and has taken over its legacy portfolio as of 30 November 2021.

[Fuel Cells and Hydrogen JU](#)

INTERNATIONAL STANDARDS FROM IEC

IEC 62282-X-XXX		
IEC 62282-2-100	Fuel cell modules	Safety
IEC 62282-3-100:2019	Stationary fuel cell power systems	Safety
IEC 62282-3-200:2015		Performance test methods
IEC 62282-3-201:2017		Performance test methods for small fuel cell power systems
IEC 62282-3-300:2012		Installation
IEC 62282-3-400:2016		Small stationary fuel cell power system with combined heat and power output
IEC 62282-4-101:2022	Fuel cell power systems for industrial electric trucks	Safety
IEC 62282-4-102:2017		Performance test methods

INTERNATIONAL STANDARDS FROM IEC

IEC 62282-X-XXX		
IEC 62282-4-600:2022	Fuel cell power systems for propulsion other than road vehicles and auxiliary power units (APU)	Fuel cell/battery hybrid systems performance test methods for excavators
IEC 62282-5-100:2018	Portable fuel cell power systems	Safety
IEC 62282-6-100:2010	Micro fuel cell power systems	Safety
IEC 62282-6-200:2016		Performance test methods
IEC 62282-6-300:2012		Fuel cartridge interchangeability
IEC 62282-6-400:2019		Power and data interchangeability

INTERNATIONAL STANDARDS FROM IEC

IEC 62282-X-XXX		
IEC TS 62282-7-1:2017	Test methods	Single cell performance tests for polymer electrolyte fuel cells (PEFC)
IEC 62282-7-2:2021		Single cell and stack performance tests for solid oxide fuel cells (SOFCs)
IEC 62282-8-101:2020	Energy storage systems using fuel cell modules in reverse mode	Test procedures for the performance of solid oxide single cells and stacks, including reversible operation
IEC 62282-8-102:2019		Test procedures for the performance of single cells and stacks with proton exchange membrane, including reversible operation
IEC 62282-8-201:2020		Test procedures for the performance of power-to-power systems

INTERNATIONAL STANDARDS FROM IEC

IEC 62282-X-XXX		
IEC TS 62282-9-101:2020	Evaluation methodology for the environmental performance of fuel cell power systems based on life cycle thinking	Streamlined life-cycle considered environmental performance characterization of stationary fuel cell combined heat and power systems for residential applications
IEC TS 62282-9-102:2021		Product category rules for environmental product declarations of stationary fuel cell power systems and alternative systems for residential applications

STANDARD IEC 62282-3-200:2015

FOREWORD.....	5
INTRODUCTION.....	7
1 Scope.....	8
2 Normative references	9
3 Terms, definitions, operating process and symbols	11
3.1 Terms and definitions.....	11
3.2 Operating process.....	16
3.3 Symbols.....	17
4 Reference conditions.....	20
4.1 General.....	20
4.2 Temperature and pressure.....	21
4.3 Heating value base	21
5 Item of performance test.....	21
6 Test preparation	22
6.1 General.....	22
6.2 Uncertainty analysis.....	22
6.2.1 Uncertainty analysis items	22
6.2.2 Data acquisition plan	22

- alkaline fuel cells (AFC);
- phosphoric acid fuel cells (PAFC);
- polymer electrolyte fuel cells (PEFC);
- molten carbonate fuel cells (MCFC);
- solid oxide fuel cells (SOFC).

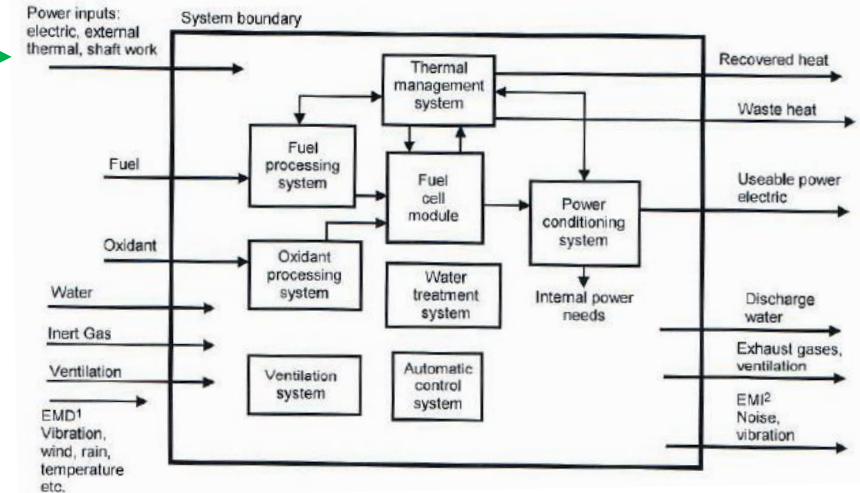
This part of IEC 62282 covers operational and environmental aspects of the stationary fuel cell power systems performance. The test methods apply as follows:

- power output under specified operating and transient conditions;
- electrical and heat recovery efficiency under specified operating conditions;
- environmental characteristics; for example, exhaust gas emissions, noise, etc. under specified operating and transient conditions.

This standard does not provide coverage for electromagnetic compatibility (EMC).

STANDARD IEC 62282-3-200:2015

FOREWORD.....	5
INTRODUCTION.....	7
1 Scope.....	8
2 Normative references.....	9
3 Terms, definitions, operating process and symbols.....	11
3.1 Terms and definitions.....	11
3.2 Operating process.....	16
3.3 Symbols.....	17
4 Reference conditions.....	20
4.1 General.....	20
4.2 Temperature and pressure.....	21
4.3 Heating value base.....	21
5 Item of performance test.....	21
6 Test preparation.....	22
6.1 General.....	22
6.2 Uncertainty analysis.....	22
6.2.1 Uncertainty analysis items.....	22
6.2.2 Data acquisition plan.....	22



STANDARD IEC 62282-3-200:2015

FOREWORD.....	5
INTRODUCTION.....	7
1 Scope.....	8
2 Normative references.....	9
3 Terms, definitions, operating process and symbols.....	11
3.1 Terms and definitions.....	11
3.2 Operating process.....	16
3.3 Symbols.....	17
4 Reference conditions.....	20
4.1 General.....	20
4.2 Temperature and pressure.....	21
4.3 Heating value base.....	21
5 Item of performance test.....	21
6 Test preparation.....	22
6.1 General.....	22
6.2 Uncertainty analysis.....	22
6.2.1 Uncertainty analysis items.....	22
6.2.2 Data acquisition plan.....	22

4.2 Temperature and pressure

The reference conditions are specified as follows:

- reference temperature: $T_0 = 288,15 \text{ K (15 } ^\circ\text{C)}$;
- reference pressure: $p_0 = 101,325 \text{ kPa}$.

Table 2 – Test classification and test item

Test	
Operational aspects	Environmental aspects
Efficiency test	Exhaust gas emission test
Electric power/thermal power response characteristics test	Noise level test
Start-up/shutdown characteristics test	Vibration level test
Purge gas consumption test	Discharge water quality test
Water consumption test	

FUEL CELLS – TESTING CONDITIONS

Test and operative conditions are needed to be accurately recorded because dramatically affect fuel cell performance. For example, a “bad” PEMFC operating at 80°C on humidified oxygen and hydrogen gases under 5 bar pressure may show better j/V curve performance than a “good” PEMFC operating at 30°C on dry air and dilute hydrogen at atmospheric pressure. Only if the two fuel cells are tested under identical conditions, the truly good fuel cell will become apparent.

$$E(P, T) = -\frac{\Delta G^0(T)}{nF} + \frac{RT}{nF} \ln \left(\frac{(P_A/P^0)^{v_A} (P_B/P^0)^{v_B}}{(P_C/P^0)^{v_A} (P_D/P^0)^{v_B}} \right)$$

FUEL CELLS – TESTING CONDITIONS

Warm-up

To ensure that a fuel cell system is well equilibrated, it is customary to conduct a standardized warm-up procedure prior to cell characterization. A typical warm-up procedure might involve operating the cell at a fixed current load for 30 ÷ 60 minutes prior to testing. Failure to properly warm up a fuel cell system can result in highly nonstationary (non-steady-state) behaviour.

FUEL CELLS – TESTING CONDITIONS

Temperature

It is important to document and maintain a constant fuel cell temperature during measurement. Both the gas inlet and exit temperatures should be measured as well as the temperature of the fuel cell itself. Sophisticated techniques even allow temperature distributions across a fuel cell device to be monitored in real time. In general, increased temperature will improve performance due to improved kinetics and conduction processes (For PEMFCs, this is only true up to about 80°C, above which membrane drying becomes an issue).

FUEL CELLS – TESTING CONDITIONS

Flow Rate

Flow rates are generally set using mass flow controllers. During a j/V test, there are two main ways to handle reactant flow rates. In the first method, flow rates are held constant during the entire test at a flow rate that is sufficiently high so that even at the largest current densities there is sufficient supply. This method is known as the fixed-flow-rate condition. In the second method, flow rates are adjusted stoichiometrically with the current so that the ratio between reactant supply and current consumption is always fixed. This method is known as the fixed-stoichiometry condition. Fair j/V curve comparisons should be done using the same flow rate method. Increased flow usually improves performance (For PEMFCs, increasing the flow rate of extremely humid or extremely dry gases can upset the water balance in the fuel cell and actually decrease performance).

FUEL CELLS – TESTING CONDITIONS

Compression Force

For most fuel cell assemblies, there is an optimal cell compression force, which leads to best performance; thus, cell compression force should be noted and monitored. Cells with lower compression forces can suffer increased ohmic loss, while cells with higher compression forces can suffer increased pressure or concentration losses.

STANDARD IEC 62282-3-200:2015

7	Measurement instruments and measurement methods.....	22
7.1	General.....	22
7.2	Measurement instruments.....	23
7.3	Measurement methods.....	23
7.3.1	Electric power measurements.....	23
7.3.2	Fuel input measurement.....	24
7.3.3	Recovered heat measurement.....	27
7.3.4	Purge gas flow measurement.....	27
7.3.5	Oxidant (air) input measurement.....	28
7.3.6	Other fluid flow measurement.....	29
7.3.7	Exhaust gas flow measurement.....	29
7.3.8	Discharge water measurement.....	30
7.3.9	Noise level measurement.....	31
7.3.10	Vibration level measurement.....	31
7.3.11	Total harmonic distortion measurement.....	31
7.3.12	Ambient condition measurement.....	31
8	Test plan.....	32
8.1	General.....	32
8.2	Ambient conditions.....	32
8.3	Maximum permissible variation in steady-state operating conditions.....	33
8.4	Test operating procedure.....	33
8.5	Duration of test and frequency of readings.....	33

Location for measurement shall be as follows:

- In order to measure electric power output, an electric power meter, voltage meter, current meter and power factor meter shall be located at the electric output interface point.
- In order to measure electric power input for auxiliary machines and equipment from an external power source, an electric power meter, voltage meter, current meter and power factor meter shall be located at the electric input interface point.
- Power factor measurements shall be conducted with the fuel cell power system connected to an external load or connected to the local electric power grid.

Gaseous fuel characteristics shall include the determination of

- heating value,
- temperature,
- pressure,
- density.

7.3.2.2.4 Gaseous fuel temperature measurement

Recommended instruments for measuring temperature directly are as follows:

- thermocouples with transducer;
- resistance thermometer with transducer.

Temperature sensors shall be appropriate in terms of accuracy.

STANDARD IEC 62282-3-200:2015

7	Measurement instruments and measurement methods.....	22
7.1	General.....	22
7.2	Measurement instruments.....	23
7.3	Measurement methods.....	23
7.3.1	Electric power measurements.....	23
7.3.2	Fuel input measurement.....	24
7.3.3	Recovered heat measurement.....	27
7.3.4	Purge gas flow measurement.....	27
7.3.5	Oxidant (air) input measurement.....	28
7.3.6	Other fluid flow measurement.....	29
7.3.7	Exhaust gas flow measurement.....	29
7.3.8	Discharge water measurement.....	30
7.3.9	Noise level measurement.....	31
7.3.10	Vibration level measurement.....	31
7.3.11	Total harmonic distortion measurement.....	31
7.3.12	Ambient condition measurement.....	31
8	Test plan.....	32
8.1	General.....	32
8.2	Ambient conditions.....	32
8.3	Maximum permissible variation in steady-state operating conditions.....	33
8.4	Test operating procedure.....	33
8.5	Duration of test and frequency of readings.....	33

Table 2 – Test classification and test item

Test	
Operational aspects	Environmental aspects
Efficiency test	Exhaust gas emission test
Electric power/thermal power response characteristics test	Noise level test
Start-up/shutdown characteristics test	Vibration level test
Purge gas consumption test	Discharge water quality test
Water consumption test	

Listed test items shall be carried out under different conditions depending upon the purpose of the test. The different conditions are as follows:

- steady state at rated power;
- steady state at partial load near the mid-point between rated power and minimum power;
- steady state at pre-generation state;
- steady state at minimum power;
- transient state;
- cold and storage state.

