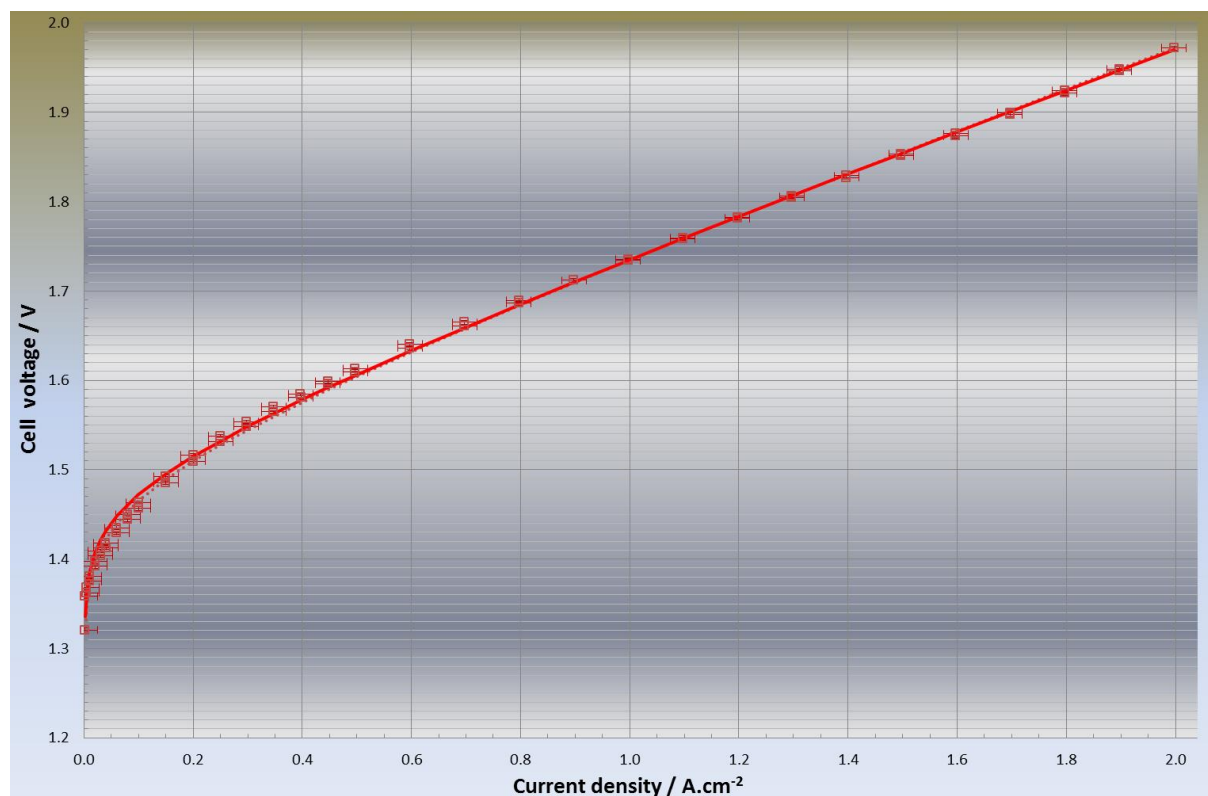


# JRC VALIDATED METHODS, REFERENCE METHODS AND MEASUREMENTS REPORT

## EU Harmonised Polarisation Curve Test Method for Low Temperature Water Electrolysis

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



2018

Report EUR xxxxx EN

European Commission  
Joint Research Centre  
Directorate C: Energy, Transport and Climate

Contact information  
Georgios Tsotridis  
Address: Joint Research Centre, Westerduinweg 3, NL-1755 LE Petten  
E-mail: Georgios.Tsotridis@ec.europa.eu  
Tel.: +31 224 56 5122

JRC Science Hub  
<https://ec.europa.eu/jrc>

#### Legal Notice

This publication is a Validated Methods, Reference Methods and Measurements Report by the Joint Research Centre, the European Commission's in-house science service. It aims to provide evidence-based scientific support to the European policy-making process. The scientific output expressed does not imply a policy position of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use which might be made of this publication.

All images © European Union 2018

JRC104045

EUR xxxxx EN

ISBN xxx-xx-xx-xxxx-x (print)  
ISBN xxx-xx-xx-xxxx-x (PDF)

ISSN xxxx-xxxx (print)  
ISSN xxxx-xxxx (online)

doi:xx.xxxx/xxxx

Luxembourg: Publications Office of the European Union, 2018

© European Union, 2018

Reproduction is authorised provided the source is acknowledged.