STANDARD IEC 62282-3-200:2015

7	Measurement instruments and measurement methods.....	22
7.1	General.....	22
7.2	Measurement instruments.....	23
7.3	Measurement methods.....	23
7.3.1	Electric power measurements.....	23
7.3.2	Fuel input measurement.....	24
7.3.3	Recovered heat measurement.....	27
7.3.4	Purge gas flow measurement.....	27
7.3.5	Oxidant (air) input measurement.....	28
7.3.6	Other fluid flow measurement.....	29
7.3.7	Exhaust gas flow measurement.....	29
7.3.8	Discharge water measurement.....	30
7.3.9	Noise level measurement.....	31
7.3.10	Vibration level measurement.....	31
7.3.11	Total harmonic distortion measurement.....	31
7.3.12	Ambient condition measurement.....	31
8	Test plan.....	32
8.1	General.....	32
8.2	Ambient conditions.....	32
8.3	Maximum permissible variation in steady-state operating conditions.....	33
8.4	Test operating procedure.....	33
8.5	Duration of test and frequency of readings.....	33

Table 4 – Maximum permissible variations in test operating conditions

Parameter	Allowable variation during a test run
System stabilization parameter as specified by the manufacturer and agreed to by all parties	As specified
Electric power output in kW	± 2 %
Barometric pressure at site	± 0,5 %
Inlet oxidant (air) temperature	± 3 K
Heat value – fuel per unit volume	± 1 %
Gaseous fuel pressure as delivered to system	± 1 %
Absolute exhaust pressure	± 0,5 %
Absolute inlet oxidant (air) pressure to system	± 0,5 %
Inlet fuel flow	± 2 %
Inlet fuel temperature	± 2 K
Inlet oxidant (air) flow rate	Not specified
Recovered thermal power output	± 2 %
Total harmonic distortion THD ^a	± 2 %
NOTE This table refers to ASME PTC 50.	
^a For THD only: for the THD with a mean value of 5 %, its values between 3 % and 7 % are acceptable.	

STANDARD IEC 62282-3-200:2015

9	Test methods and computation of test results	34	9.2.3	Computation of inputs	34
9.1	General	34	9.2.4	Computation of output	44
9.2	Efficiency test	34	9.2.5	Computation of waste heat rate	45
9.2.1	General	34	9.2.6	Computation of efficiencies	45
9.2.2	Test method	34	9.3	Electric power and thermal power response characteristics test	46
			9.3.1	General	46
			9.3.2	Criteria for the determination of attaining the steady-state set value	47
			9.3.3	Electric power output response time test	48
			9.3.4	90 % response time of rated net electric power output (optional)	49
			9.3.5	Thermal power output response time test	50
			9.4	Start-up and shutdown characteristics test	51
			9.4.1	General	51
			9.4.2	Test method for start-up characteristics test	51
			9.4.3	Test method for shutdown characteristics test	51
			9.4.4	Calculation of the start-up time	52
			9.4.5	Calculation of the shutdown time	52
			9.4.6	Calculation of the different forms of start-up energy	52
			9.4.7	Calculation of the start-up energy	54
			9.5	Purge gas consumption test	54
			9.5.1	General	54
			9.5.2	Test method	54
			9.6	Water consumption test (optional)	55
			9.6.1	General	55
			9.6.2	Test method	55

STANDARD IEC 62282-3-200:2015

9	Test methods and computation of test results	34
9.1	General	34
9.2	Efficiency test	34
9.2.1	General	34
9.2.2	Test method	34
9.2.3	Computation of inputs	34
9.2.4	Computation of output	44
9.2.5	Computation of waste heat rate	45
9.2.6	Computation of efficiencies	45
9.3	Electric power and thermal power response characteristics test	46
9.3.1	General	46
9.3.2	Criteria for the determination of attaining the steady-state set value	47
9.3.3	Electric power output response time test	48
9.3.4	90 % response time of rated net electric power output (optional)	49
9.3.5	Thermal power output response time test	50

Average gaseous fuel input

- 1) The total volume of gaseous fuel input over the test duration in m^3 shall be obtained by integrating the volumetric flow rate in m^3/s to be measured over the test run period.
- 2) The average volumetric flow rate of gaseous fuel under the test conditions, q_{VF} in m^3/s , shall be obtained by dividing the total volume in m^3 by the test duration in s.
- 3) The average volumetric flow rate of gaseous fuel under the reference conditions, q_{V10} in m^3/s , shall be calculated by the following equation. The average values of fuel temperature and pressure obtained over the test duration shall be used:

$$q_{V10} = q_{VF} \cdot (T_0 / T_f) \cdot (p_f / p_0) \quad (4)$$

where

- q_{V10} is the average volumetric flow rate of fuel under reference conditions (m^3/s);
 q_{VF} is the average volumetric flow rate of fuel at average temperature T_f and average pressure p_f (m^3/s);
 T_0 is the reference temperature (288,15 K);
 p_0 is the reference pressure (101,325 kPa);
 T_f is the average fuel temperature over the test duration (K);
 p_f is the average fuel pressure over the test duration (kPa).

STANDARD IEC 62282-3-200:2015

The average gaseous fuel power input, P_{fin} in kJ/s, shall be calculated either for volumetric flow rate or for mass flow rate according to the following procedure. The average values of fuel temperature and pressure obtained over the test duration shall be used.

a) Volumetric flow rate

- 1) The energy input of gaseous fuel per mole at average temperature T_f and average pressure p_f of a mixture of known composition, E_{mf} in kJ/mol, shall be calculated by the following equation:

$$E_{mf} = H_{f0} + H_{mf} - H_{mf0} + E_{mpf} \quad (7)$$

where

E_{mf} is the energy input of fuel per mole (kJ/mol), as given in worksheet 1 of Annex B;

H_{f0} is the heating value of fuel under reference conditions (kJ/mol);

H_{mf} is the molar enthalpy of fuel at average temperature T_f (kJ/mol);

H_{mf0} is the molar enthalpy of fuel at reference temperature T_0 (kJ/mol);

E_{mpf} is the pressure energy of fuel at average pressure p_f (kJ/mol).

If the fuel cell power system is used as a topping of combined cycle, E_{mpf} may be ignored.

$$H_{f0} = \sum_{j=1}^N x_j \cdot H_{f0j} \quad (8)$$

where

H_{f0j} is the heating value of component j at reference temperature T_0 (kJ/mol);

x_j is the molar ratio of component j , as given in worksheet 1 of Annex B;

j is a component of fuel;

N is the number of fuel gas constituents.

NOTE 2 The numerical values of H_{f0j} are given in Table B.1.

The molar enthalpy of fuel, H_{mf} in kJ/mol, is calculated by the following equation:

$$H_{mf} = \sum_{j=1}^N x_j \cdot H_{mfj} \quad (9)$$

where

H_{mfj} is the molar enthalpy of component j at average temperature T_f (kJ/mol);

x_j is the molar ratio of component j .

The molar enthalpy of component j , H_{mfj} in kJ/mol, is given by the following equation:

$$H_{mfj} = \left(A_j \cdot T_f + \frac{B_j \cdot T_f^2}{2 \times 10^3} + \frac{C_j \cdot T_f^3}{3 \times 10^6} \right) \times 10^{-3} \quad (10)$$

where

A_j , B_j and C_j are the constants of component j and given in worksheet 1 of Annex B;

T_f is the temperature of fuel under test conditions (K).

NOTE 3 The molar enthalpy of fuel, H_{mf0} in kJ/mol, at reference temperature is calculated by substituting T_0 for T_f in the above equation of H_{mfj} .

The pressure energy of fuel, E_{mpf} in kJ/mol, is calculated by the following equation:

$$E_{mpf} = R \cdot T_0 \cdot \ln(p_f / p_0) \times 10^{-3} \quad (11)$$

where

E_{mpf} is the pressure energy of fuel at average pressure p_f (kJ/mol);

R is the universal gas constant (8,314 J/(mol·K));

T_0 is the reference temperature (288,15 K);

p_0 is the reference pressure (101,325 kPa);

p_f is the average pressure of fuel (kPa).

If the fuel cell power system is used as a topping of combined cycle, E_{mpf} may be ignored.

STANDARD IEC 62282-3-200:2015

NOTE 4 See ISO 11086 for the definition of "combined cycle".

- 2) The average gaseous fuel power input, P_{fin} in kJ/s, shall be calculated by the following equation:

$$P_{fin} = q_{Vf0} \cdot E_{mf} / V_{m0} \quad (12)$$

where

P_{fin} is the average gaseous fuel power input (kJ/s);

q_{Vf0} is the average volumetric flow rate of fuel under reference conditions from equation (4) (m^3/s);

E_{mf} is the energy input of the fuel per mole (kJ/mol);

V_{m0} is the reference molar volume of ideal gas ($2,3645 \times 10^{-2} m^3/mol$)

NOTE 5 The reference temperature for this standard is 288.15 K.

STANDARD IEC 62282-3-200:2015

9.2.3	Computation of inputs	34
9.2.4	Computation of output	44
9.2.5	Computation of waste heat rate	45
9.2.6	Computation of efficiencies	45
9.3	Electric power and thermal power response characteristics test	46
9.3.1	General	46
9.3.2	Criteria for the determination of attaining the steady-state set value	47
9.3.3	Electric power output response time test	48
9.3.4	90 % response time of rated net electric power output (optional)	49
9.3.5	Thermal power output response time test	50
9.4	Start-up and shutdown characteristics test	51
9.4.1	General	51
9.4.2	Test method for start-up characteristics test	51
9.4.3	Test method for shutdown characteristics test	51
9.4.4	Calculation of the start-up time	52
9.4.5	Calculation of the shutdown time	52
9.4.6	Calculation of the different forms of start-up energy	52
9.4.7	Calculation of the start-up energy	54
9.5	Purge gas consumption test	54
9.5.1	General	54
9.5.2	Test method	54
9.6	Water consumption test (optional)	55
9.6.1	General	55
9.6.2	Test method	55

STANDARD IEC 62282-3-200:2015

9.6.1	General	55
9.6.2	Test method	55
9.7	Exhaust gas emission test	55
9.7.1	General	55
9.7.2	Test method	55
9.7.3	Data processing of emission concentration	56
9.7.4	Calculation of mean mass discharge rate	56
9.7.5	Calculation of mass concentration	56
9.8	Noise level test	56
9.8.1	General	56
9.8.2	Test method	56
9.8.3	Data processing	57
9.9	Vibration level test	57
9.10	Discharge water quality test	58
9.10.1	General	58
9.10.2	Test method	58
10	Test reports	59
10.1	General	59
10.2	Title page	59
10.3	Table of contents	59
10.4	Summary report	59
10.5	Detailed report	59
10.6	Full report	60
Annex A (normative)	Uncertainty analysis	61
A.1	General	61
A.2	Preparations	61
A.3	Basic assumptions	62

STANDARD IEC 62282-3-200:2015

10 Test reports

10.1 General

Test reports shall accurately, clearly and objectively present sufficient information to demonstrate that all the objectives of the tests have been attained. The reports shall contain all information developed in Clause 7. Three types of reports are required: summary, detailed and full. Each type of report shall contain the same title page and a table of contents. For fuel cell power systems tested in compliance with this part of IEC 62282, the summary report will be made available to interested parties.

10.2 Title page

The title page shall present the following information:

- a) report identification number (optional);
- b) type of report (summary, detailed or full);
- c) authors of report and their functions (job qualifications);
- d) entity conducting the test;
- e) date of report;
- f) location of test;
- g) title of the test;
- h) date and time of test;
- i) fuel cell power system identification and manufacturer's name.

10.3 Table of contents

For each type of report, a table of contents shall be provided.

STANDARD IEC 62282-3-200:2015

10.4 Summary report

The summary report shall include the following information:

- a) objective of the test;
- b) description of the test, equipment and instruments;
- c) order and date of test items and all test results;
- d) uncertainty level attached to each test result;
- e) confidence level attached to each test result;
- f) conclusions as appropriate.

10.5 Detailed report

The detailed report shall include the following information in addition to the information contained in the summary report:

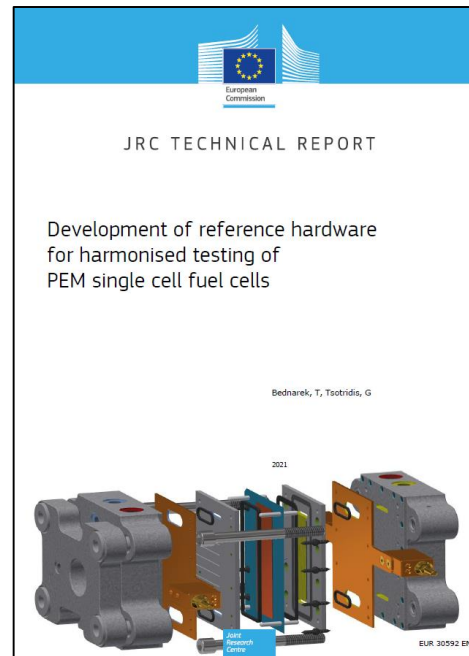
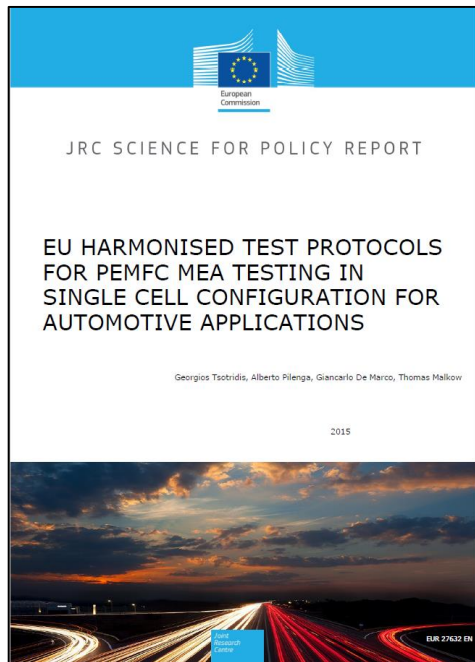
- a) type, specifications and operating configuration of the fuel cell power system and the process flow diagram showing the system boundary;
- b) description of the arrangements, location and operating conditions of the equipment and instruments;
- c) calibration results of instruments;
- d) reference to the calculation method;
- e) tabular and graphical presentation of the results;
- f) discussion of the test and its results (i.e. comments and observations).

10.6 Full report

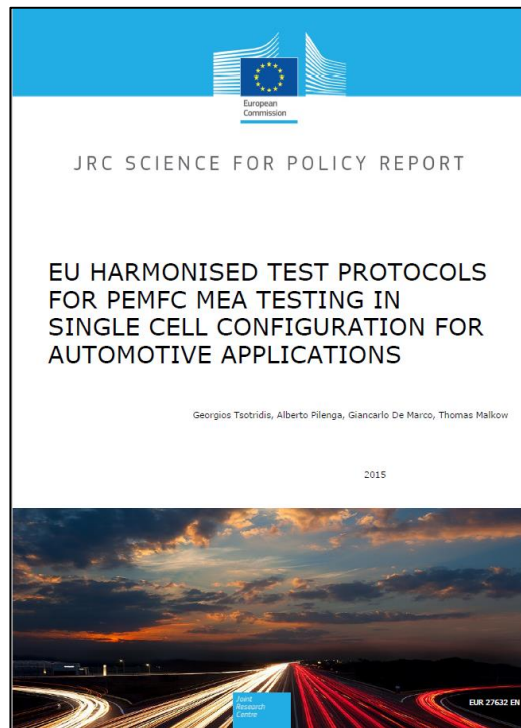
The full report shall include the following information in addition to the information contained in the detailed report:

- a) copies of original data sheets;
- b) original data sheets shall include the following information in addition to the measurement data:
 - 1) date and time of the test run,
 - 2) model number and measurement accuracy of instruments used for the test,
 - 3) ambient test conditions,
 - 4) name and qualifications of person(s) conducting the test,
 - 5) full and detailed uncertainty analysis,
 - 6) results of fuel analysis.

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1. INTRODUCTION.....	1
2. AUTOMOTIVE REFERENCE OPERATING CONDITIONS	3
2.1 CELL TEMPERATURE	3
2.2 ANODE CONDITIONS.....	3
2.3 CATHODE CONDITIONS	5
3 STRESSOR TESTS	8
3.1 STRESSOR TESTS AT OPERATING CONDITIONS	9
4 PERFORMANCE CHARACTERIZATION METHOD	21
4.1 PERFORMANCE CRITERIA	21
4.2 MEA SPECIFICATIONS	22
5 LOAD CYCLES	23
6 ENDURANCE TESTING	27
6.1 DYNAMIC LOAD CYCLING ENDURANCE TEST	27
6.2 REVERSIBLE and IRREVERSIBLE DEGRADATION	28
6.3 PERFORMANCE RECOVERY PROTOCOL.....	32
6.4 ON-OFF CYCLING ENDURANCE TEST	33
7 CONTROL ACCURACY & INSTRUMENT UNCERTAINTY	35
7.1 MEASURED PARAMETERS	36
7.2 SAMPLING FREQUENCY.....	36
BIBLIOGRAPHY	38
ABBREVIATIONS AND ACRONYMS	40
APPENDIX A: RELATIONSHIP OF RELATIVE HUMIDITY AND DEW POINT	42
APPENDIX B: PEMFC MATERIAL & COMPONENT FAILURE MODES & CAUSES	44
APPENDIX C: STRESSORS	45
APPENDIX D: TESTING PROCEDURES	49
APPENDIX E: POLARISATION CURVE TESTING PROCEDURE.....	52
APPENDIX F: FUEL CELL DYNAMIC LOAD CYCLE- FC-DLC	56
APPENDIX G: MEA SPECIFICATION	59

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	Anode (Fuel)	Cathode (Oxydant)
T_g^1	$T_C + 5K$	$T_C + 5K$
RH (%)	50	30
Corresponding dew point (%) ²	64	
P_g (kPa, abs) ³	250	230
Gas quality grade ⁴	5.0	
λ	1.3	1.5

¹ To prevent water condensation at the inlet

² at $T_C = 80^\circ\text{C}$

³ to facilitate mass transfer and adequate water management

⁴ this number defines the number of "9" defining the purity degree (i.e. 5.0 = 99.999%)

	Parameters	Symbol	Unit	Values
	Nominal cell operating temperature	T.Si.CL	$^\circ\text{C}$	80
ANODE	Fuel gas inlet temperature	T.Si.A	$^\circ\text{C}$	85
	Fuel gas inlet humidity	RH.Si.A	% RH	50
		DPT.Si.A	$^\circ\text{C}$	64 @80 $^\circ\text{C}$
	Fuel gas inlet pressure (absolute)	p.Si.A	kPa	250
	Fuel gas composition	Conc.Si.A.H2, Conc.Si.A.GasX		According to H ₂ 5.0 quality
	Fuel stoichiometry	Stoic.Si.A	-	1.3
CATHODE	Oxidant gas inlet temperature	T.Si.C	$^\circ\text{C}$	85
	Oxidant gas inlet humidity	RH.Si.C	% RH	30
		DPT.Si.C	$^\circ\text{C}$	53 @80 $^\circ\text{C}$
	Oxidant gas inlet pressure (absolute)	p.Si.C	kPa	230
	Oxidant	Conc.Si.C.O2, Conc.Si.C.GasX	-	According to ISO 8573-1:2010
	Air stoichiometry	Stoic.Si.C	-	1.5
Minimum current density for stoichiometry operation	I.S.MinGasFlow	A/cm ²	0.2	



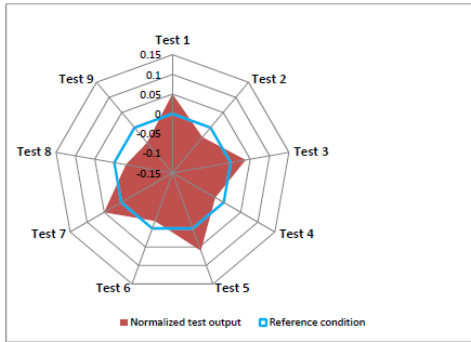
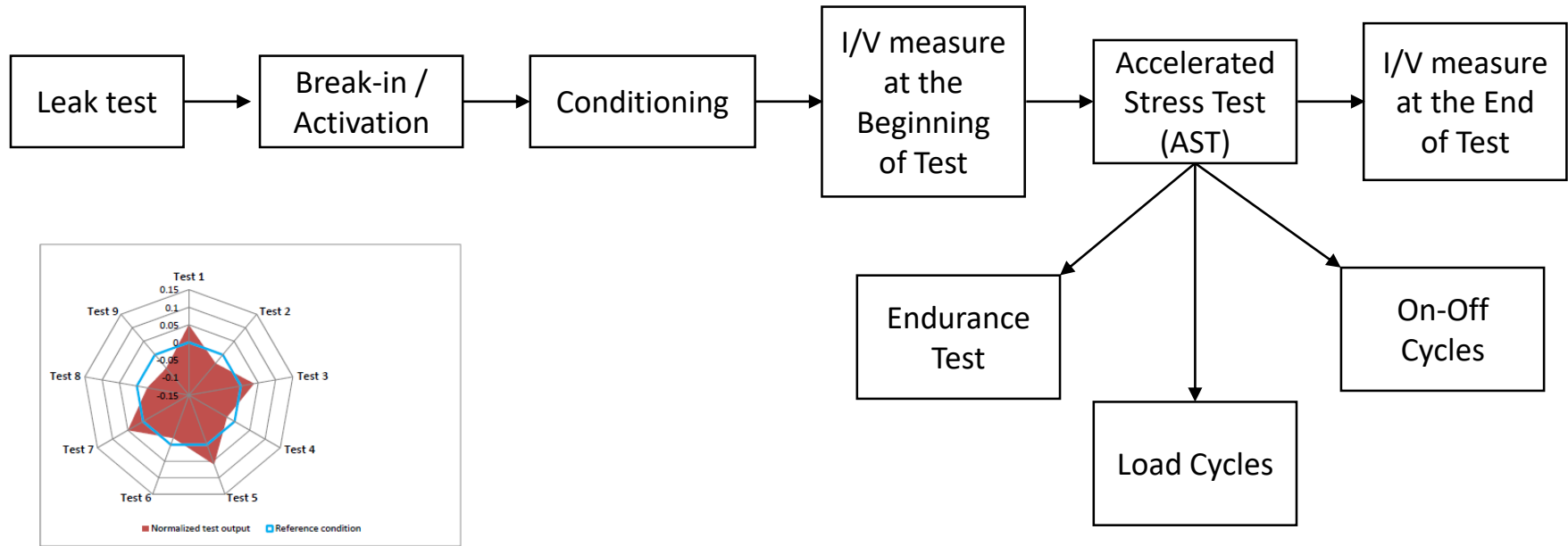
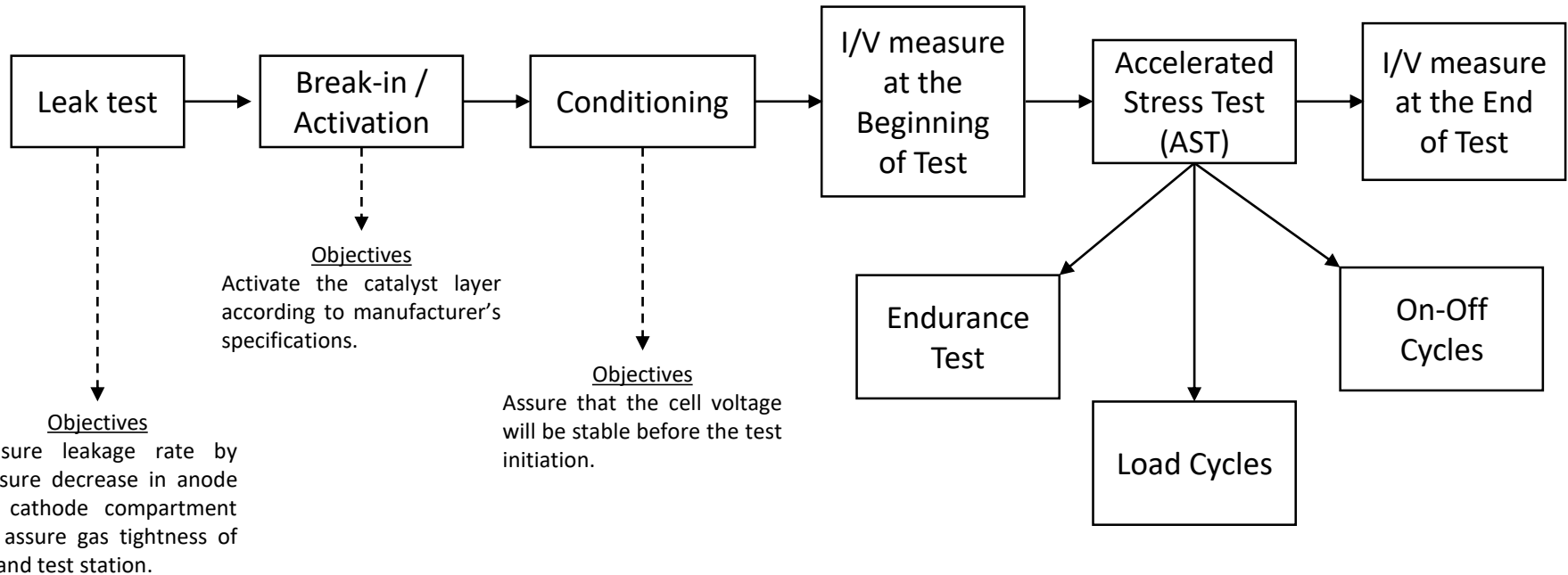


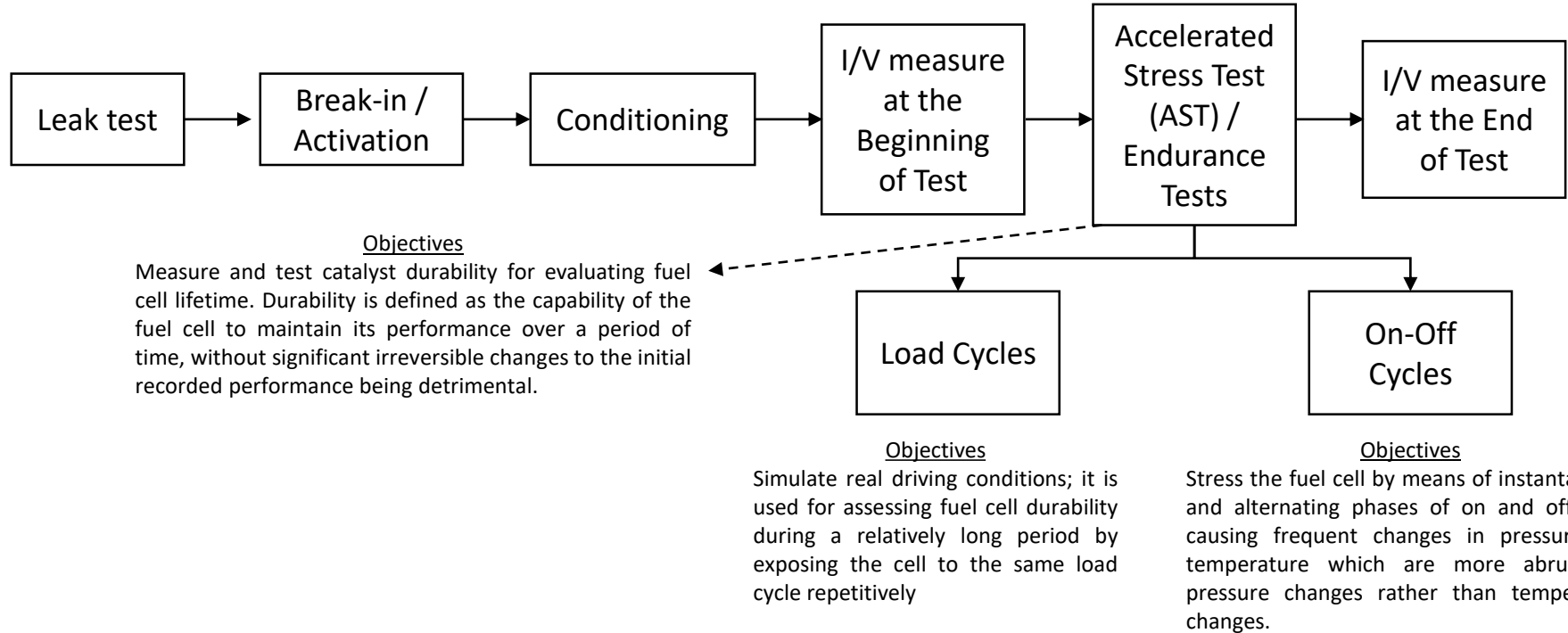
Figure 3:

Example of a spider plot showing normalised cell voltages (normalised test outputs) for 9 tests conducted under different stressor conditions with respect to the test conducted at reference conditions

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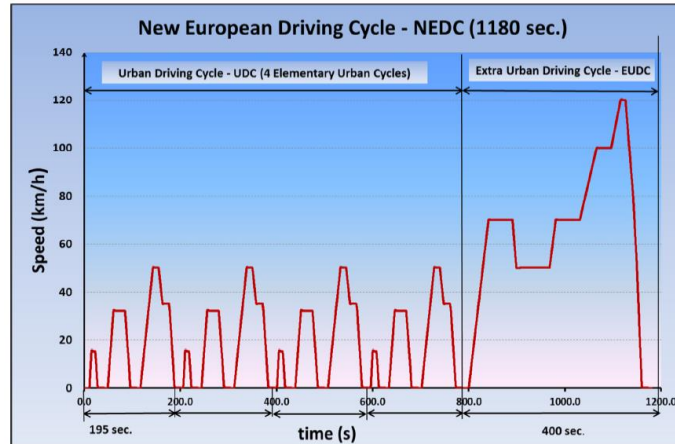


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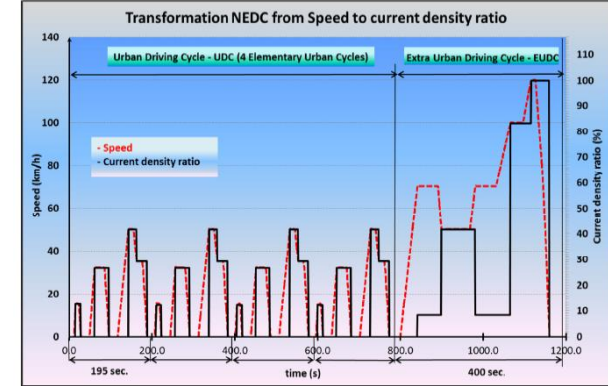
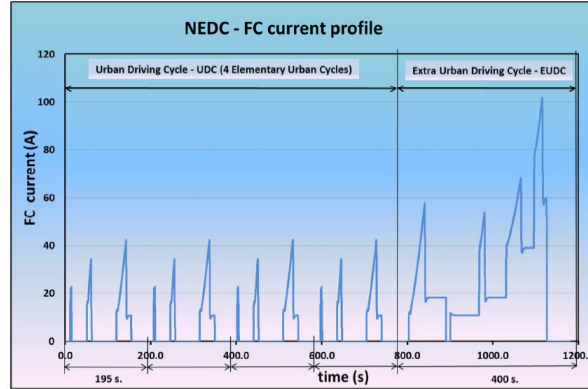
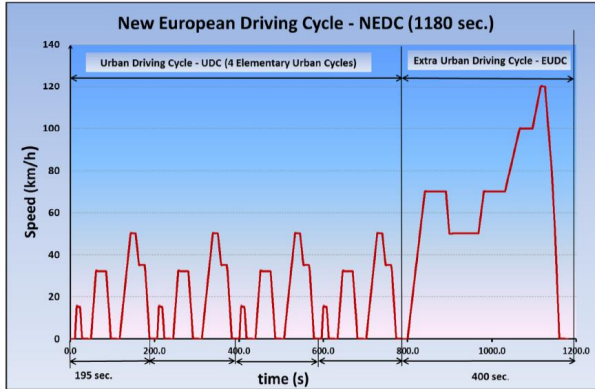


EU / GUIDELINES / LOAD CYCLES EXAMPLE

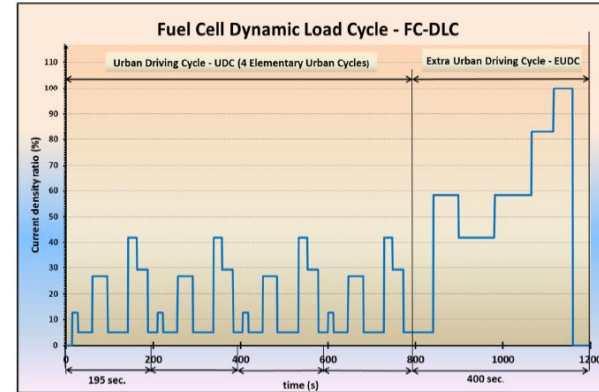
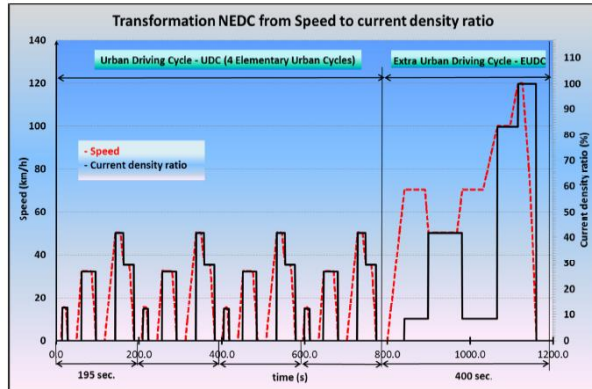
The NEDC (New European Driving Cycle) protocol is used for type approval of light-duty vehicles and features periods of acceleration, deceleration and constant speed. It consists of four repetitions of a low speed urban cycle of 195 seconds each followed up by a part which simulates a highway driving cycle of 400 seconds. In order to fill the gaps in between laboratory test rigs and real conditions the NEDC was modified to the Fuel Cell Dynamic Load Cycle (FC-DLC).



EU / GUIDELINES / LOAD CYCLES EXAMPLE



EU / GUIDELINES / LOAD CYCLES EXAMPLE



EU / GUIDELINES / HARDWARE

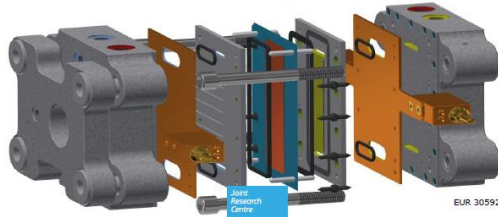


JRC TECHNICAL REPORT

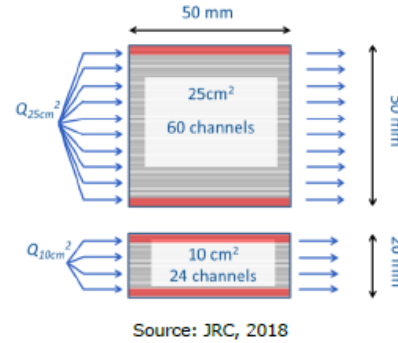
Development of reference hardware
for harmonised testing of
PEM single cell fuel cells

Bednarek, T, Toobridis, G

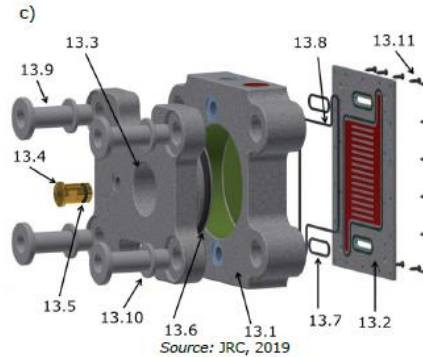
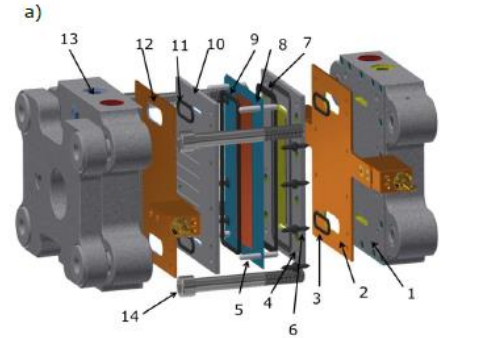
2021



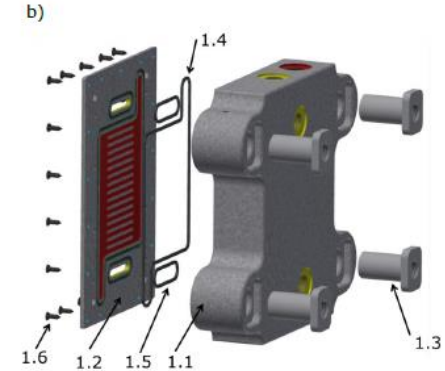
EUR 30592 EN



Source: JRC, 2018



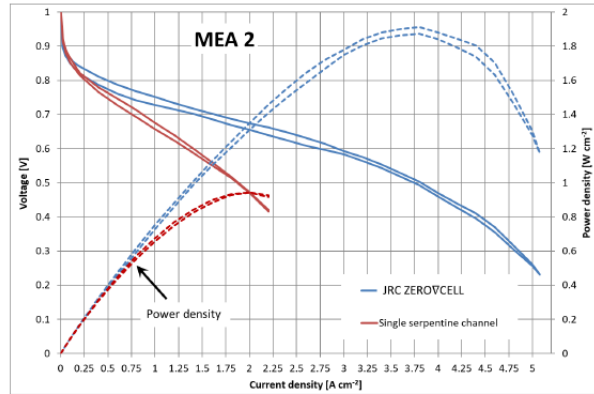
Source: JRC, 2019



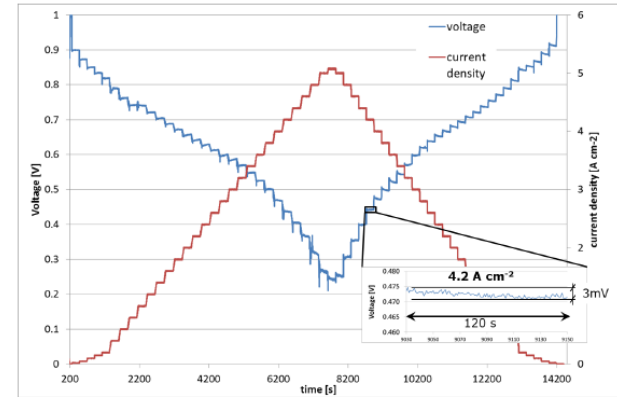
EU / GUIDELINES / HARDWARE



Source: JRC, 2019



Source: JRC, 2019



Source: JRC, 2019

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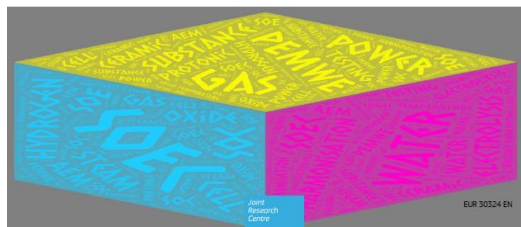
JRC VALIDATED METHODS, REFERENCE METHODS AND MEASUREMENTS REPORT

EU harmonised terminology for hydrogen generated by electrolysis

An open and comprehensive compendium

Maikow, K. T., Pilenga, A., Blagoeva, D.

2021

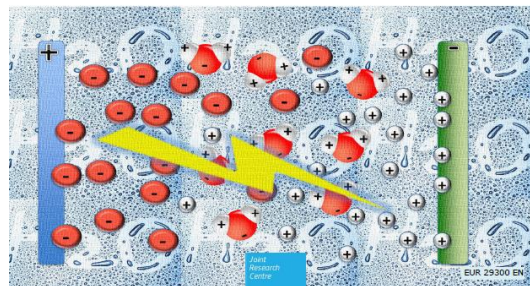


JRC TECHNICAL REPORTS

EU harmonised terminology for low-temperature water electrolysis for energy-storage applications

Tsotridis G., Pilenga A.

2018



JRC TECHNICAL REPORT

EU harmonised protocols for testing of low temperature water electrolyzers

G. Tsotridis, A. Pilenga
2021



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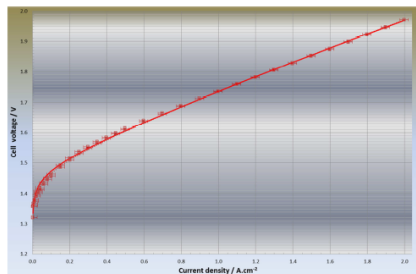


JRC VALIDATED METHODS, REFERENCE METHODS AND MEASUREMENTS REPORT

EU harmonised polarisation curve test method for low-temperature water electrolysis

Malkow T., Pilenga A., Tsostridis G., De Marco G.

2018



EUR 29162 EN



JRC VALIDATED METHODS, REFERENCE METHODS AND MEASUREMENTS REPORT

EU harmonised cyclic voltammetry test method for low-temperature water electrolysis single cells

Malkow, T., De Marco, G., Tsostridis, G.

2018



EUR 29285 EN

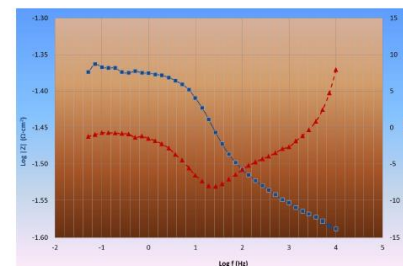


JRC VALIDATED METHODS, REFERENCE METHODS AND MEASUREMENTS REPORT

EU harmonised test procedure: electrochemical impedance spectroscopy for water electrolysis cells

Malkow, T., Pilenga, A., Tsostridis, G.

2018



EUR 29267 EN

4. Test equipment and set-up

This test procedure does not prescribe the type, geometry and size of the single cell or stack unless proprietary information, materials, designs, geometry and sizes of the MEA, mono-polar plates and cell have to be described in the test report to meet the test objective.

The test bench comprises subsystems to provide the cell with fluids in a defined manner (flow rate, pressure and temperature), a DC power supply and a heating/cooling subsystem for controlling the cell/stack temperature.

The test bench is controlled by a computer, which also acts as a data-acquisition unit. Table 3 lists the recommended test bench and sensor requirements with their main specification.

Table 3. Recommended test bench requirements and main specifications

Description	Specification	QTY
Hydrogen evolution electrode pressure sensor*	Range dependent on applied pressure	1 (minimum)
Oxygen evolution electrode pressure sensor*	Range dependent on applied pressure	1 (minimum)
Hydrogen evolution electrode temperature sensor**	Minimum range: 15-100 °C	2
Oxygen evolution electrode temperature sensor**	Minimum range: 15-100 °C	2
Hydrogen evolution electrode flow meter	Range dependent on anticipated flow	1 (optional)
Oxygen evolution electrode flow meter	Range dependent on anticipated flow	1 (optional)
Hydrogen safety sensor for the oxygen evolution electrode outlet	Range suitable to detect hydrogen in wet oxygen-rich gas to prevent occurrence of an explosive atmosphere	1
Oxygen safety sensor for the hydrogen evolution electrode outlet	Range suitable to detect hydrogen in (wet) hydrogen-rich gas to prevent occurrence of an explosive atmosphere	1
Cell/stack temperature sensor***	Minimum range: 15-100 °C	1 (optional)

Description	Specification	QTY
Adjustable flow meter for inert gas (i.e. nitrogen)	Range of flow rates suitable to dilute the evolved hydrogen to prevent occurrence of an explosive atmosphere	1 (optional)
Gas liquid separator		2
Cell/stack heating (cooling) devices	Minimum temperature range: ambient to 100 °C	Minimum 1
Water/liquid circulation pump	Range dependent on applied current density (galvanostatic control) or cut-off voltage (potentiostatic control)	Minimum 1
Water treatment device	-	1
Water conductivity meter	Minimum range: 0.1-10 ⁻⁶ S/cm	1
DC power supply	Dependent on maximum reachable current density ≥ 2 A/cm ² (galvanostatic control) Dependent on maximum cut-off voltage ≥ 2 V/cell (potentiostatic control) (optionally)	1
Control and data-acquisition hardware including software (e.g. computer)	The capacity of the data-acquisition system has to be sufficient to record all test variables with the sample rates defined	1

* The location of the sensor, usually directly after the gas liquid separator, should be mentioned in the test report. An additional sensor may be placed directly at the cell/stack inlet.

** The location of the sensor, usually directly at the cell/stack (water/liquid) outlet, should be mentioned in the test report. An additional sensor should be placed directly at the cell/stack (water/liquid) inlet.

*** The location of this sensor should be mentioned in the test report. It should be chosen so as to best represent the temperature of the cell/stack, taking into account the control equipment used in the test and the internal configuration and dimension of the cell/stack; see the recommendation of T_c in Section 5.

Important

During the test the hydrogen concentration in the gas stream from the oxygen evolution electrode should be monitored by a hydrogen gas safety sensor to trigger appropriate safety measures in case a specified threshold is approached. A threshold value of 10 % of the lower explosive limit (LEL) of hydrogen in oxygen (about 0.8 Vol-% H₂ in O₂) is advised.

Likewise, the oxygen concentration in the gas stream from the hydrogen evolution electrode should be monitored by an oxygen gas safety sensor to

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Table 4. Static TIPS

TIP	Control accuracy	Sampling rate
p_{H_2} (gauge) (set point)	$\pm 2 \%$	≥ 1 Hz
p_{O_2} (gauge) (set point)	$\pm 2 \%$	≥ 1 Hz
$P_{water/liquid, in}^{**}$ (gauge) (hydrogen evolution electrode)	$\pm 2 \%$	≥ 1 Hz
$P_{water/liquid, in}$ (gauge) (oxygen evolution electrode)	$\pm 2 \%$	≥ 1 Hz
$P_{N_2, in}^{****}$ (gauge)	$\pm 2 \%$	≥ 1 Hz
$Q_{v, N_2, in}^{**}$ (hydrogen evolution electrode)**	$\pm 1 \%$ FS	≥ 1 Hz
$Q_{v, water/liquid, in}^{**}$ (hydrogen evolution electrode)****	$\pm 1 \%$ FS	≥ 1 Hz
$Q_{v, water/liquid, in}$ (oxygen evolution electrode)****	$\pm 1 \%$ FS	≥ 1 Hz
T_c^{*****} (set point)	± 2 K	≥ 1 Hz
$T_{water/liquid, out}^{***}$ (hydrogen evolution electrode)*****	± 2 K	≥ 1 Hz
$T_{water/liquid, out}^{***}$ (oxygen evolution electrode)*****	± 2 K	≥ 1 Hz

(water/liquid) outlet temperature, $T_{water/liquid, in}$ are static TIPS (**set points**) and $T_{water/liquid, out}$ are variable TIPS.

The variable TIPS applied during the test are given in Table 5.

Table 5. Variable TIPS

TIP	Control accuracy	Sampling rate
j (galvanostatic control)	$\pm 2 \%$ for $j < 0.1$ A/cm ² $\pm 1 \%$ for $j \geq 0.1$ A/cm ²	≥ 1 Hz
$P_{N_2, in}^*$ (gauge)	$\pm 2 \%$	≥ 1 Hz
$T_{N_2, in}^*$ (hydrogen evolution electrode)***	± 2 K	≥ 1 Hz
$T_{water/liquid, in}^{**}$ (hydrogen evolution electrode)***	± 2 K	≥ 1 Hz
$T_{water/liquid, in}$ (oxygen evolution electrode)****	± 2 K	≥ 1 Hz
U (potentiostatic control)	± 1 mV/cell	≥ 1 Hz

* Only relevant when used for PEMWE with no intended presence of liquid water.

** Only relevant for PEMWE with intended presence of liquid water.

*** The temperature may vary during the test depending on the regulation of the cell/stack temperature. If the cell/stack (water/liquid) outlet temperature **set point** is regulated by the variation of the cell/stack (water/liquid) outlet temperature, $T_{water/liquid, in}$ are static TIPS (**set points**) and $T_{water/liquid, out}$ are variable TIPS.

The difference between the ascending polarisation curve and the descending polarisation curve (hysteresis) provides information on whether or not the cell/stack was in (thermal) equilibrium during the measurement. A small hysteresis implies that this was the case.

The static TIPS are to be maintained at their values/ranges during the measurement.

All TIPS and TOPs should be recorded versus the entire test duration with the specified sampling rate (see Table 4, Table 5 and Table 6).

The polarisation curve measurement is performed up to a maximum/minimum value (Table 7) either by:

- **method A** (linear current sweep): continuous increase/decrease of current density at a specified rate; or
- **method B** (stepwise steady-state current sweep): applying consecutive current density steps (Table 7).

For method A, the current is linearly varied, e.g. 0.080 A/cm² (PEMWE) and 0.016 A/cm² (AWE and AEMWE) per minute.

Note that the actual rate of the current density to be used in the test will depend on the equipment used.

Table 7. Polarisation curve set points for method B (galvanostatic control)

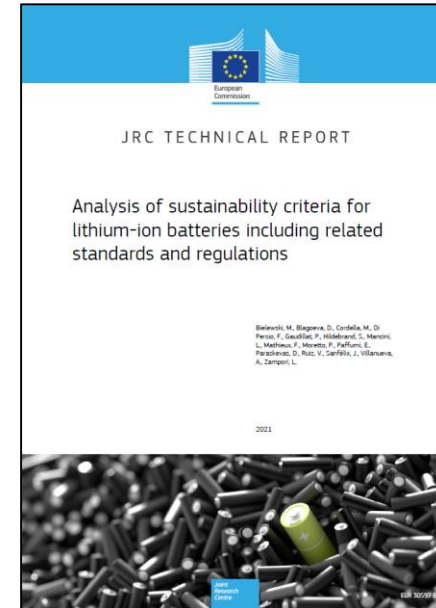
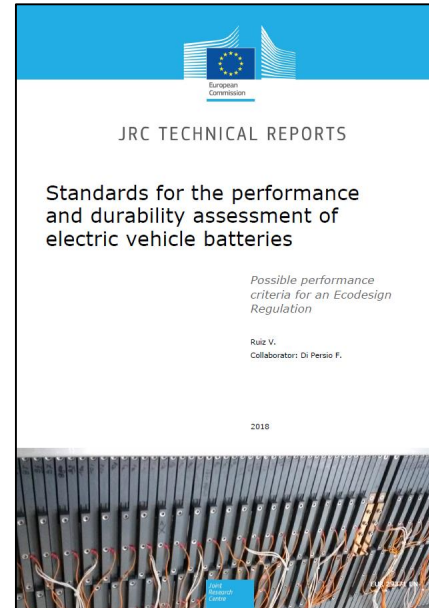
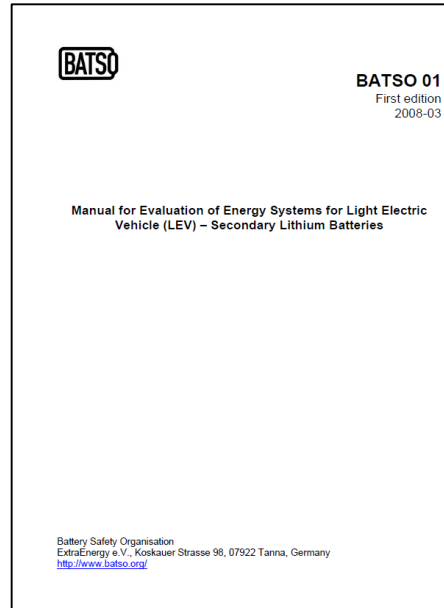
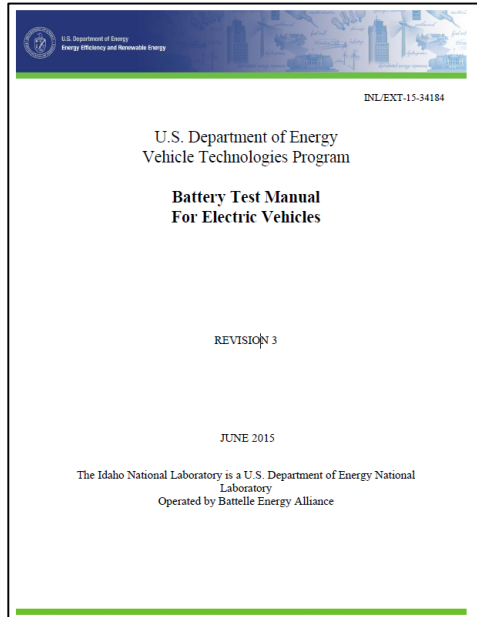
Set point <i>k</i> *	Current density (A/cm ²)			Step duration (s)	
	PEMWE	Alkaline WE	AEMWE	Dwell time**	Data acquisition***
1	0.001	0.0002	0.0002	30	30
2	0.005	0.0010	0.0010	30	30
3	0.010	0.0020	0.0020	30	30
4	0.025	0.0050	0.0050	30	30
5	0.050	0.0100	0.0100	30	30
6	0.075	0.0150	0.0150	30	30
7	0.100	0.0200	0.0200	30	30
8	0.150	0.0300	0.0300	30	30
9	0.200	0.0400	0.0400	30	30
10	0.250	0.0500	0.0500	30	30

Set point <i>k</i> *	Current density (A/cm ²)			Step duration (s)	
	PEMWE	Alkaline WE	AEMWE	Dwell time**	Data acquisition***
11	0.300	0.0600	0.0600	30	30
12	0.350	0.0700	0.0700	30	30
13	0.400	0.0800	0.0800	30	30
14	0.450	0.0900	0.0900	30	30
15	0.500	0.1000	0.1000	30	30
16	0.600	0.1200	0.1200	30	30
17	0.700	0.1400	0.1400	30	30
18	0.800	0.1600	0.1600	30	30
19	0.900	0.1800	0.1800	30	30
20	1.000	0.2000	0.2000	30	30
21	1.100	0.2200	0.2200	30	30
22	1.200	0.2400	0.2400	30	30
23	1.300	0.2600	0.2600	30	30
24	1.400	0.2800	0.2800	30	30
25	1.500	0.3000	0.3000	30	30
26	1.600	0.3200	0.3200	30	30
27	1.700	0.3400	0.3400	30	30
28	1.800	0.3600	0.3600	30	30
29	1.900	0.3800	0.3800	30	30
30****	2.000	0.4000	0.4000	30	30

* Depending on the actual equipment used in the test, the set points at low current densities may be skipped to start, for example at or above 0.1 A/cm².

** Generally, the dwell time should be chosen so that the cell voltage does not deviate by more than ± 5 mV over a duration of 30 s. For stacks this criterion may also be applied by dividing the stack voltage by the number of cells in the stack to check on the deviation of the resulting mean cell voltage. Particularly for stacks (with a large cell area), the dwell time should be chosen so as to allow thermal equilibrium to be obtained, for example by checking whether the cell/stack temperature and/or its gradient is within a specified range (depending on the measurement equipment used in the test) over a specified duration (depending on the control equipment used in

BATTERIES / AVAILABLE GUIDELINES



BATTERIES / AVAILABLE GUIDELINES



JRC TECHNICAL REPORTS

Standards for the performance and durability assessment of electric vehicle batteries

Possible performance criteria for an Ecodesign Regulation

Ruiz V.
Collaborator: Di Persio F.

2018

Contents

Foreword	1	4 Considerations about EV batteries performance	16
Acknowledgements	2	4.1 Analysis of functional parameters and essential performance standards for BEV, HEV, PHEV and FCV batteries	17
Abstract	3	4.1.1 Supporting standards	22
1 Introduction	4	4.1.2 Ongoing efforts	22
1.1 Scope	4	4.2 Analysis of functional parameters and essential performance standards for LEV batteries	29
1.2 First steps	7	5 Considerations about EV batteries durability and its relationship to the Circular economy	33
1.3 Battery and electric vehicle terminology	7	5.1 Battery durability	36
2 Battery technologies in the EV market	9	5.2 Analysis of cycle life standards for EV batteries	38
2.1 Lithium-ion batteries	9	5.3 Analysis of U.S. Department of Energy cycle life EV batteries manuals	42
2.2 Other battery chemistries	10	5.4 Considerations about second use applications	48
3 Standardisation and legislative framework	11	6 Identification of needs	52
3.1 European standardisation landscape	11	References	54
3.1.1 Horizontal standards on materials efficiency	12	List of abbreviations	59
3.2 Global standardisation and regulatory landscape	14	List of schemes	61
3.2.1 International Electrotechnical Commission (IEC)	14	List of tables	62
3.2.2 International Organisation for Standardisation (ISO)	14	List of figures	63
3.2.3 Society of Automotive Engineers International (SAE)	14		
3.2.4 U.S. Department of Energy test manuals	15		

BATTERIES / AVAILABLE GUIDELINES



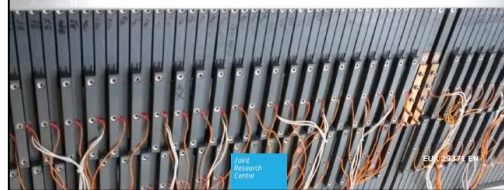
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Cycle life ageing The performance of functional parameters (e.g. capacity) are measured as a function of cycle number during electrochemical cycling at a predefined temperature, current rate and upper and lower cut off voltages

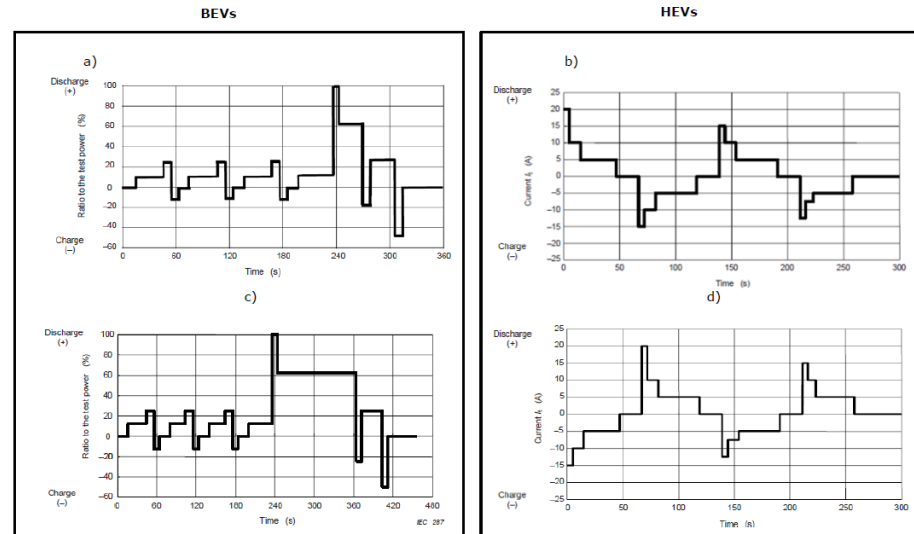


Figure 4. Profiles for cycle life testing: a) dynamic discharge power Profile A for BEV [33, 35], b) discharge-rich Profile for HEV [32], c) dynamic discharge power Profile B (hill-climbing) for BEV [33, 35], d) charge-rich Profile for HEV [35]. Reprints from IEC 62660-1 ed.1.0 [35]¹⁵

BATTERIES / INTERNATIONAL STANDARDS

Section	Criteria	Related standards, regulations and other reference documents	Conclusions/comments
2. ELECTROCHEMICAL PERFORMANCE AND DURABILITY			
2.1	Initial performance	ISO 12405-4:2018 [6] IEC 61427-2:2015 [17] Commission Regulation (EU) No 1103/2010 [18]	Round-trip Efficiency (RTE) is a good criterion to reflect the overall efficiency of the battery system. A criterion on energy density could have positive impact on energy consumption, but not advisable due to its anticipated negative impact on other sustainability criteria.
2.2	Capacity fade, power fade, RTE fade	ISO 12405-4:2018 [6] IEC 62660-1:2018 [26] IEC 62620:2014 [7] IEC 61427-1:2013 [27] IEC 61427-2:2015 [17] GTR EVE (ongoing)	Despite availability of standards for the measurement of these criteria, test procedures reflecting real time operation remain challenging, due to long test durations. Real performance and degradation data are necessary to develop fit-for-purpose tests.
2.3	Calendar life	ISO 12405-4:2018 [6] IEC 62620:2014 [7]	Current standards are only available for testing of short-term degradation. Long-term aging studies are not feasible in industrial cell production. Environmental conditions can be adjusted to accelerate degradation, but it might promote other degradation mechanism different from those occurring during real-time ageing.

BATTERIES / INTERNATIONAL STANDARDS

Section	Criteria	Related standards, regulations and other reference documents	Conclusions/comments
3. REUSABILITY, REPARABILITY AND RECYCLABILITY			
3.1	Labelling/markings	IEC 62902:2019 [38] SAE J3071:2016 [39] SAE J2984:2013 [40]	Information about battery composition facilitates 2 nd use applications and maximises substance recuperation during recycling.
3.2-3.4	Repair, reuse, remanufacture, repurpose	EN 45554:2020 [43] EN 45556:2019 [44] EC 715/2007 [41] ANSI/CAN/UL 1974:2018 [45]	Extending lifetime of batteries has a positive impact on the environment, the use of primary resources and cost for consumers. Facilitating the access to battery parts has also a positive effect on the effectiveness and cost of maintenance, remanufacturing, and repair. Manufacturers have to ensure easy access to usage information stored in the BMS in order to be able to reuse cells (and other components). This requires some standardisation of the cell and module design. The competition in price between 2 nd use and new batteries remains challenging but will be handled by the market.

Section	Criteria	Related standards, regulations and other reference documents	Conclusions/comments
3.5, 3.6, 3.9	Recycling	Directive 2012/19/EU (WEEE) [51] Directive 2000/53/EC [49] Regulation (EU) No 517/2014 [50] EN 45559:2019 [42] EN 45555:2019 [52] EN 45557:2020 [53] EN 45558:2019 [54]	Facilitating the access to the parts of concern for recyclers by setting design requirements has a positive effect on the effectiveness and cost of dismantling for recycling. Increased recyclability enables a larger flow of recyclable materials, and supports compliance with the WEEE directive.
3.7	Critical raw materials (CRM)	Commission communication COM/2017/0490 final [57] EN 45558:2019 [54]	Providing information on the CRM content can help improve the recycling of waste containing CRMs, and may incentivise pro-active manufacturers to implement strategies for the reduction of the CRM content in their products.
3.8	Recycled content	EN 45557:2020 [53]	The declaration of recycled content in a battery improves the transparency of the material origins, both for customers and regulatory bodies, and has the potential to help recycling markets and the generation of quality secondary materials. However, not every material in a battery is recycled at the moment. A credible traceability system throughout the value chain is required.

BATTERIES / INTERNATIONAL STANDARDS

Section	Criteria	Related standards, regulations and other reference documents	Conclusions/comments
4. CARBON FOOTPRINT			
4.1	Carbon footprint	ISO 14040:2006 [65] ISO 14044:2006 [66] ISO 14067:2018 [67]	Making the information about the carbon footprint of a battery available incentivises cell manufacturers to invest into an environmentally friendlier cell production throughout the value chain.

BATTERIES / INTERNATIONAL STANDARDS

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BATTERIES / INTERNATIONAL STANDARDS

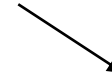
Section	Criteria	Related standards, regulations and other reference documents	Conclusions/comments
5. SAFETY			
5.1	Normal and abnormal operation	UN Regulation No. 100.02 [72] GTR No. 20 [73] UN Regulation No. 136 [74] ISO 6469-1:2009 [77] IEC 62660-2:2018 [78] IEC 62660-3:2016 [79] SAE J2929:2013 [80] SAE J2464:2009 [81] IEC 62619:2017 [82] IEC/TS 62933-5-1:2017 [83] IEC 63056:2020 [85]	Careful analysis of existing standards and regulations is needed, in order to identify gaps and areas of improvement and harmonisation. GTR No 20 is mandatory in the EU. A new version is under preparation now. For stationary applications, the standardisation frame is less developed. The compliance to the following tests is recommended: vibration, thermal shock and cycling, external short circuit protection, overcharge protection, over-discharge protection, over-temperature protection, overcurrent protection, thermal propagation, drop, impact, internal short circuit and thermal abuse.

Section	Criteria	Related standards, regulations and other reference documents	Conclusions/comments
5.2	2 nd use	ANSI/CAN/UL 1974:2018 [45]	The safest approach is to require safety testing specific to the new application. However, a broader spread of performances is to be expected, especially if cells with a different ageing profile are reused in one system.
5.3	Transport	UN transport Regulation 38.3:2019 [88] IEC 62281:2019 [89] SAE J2950:2012 [90] ANSI/CAN/UL 1974 [45]	Battery systems containing reused batteries need to comply with the same transportation regulations as new batteries.
5.4	Storage	ANSI/CAN/UL 1974 [45]	Ambient storage conditions are to be recorded on minimum a daily basis. The open circuit voltage is to be recorded at the beginning and the end of storage.
5.5	Handling/dismantling	SAE J2990:2019 [91] SAE J2974:2019 [62]	Dismantling personnel have to have the appropriate safety training.

IEC 62660-X:XXXX



Secondary lithium-ion cells for the propulsion of
electric road vehicles



EN IEC 62660-1:2019

Part 1: Performance testing

EN IEC 62660-2:2019

Part 2: Reliability and abuse testing

EN IEC 62660-3:2022

Part 3: Safety requirements

IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE.....	5
1 Campo di applicazione.....	7
2 Riferimenti normativi.....	7
3 Termini e definizioni.....	7
4 Condizioni di prova.....	9
4.1 Generalità.....	9
 4.2 Strumenti di misura.....	9
4.3 Tolleranza.....	10
4.4 Stabilizzazione termica.....	10
5 Misura delle dimensioni.....	10
6 Misura della massa.....	12
7 Misure elettriche.....	12
7.1 Generalità.....	12
7.2 Condizioni generali di carica.....	12
7.3 Capacità.....	12
7.4 Impostazione del valore del SOC.....	13
7.5 Potenza.....	13
7.6 Energia.....	15
7.7 Prova di immagazzinamento.....	17
7.8 Prova di durata di vita ciclica.....	18
7.9 Prova dell'efficienza energetica.....	27
Allegato A (informativo) Condizioni selettive per le prove.....	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica.....	34
Allegato C (informativo) Prova della caratteristica corrente-tensione.....	37
Bibliografia.....	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee.....	41

1 Campo di applicazione

La presente Parte della IEC 62660 specifica le prove di prestazione e di durata di vita in servizio degli accumulatori agli ioni di litio, utilizzati nella propulsione di veicoli elettrici, compresi i veicoli elettrici a batterie (BEV) e i veicoli elettrici ibridi (HEV).

4.2 Strumenti di misura

4.2.1 Gamma dei valori dei dispositivi di misura

Gli strumenti utilizzati devono permettere di misurare i valori di tensione, corrente e temperatura. La gamma di valori di questi strumenti e i metodi di misura devono essere scelti in modo da garantire la precisione specificata per ciascuna prova.

Per gli strumenti analogici questo implica che le letture siano effettuate nell'ultimo terzo della scala graduata.

Possono essere utilizzati altri strumenti di misura, a condizione che questi siano in grado di fornire una precisione equivalente.

4.2.2 Misura della tensione

La resistenza dei voltmetri impiegati deve essere pari ad almeno 1 M Ω /V.

4.2.3 Misura della corrente

L'intero complesso di amperometro, derivatore e cavi deve avere classe di precisione 0,5 o migliore.

4.2.4 Misure della temperatura

La temperatura dell'elemento deve essere misurata utilizzando un dispositivo di misura della temperatura superficiale, in grado di fornire la definizione di scala equivalente e la precisione di taratura specificate in 4.2.1. La temperatura deve essere misurata in un punto che rifletta, il più fedelmente possibile, la temperatura dell'elemento. La temperatura, se necessario, può essere misurata in altri punti ritenuti appropriati.

Nella Figura 1 sono mostrati esempi della misura della temperatura. Per la misura della temperatura si devono seguire le istruzioni specificate dal costruttore dell'elemento.

IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE	5
1 Campo di applicazione	7
2 Riferimenti normativi	7
3 Termini e definizioni	7
4 Condizioni di prova	9
4.1 Generalità	9
4.2 Strumenti di misura	9
4.3 Tolleranza	10
4.4 Stabilizzazione termica	10
5 Misura delle dimensioni	10
6 Misura della massa	12
7 Misure elettriche	12
7.1 Generalità	12
7.2 Condizioni generali di carica	12
7.3 Capacità	12
7.4 Impostazione del valore del SOC	13
7.5 Potenza	13
7.6 Energia	15
7.7 Prova di immagazzinamento	17
7.8 Prova di durata di vita ciclica	18
7.9 Prova dell'efficienza energetica	27
Allegato A (informativo) Condizioni selettive per le prove	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica	34
Allegato C (informativo) Prova della caratteristica corrente-tensione	37
Bibliografia	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee	41

4.3 Tolleranza

La precisione complessiva dei valori controllati o misurati, rispetto ai valori specificati o effettivi, deve essere compresa nelle seguenti tolleranze:

- $\pm 0,1$ % per la tensione;
- ± 1 % per la corrente;
- ± 2 K per la temperatura;
- $\pm 0,1$ % per il tempo;
- $\pm 0,1$ % per la massa;
- $\pm 0,1$ % per le dimensioni.

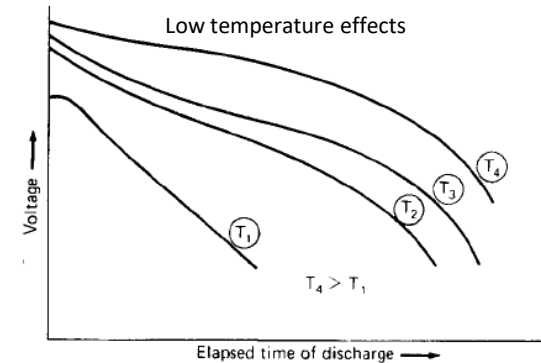
Queste tolleranze includono la precisione combinata degli strumenti di misura, della tecnica di misura utilizzata e di tutte le altre fonti di errore contenute nella procedura di prova.

4.4 Stabilizzazione termica

Per la stabilizzazione della temperatura dell'elemento, questo deve essere esposto a una temperatura ambiente specificata per un minimo di 12 h. Questo periodo può essere ridotto quando viene raggiunta la stabilità termica. La stabilità termica viene considerata raggiunta se, dopo un intervallo di 1 h, la variazione della temperatura dell'elemento risulta inferiore a 1 K.

BATTERIES – TESTING CONDITIONS

Temperature Batteries perform poorly at extremely low and high temperatures. At low temperature, ionic diffusion and migration can be hindered and damaging side reactions (e.g., lithium plating) can occur, resulting in reduction of chemical activity and increase of internal resistance. High temperatures favor other side reactions, such as corrosion and gas generation. Moreover, the internal resistance decreases, the discharge voltage increases and, the capacity and energy output usually increase together with chemical activity and it could lead to a rapid self-discharge processes causing a net loss of capacity. For Pb–acid batteries, charge and discharge temperatures should be limited to an operating range of $-40 \div 60$ °C. Li-ion batteries have an operating range of $-20 \div 60$ °C. Ni-MH have the narrowest operating range of $-20 \div 45$ °C.



IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE	5
1 Campo di applicazione	7
2 Riferimenti normativi	7
3 Termini e definizioni	7
4 Condizioni di prova	9
4.1 Generalità	9
4.2 Strumenti di misura	9
4.3 Tolleranza	10
4.4 Stabilizzazione termica	10
5 Misura delle dimensioni	10
6 Misura della massa	12
7 Misure elettriche	12
7.1 Generalità	12
7.2 Condizioni generali di carica	12
7.3 Capacità	12
7.4 Impostazione del valore del SOC	13
7.5 Potenza	13
7.6 Energia	15
7.7 Prova di immagazzinamento	17
7.8 Prova di durata di vita ciclica	18
7.9 Prova dell'efficienza energetica	27
Allegato A (informativo) Condizioni selettive per le prove	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica	34
Allegato C (informativo) Prova della caratteristica corrente-tensione	37
Bibliografia	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee	41

7 Misure elettriche

7.1 Generalità

Durante ciascuna prova devono essere registrati i valori di tensione, corrente e temperatura.

Prima di ciascuna prova, se non diversamente specificato, la temperatura dell'elemento deve essersi stabilizzata alla temperatura del locale, conformemente a quanto indicato in 4.4.

Se non diversamente specificato la temperatura ambiente deve corrispondere alla temperatura del locale.

7.2 Condizioni generali di carica

Se non diversamente indicato nel presente documento, prima di effettuare le prove di misura dei parametri elettrici, l'elemento deve essere sottoposto a carica come segue.

Prima della carica, l'elemento deve essere scaricato alla temperatura del locale, alla corrente costante descritta in Tabella 1, sino alla tensione di fine scarica specificata dal costruttore dell'elemento. Successivamente l'elemento deve essere sottoposto a carica, alla temperatura del locale, applicando il metodo di carica dichiarato dal costruttore dell'elemento stesso.

7.3 Capacità

La capacità di un elemento deve essere misurata in accordo alle seguenti fasi.

Fase 1 – L'elemento deve essere caricato come previsto in 7.2.

Dopo la ricarica, la temperatura dell'elemento deve essere stabilizzata come indicato in 4.4.

Fase 2 – L'elemento deve essere scaricato alla temperatura specificata, ad una corrente costante $I_1(A)$, sino a raggiungere la tensione di fine scarica specificata dal costruttore dell'elemento. Devono essere applicate la corrente di scarica e le temperature degli elementi indicate nella Tabella 1.

Oltre alla Tabella 1, possono essere scelte altre condizioni di prova specifiche, sulla base di un accordo tra il costruttore dell'elemento e il cliente. Le condizioni selettive di prova sono riportate nella Tabella A.1.

Tabella 1 – Condizioni per la scarica

Temperatura dell'elemento °C	Corrente di scarica A	
	Applicazione BEV	Applicazione HEV
0		
25	1/3 I_1	1 I_1
45		

IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE	5
1 Campo di applicazione	7
2 Riferimenti normativi	7
3 Termini e definizioni	7
4 Condizioni di prova	9
4.1 Generalità	9
4.2 Strumenti di misura	9
4.3 Tolleranza	10
4.4 Stabilizzazione termica	10
5 Misura delle dimensioni	10
6 Misura della massa	12
7 Misure elettriche	12
7.1 Generalità	12
7.2 Condizioni generali di carica	12
7.3 Capacità	12
7.4 Impostazione del valore del SOC	13
7.5 Potenza	13
7.6 Energia	15
7.7 Prova di immagazzinamento	17
7.8 Prova di durata di vita ciclica	18
7.9 Prova dell'efficienza energetica	27
Allegato A (informativo) Condizioni selettive per le prove	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica	34
Allegato C (informativo) Prova della caratteristica corrente-tensione	37
Bibliografia	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee	41

7.4 Impostazione del valore del SOC

Gli elementi in prova devono essere caricati, salvo diversa indicazione, come specificato nel seguito. L'impostazione del valore del SOC è la procedura che deve essere seguita per predisporre gli elementi con i diversi valori di SOC per le prove del presente documento.

Fase 1 – L'elemento deve essere caricato come indicato in 7.2.

Fase 2 – L'elemento deve essere lasciato a riposo alla temperatura del locale, come previsto in 4.4.

Fase 3 – L'elemento deve essere scaricato a corrente costante, come indicato nella Tabella 1, per $(100 - n)/100 \times 3$ h per le applicazioni BEV e per $(100 - n)/100 \times 1$ h per le applicazioni HEV, dove n è il valore del SOC (%) da impostare per ogni prova.

IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE	5
1 Campo di applicazione	7
2 Riferimenti normativi	7
3 Termini e definizioni	7
4 Condizioni di prova	9
4.1 Generalità	9
4.2 Strumenti di misura	9
4.3 Tolleranza	10
4.4 Stabilizzazione termica	10
5 Misura delle dimensioni	10
6 Misura della massa	12
7 Misure elettriche	12
7.1 Generalità	12
7.2 Condizioni generali di carica	12
7.3 Capacità	12
7.4 Impostazione del valore del SOC	13
7.5 Potenza	13
7.6 Energia	15
7.7 Prova di immagazzinamento	17
7.8 Prova di durata di vita ciclica	18
7.9 Prova dell'efficienza energetica	27
Allegato A (informativo) Condizioni selettive per le prove	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica	34
Allegato C (informativo) Prova della caratteristica corrente-tensione	37
Bibliografia	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee	41

7.5.3.1 Calcolo della potenza

La potenza deve essere calcolata utilizzando l'equazione (1) ed essere arrotondata alle tre cifre significative.

$$P_d = U_d \times I_{dmax} \quad (1)$$

dove

P_d è la potenza (W);

U_d è la tensione misurata al termine dell'impulso di 10 s della scarica I_{dmax} (V);

I_{dmax} è la massima corrente di scarica specificata dal costruttore dell'elemento (A).

Se P_d è un valore stimato, questo deve essere dichiarato.

7.5.3.2 Densità di potenza per unità di massa

La densità di potenza in rapporto alla massa deve essere calcolata dall'equazione (2) e arrotondata alle tre cifre significative.

$$\rho_{pd} = \frac{P_d}{m} \quad (2)$$

dove

ρ_{pd} è la densità di potenza (W/kg);

P_d è la potenza (W);

m è la massa dell'elemento (kg).

7.5.3.3 Densità di potenza per unità di volume

La densità di potenza volumetrica deve essere calcolata utilizzando l'equazione (3) e arrotondata alle tre cifre significative.

$$\rho_{pvim} = \frac{P_d}{V} \quad (3)$$

dove

ρ_{pvim} è la densità di potenza volumetrica (W/l);

P_d è la potenza (W);

V è il volume dell'elemento (l).

IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE	5
1 Campo di applicazione	7
2 Riferimenti normativi	7
3 Termini e definizioni	7
4 Condizioni di prova	9
4.1 Generalità	9
4.2 Strumenti di misura	9
4.3 Tolleranza	10
4.4 Stabilizzazione termica	10
5 Misura delle dimensioni	10
6 Misura della massa	12
7 Misure elettriche	12
7.1 Generalità	12
7.2 Condizioni generali di carica	12
7.3 Capacità	12
7.4 Impostazione del valore del SOC	13
7.5 Potenza	13
7.6 Energia	15
7.7 Prova di immagazzinamento	17
7.8 Prova di durata di vita ciclica	18
7.9 Prova dell'efficienza energetica	27
Allegato A (informativo) Condizioni selettive per le prove	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica	34
Allegato C (informativo) Prova della caratteristica corrente-tensione	37
Bibliografia	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee	41

7.6.1 Generalità

Questa prova ha lo scopo di determinare la densità di energia che può essere erogata da un elemento, nelle condizioni d'uso rappresentative delle applicazioni BEV e HEV.

Sulla base della prova indicata in 7.6.2, la densità di energia di un elemento deve essere calcolata come indicato in 7.6.3.

7.6.2 Metodo di prova

La densità di energia per la massa (Wh/kg) e la densità di energia volumetrica (Wh/l) degli elementi, in una certa scarica di corrente di $1/3 I_1$ (A) per le applicazioni BEV, e di $1 I_1$ (A) per quelle HEV, devono essere determinate applicando la seguente procedura.

a) Misura della massa

La massa dell'elemento deve essere misurata come specificato nell'Articolo 6.

b) Misura delle dimensioni

Le dimensioni dell'elemento devono essere misurate come specificato nell'Articolo 5.

c) Misura della capacità

La capacità dell'elemento deve essere determinata come specificato in 7.3, alla temperatura del locale.

d) Calcolo della tensione media

Il valore della tensione media durante la scarica, nella prova di capacità di cui sopra, deve essere ottenuto integrando la tensione di scarica nel tempo e dividendo il risultato per la durata della scarica. La tensione media viene calcolata in maniera semplice con il seguente metodo: Le tensioni di scarica U_1, U_2, \dots, U_n vengono rilevate ogni 5 s dall'inizio della scarica e le tensioni che interrompono la tensione di fine scarica in meno di 5 s vengono ignorate. La tensione media U_{avr} viene quindi calcolata in maniera semplificata, applicando l'equazione (7) e arrotondando il risultato alle tre cifre significative.

$$U_{avr} = \frac{U_1 + U_2 + \dots + U_n}{n} \quad (7)$$

7.6.3 Calcolo della densità di energia

IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE	5
1 Campo di applicazione	7
2 Riferimenti normativi	7
3 Termini e definizioni	7
4 Condizioni di prova	9
4.1 Generalità	9
4.2 Strumenti di misura	9
4.3 Tolleranza	10
4.4 Stabilizzazione termica	10
5 Misura delle dimensioni	10
6 Misura della massa	12
7 Misure elettriche	12
7.1 Generalità	12
7.2 Condizioni generali di carica	12
7.3 Capacità	12
7.4 Impostazione del valore del SOC	13
7.5 Potenza	13
7.6 Energia	15
7.7 Prova di immagazzinamento	17
7.8 Prova di durata di vita ciclica	18
7.9 Prova dell'efficienza energetica	27
Allegato A (informativo) Condizioni selettive per le prove	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica	34
Allegato C (informativo) Prova della caratteristica corrente-tensione	37
Bibliografia	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee	41

7.7.2 Prova di mantenimento della carica

Questa prova ha lo scopo di determinare le caratteristiche di mantenimento della carica di un elemento in condizioni di immagazzinamento, compreso il trasporto.

Le caratteristiche di mantenimento della carica dell'elemento con un SOC del 50 % devono essere determinate applicando la seguente procedura.

Fase 1 – L'elemento deve essere caricato come indicato in 7.2.

Fase 2 – L'elemento deve essere scaricato al 50 % del SOC, applicando il metodo specificato in 7.4. Quindi, l'elemento deve essere stabilizzato alla temperatura del locale per 1 h.

NOTA Il valore del SOC può essere modificato sulla base di un accordo tra il cliente ed il costruttore dell'elemento.

Fase 3 – Scaricare l'elemento sino alla tensione di fine scarica, con una corrente di scarica pari a $1/3 I_t$ (A) per le applicazioni BEV e a $1 I_t$ (A) per le applicazioni HEV, alla temperatura del locale. Questa capacità di scarica è indicata come C_b .

Fase 4 – Ripetere le fasi 1 e 2 una sola volta.

Fase 5 – L'elemento deve essere immagazzinato per 28 giorni a una temperatura ambiente di 45 °C.

Fase 6 – Dopo la fase 5, l'elemento deve essere stabilizzato alla temperatura del locale come indicato in 4.4. Quindi, scaricare l'elemento a una corrente costante di $1/3 I_t$ (A) per le applicazioni BEV e a $1 I_t$ (A) per le applicazioni HEV, fino al raggiungimento della tensione di fine scarica, e quindi misurare la capacità dell'elemento. Questa capacità di scarica è indicata come C_r .

IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE	5
1 Campo di applicazione	7
2 Riferimenti normativi	7
3 Termini e definizioni	7
4 Condizioni di prova	9
4.1 Generalità	9
4.2 Strumenti di misura	9
4.3 Tolleranza	10
4.4 Stabilizzazione termica	10
5 Misura delle dimensioni	10
6 Misura della massa	12
7 Misure elettriche	12
7.1 Generalità	12
7.2 Condizioni generali di carica	12
7.3 Capacità	12
7.4 Impostazione del valore del SOC	13
7.5 Potenza	13
7.6 Energia	15
7.7 Prova di immagazzinamento	17
7.8 Prova di durata di vita ciclica	18
7.9 Prova dell'efficienza energetica	27
Allegato A (informativo) Condizioni selettive per le prove	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica	34
Allegato C (informativo) Prova della caratteristica corrente-tensione	37
Bibliografia	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee	41

7.8 Prova di durata di vita ciclica

7.8.1 Generalità

Questa prova ha lo scopo di determinare le caratteristiche di degrado di un elemento, a seguito dei cicli di carica e scarica, che costituiscono le normali condizioni di utilizzo delle applicazioni BEV e HEV.

Le prestazioni di durata di vita ciclica di un elemento per un'applicazione BEV e un'applicazione HEV devono essere determinate effettuando, rispettivamente, le prove in 7.8.2 e 7.8.3.

La sequenza di prova è mostrata nell'Allegato B.

7.8.2 Prova del ciclo BEV

7.8.2.1 Misura della prestazione iniziale

Prima di iniziare la prova del ciclo di carica e scarica, misurare la capacità, la capacità di scarica dinamica e la potenza, come prestazioni iniziali dell'elemento.

- Capacità

La capacità deve essere misurata come specificato in 7.3, a 25 °C.

- Capacità di scarica dinamica C_D

La capacità di scarica dinamica C_D deve essere misurata a 25 °C e a 45 °C.

La capacità di scarica dinamica è definita dal valore integrato nel tempo della corrente di carica e di scarica, confermato dalla seguente prova: scaricare ripetutamente l'elemento completamente carico, applicando il profilo di scarica dinamico A, specificato nella Tabella 3 e mostrato nella Figura 3, fino a quando la tensione raggiunge il limite inferiore specificato dal costruttore dell'elemento.

- Potenza

La potenza deve essere misurata come specificato in 7.5 a 25 °C e al 50 % del SOC.

IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE	5
1 Campo di applicazione	7
2 Riferimenti normativi	7
3 Termini e definizioni	7
4 Condizioni di prova	9
4.1 Generalità	9
4.2 Strumenti di misura	9
4.3 Tolleranza	10
4.4 Stabilizzazione termica	10
5 Misura delle dimensioni	10
6 Misura della massa	12
7 Misure elettriche	12
7.1 Generalità	12
7.2 Condizioni generali di carica	12
7.3 Capacità	12
7.4 Impostazione del valore del SOC	13
7.5 Potenza	13
7.6 Energia	15
7.7 Prova di immagazzinamento	17
7.8 Prova di durata di vita ciclica	18
7.9 Prova dell'efficienza energetica	27
Allegato A (informativo) Condizioni selettive per le prove	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica	34
Allegato C (informativo) Prova della caratteristica corrente-tensione	37
Bibliografia	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee	41

7.8.2.2 Ciclo di carica e scarica

La prova del ciclo di carica e scarica deve essere effettuata come segue.

- All'inizio della prova, la temperatura dell'elemento deve essere di 45 °C, quella dell'ambiente di 45 °C.
- Fasi della prova

La procedura dalla fase 1 alla fase 5 deve essere continuamente ripetuta per 28 giorni. Tra ciascuna fase è possibile impostare un tempo di riposo inferiore a 4 h. Misurare quindi le prestazioni dell'elemento come specificato in c) di 7.8.2.2. Questa procedura deve essere ripetuta fino al termine della prova specificato in d) di 7.8.2.2.

Fase 1 - L'elemento deve essere completamente scaricato seguendo il metodo specificato dal costruttore dell'elemento.

Fase 2 – Gli elementi devono essere completamente caricati, secondo le modalità indicate dal costruttore dell'elemento. Il tempo di carica deve essere inferiore a 12 h.

Fase 3 – Scaricare l'elemento applicando il profilo di scarica dinamica A specificato nella Tabella 3 e nella Figura 3, fino a quando la capacità di scarica non raggiunge l'equivalente del 50 % ± 5 % della capacità di scarica dinamica iniziale C_D a 45 °C.

Se la tensione raggiunge il limite inferiore specificato dal costruttore dell'elemento durante la fase 3, la prova deve essere interrotta, nonostante quanto indicato in d) di 7.8.2.2 e, a questo punto devono essere misurate le prestazioni dell'elemento, come specificato in c) di 7.8.2.2.

Se, durante la fase 3, la temperatura dell'elemento raggiunge il limite superiore specificato dal costruttore dell'elemento, la durata del passo di prova 20 nella Tabella 3 può essere prolungata di un valore appropriato. Deve essere registrata la durata effettiva.

Se la tensione raggiunge il limite massimo specificato dal costruttore dell'elemento durante un passo di carica della Tabella 3, deve essere effettuata la carica a tensione costante alla massima tensione fino alla fine della durata di questo passo.

IEC 62660-1:2019 – PART 1: PERFORMANCE TESTING

INDICE

INTRODUZIONE	5
1 Campo di applicazione	7
2 Riferimenti normativi	7
3 Termini e definizioni	7
4 Condizioni di prova	9
4.1 Generalità	9
4.2 Strumenti di misura	9
4.3 Tolleranza	10
4.4 Stabilizzazione termica	10
5 Misura delle dimensioni	10
6 Misura della massa	12
7 Misure elettriche	12
7.1 Generalità	12
7.2 Condizioni generali di carica	12
7.3 Capacità	12
7.4 Impostazione del valore del SOC	13
7.5 Potenza	13
7.6 Energia	15
7.7 Prova di immagazzinamento	17
7.8 Prova di durata di vita ciclica	18
7.9 Prova dell'efficienza energetica	27
Allegato A (informativo) Condizioni selettive per le prove	32
Allegato B (informativo) Sequenza di prova della durata di vita ciclica	34
Allegato C (informativo) Prova della caratteristica corrente-tensione	37
Bibliografia	40
Allegato ZA (normativo) Riferimenti normativi alle Pubblicazioni Internazionali con le corrispondenti Pubblicazioni Europee	41

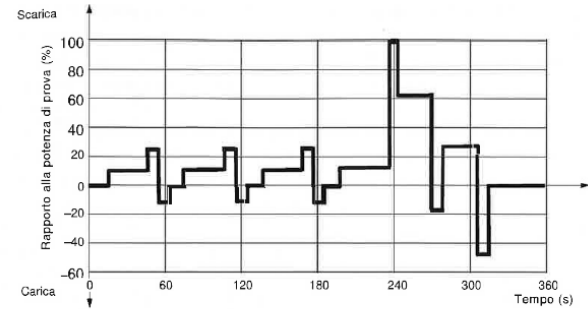


Figura 3 – Profilo di scarica dinamica A per la prova di ciclo BEV

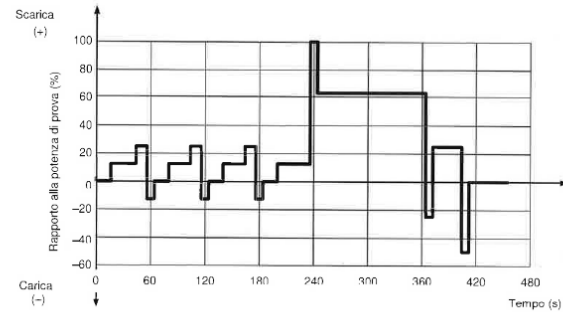


Figura 4 – Profilo di scarica dinamica B per la prova di ciclo per le applicazioni BEV

IEC 62660-1:2019 – PART 2: RELIABILITY AND ABUSE TESTING

CONTENTS

FOREWORD.....	3
INTRODUCTION.....	5
1 Scope.....	6
2 Normative references.....	6
3 Terms and definitions.....	6
4 Test conditions.....	8
4.1 General.....	8
4.2 Measuring instruments.....	8
4.2.1 Range of measuring devices.....	8
4.2.2 Voltage measurement.....	8
4.2.3 Current measurement.....	8
4.2.4 Temperature measurements.....	8
4.2.5 Other measurements.....	9
4.3 Tolerance.....	9
4.4 Thermal stabilization.....	9
5 Electrical measurement.....	9
5.1 General charge conditions.....	9
5.2 Capacity.....	10
5.3 SOC adjustment.....	10
6 Reliability and abuse tests.....	10
6.1 General.....	10
6.2 Mechanical test.....	11
6.2.1 Vibration.....	11
6.2.2 Mechanical shock.....	12
6.2.3 Crush.....	13
6.3 Thermal test.....	14
6.3.1 High temperature endurance.....	14
6.3.2 Temperature cycling.....	14
6.4 Electrical test.....	15
6.4.1 External short circuit.....	15
6.4.2 Overcharge.....	16
6.4.3 Forced discharge.....	16

6.2.1 Vibration

6.2.1.1 Purpose

This test is performed to characterize cell responses to vibration assumed in the use of a vehicle.

6.2.1.2 Test

The test shall be performed as follows.

- Adjust the SOC of the cell to 100 % for BEV application, and to 80 % for HEV application in accordance with 5.3.
- Perform the test referring to IEC 60068-2-64 random vibration. Use test duration of 8 h for each plane of the test cell.
- The RMS acceleration value shall be $27,8 \text{ m/s}^2$. The power spectrum density (PSD) plotted against frequency is shown in Figure 2 and Table 2. The maximum frequency shall be 2 000 Hz.

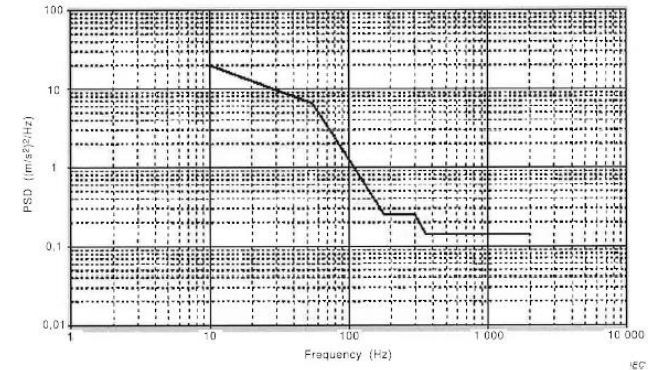


Figure 2 – PSD of acceleration plotted against frequency

IEC 62660-1:2019 – PART 2: RELIABILITY AND ABUSE TESTING

CONTENTS

FOREWORD.....	3
INTRODUCTION.....	5
1 Scope.....	6
2 Normative references.....	6
3 Terms and definitions.....	6
4 Test conditions.....	8
4.1 General.....	8
4.2 Measuring instruments.....	8
4.2.1 Range of measuring devices.....	8
4.2.2 Voltage measurement.....	8
4.2.3 Current measurement.....	8
4.2.4 Temperature measurements.....	8
4.2.5 Other measurements.....	9
4.3 Tolerance.....	9
4.4 Thermal stabilization.....	9
5 Electrical measurement.....	9
5.1 General charge conditions.....	9
5.2 Capacity.....	10
5.3 SOC adjustment.....	10
6 Reliability and abuse tests.....	10
6.1 General.....	10
6.2 Mechanical test.....	11
6.2.1 Vibration.....	11
6.2.2 Mechanical shock.....	12
6.2.3 Crush.....	13
6.3 Thermal test.....	14
6.3.1 High temperature endurance.....	14
6.3.2 Temperature cycling.....	14
6.4 Electrical test.....	15
6.4.1 External short circuit.....	15
6.4.2 Overcharge.....	16
6.4.3 Forced discharge.....	16

6.2.3 Crush

6.2.3.1 Purpose

This test is performed to characterize cell responses to external load forces that can cause deformation.

6.2.3.2 Test

The test shall be performed as follows.

- Adjust the SOC of the cell to 100 % for BEV application and 80 % for HEV application in accordance with 5.3.
- The cell shall be placed on an insulated flat surface and be crushed with a crushing tool consisting of a round or semicircular bar, or sphere or hemisphere with a 150 mm diameter. It is recommended to use the round bar to crush a cylindrical cell, and the sphere for a prismatic cell (see Figure 3). The force for the crushing shall be applied in a direction nearly perpendicular to a larger side of a layered face of positive and negative electrodes inside the cell. The crushing tool shall be selected so that the cell is deformed nearly in proportion to the increase of crushing force.
- The force shall be released when an abrupt voltage drop of one-third of the original cell voltage occurs, or a deformation of 15 % or more of the initial cell dimension occurs, or the force of 1 000 times the weight of the cell is applied. The cells remain on test for 24 h or until the case temperature declines by 20 % of the maximum temperature rise, whichever is the sooner.

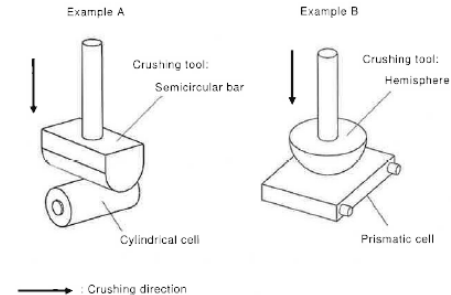


Figure 3 – Examples of crush test



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