Printed in Petten (*The Netherlands*)



This report on "EU Harmonised Polarisation Curve Test Method for Low Temperature Water Electrolysis" was carried out under the Framework Contract between the Joint Research Centre and the Fuel Cells and Hydrogen second Joint Undertaking (FCH2JU), Rolling Plan 2017.

The polarization curve test method is the basic method used to characterize low temperature water electrolysis (WE) single cells and stacks at specified operating conditions (temperature and pressure). The procedure is applicable to Polymer Electrolyte Membrane Water Electrolysis (PEMWE), Alkaline Water Electrolysis (AWE) and Anion Exchange Membrane Water Electrolysis (AEMWE) single cells and stacks. It provides information on the reaction kinetics, Ohmic resistance and mass transport resistance of the cell / stack.

This procedure is a general characterization method that is used in research and development of low temperature WE single cells and stacks at specified operating conditions (temperature and pressure). The test can be used as a baseline measurement for the qualification of a WE cell or stack in a given application particular energy storage applications.



# **EU Harmonised Polarisation Curve Test Method for Low Temperature Water Electrolysis**

T Malkow, A Pilenga, G Tsotridis, G De Marco



---

# **LIST OF CONTRIBUTORS**

(in alphabetical order of their organisations)



Aragon Hydrogen  
Foundation

Laura Abadía Albás



Fundación "Agencia  
Aragonesa para la  
Investigación y el  
Desarrollo" (ARAID)

Vanesa Gil Hernández

AREVA H<sub>2</sub>Gen

AREVA H<sub>2</sub>Gen

Fabien Auprêtre



Commissariat à l'énergie  
atomique et aux énergies  
alternatives

Frederic Fouda-Onana



Deutsches Zentrum  
für Luft- und Raumfahrt  
German Aerospace Center

Deutsches Zentrum für  
Luft- und Raumfahrt e. V.

Regine Reißner  
Aldo Gago



Energy Research Centre  
of Netherlands

Frans van Berkel  
Arend de Groot



Materials Science and Technology

Swiss Federal  
Laboratories for Materials  
Science and Technology

Ulrich Vogt  
Wenbo Ju



IMWS

Fraunhofer-Institut für  
Mikrostruktur von  
Werkstoffen und  
Systemen

Dominik Härle

HYDROGENICS  
SHIFT POWER | ENERGIZE YOUR WORLD

HYDROGENICS

Jan Vaes

Sam Milis



Industrie Haute  
Technologie

Pablo Marcuello

|   |   |   |
|---|---|---|
|  <p>UNIVERSITÉ<br/>PARIS<br/>SUD<br/>Comprendre le monde,<br/>construire l'avenir®</p> | <p>Institut de Chimie<br/>Moléculaire et des<br/>Matériaux d'Orsay –<br/>Université Paris-Sud</p> | <p>Pierre Millet</p>                          |
|  <p>Consiglio Nazionale<br/>delle Ricerche</p>   | <p>Istituto di Tecnologia<br/>Avanzate per L'Energia<br/>"Nicola Giordano"</p>                    | <p>Antonino Aricó</p>                         |
|  <p>ITM<br/>POWER</p>  | <p>ITM power</p>  | <p>Frederic Marchal<br/>Marcus Newborough</p> |
|  <p>nel</p>  | <p>Nel Hydrogen</p>   | <p>Anders Søreng<br/>Marius Bornstein</p>     |
|  <p>P V 3<br/>TECHNOLOGIES</p>  | <p>PV3 Technologies Ltd</p>   | <p>Nicholas van Dijk</p>                      |
|  <p>SIEMENS</p>  | <p>Siemens</p>  | <p>Richard Wagner<br/>Manfred Waidhas</p>     |
|  <p>SINTEF</p>   | <p>SINTEF</p>   | <p>Magnus Thomassen</p>                       |
|  <p>Z<br/>B<br/>T</p>  | <p>Zentrum für<br/>BrennstoffzellenTechnik</p>  | <p>Ivan Radev<br/>Sebastian Stypka</p>        |
|  <p>ZSW</p>  | <p>Zentrum für<br/>Sonnenenergie- und<br/>Wasserstoff-Forschung<br/>BW</p>                        | <p>Ludwig Jörissen</p>                        |

## Table of Contents

|   |    |
|---|----|
| Contents.....   | v  |
| ACKNOWLEDGMENTS .....   | vi |
| 1. Introduction .....   | 1  |
| 2. Objective and scope .....  | 1  |
| 3. Terminology, definitions, and symbols .....                      | 2  |
| 3.1 Terminology and definitions .....                               | 2  |
| 3.2 Used abbreviations.....   | 2  |
| 3.3 Symbols.....  | 3  |
| 4. Test equipment and setup.....                                    | 5  |
| 5. Test Input parameter (TIP) and Test Output parameter (TOP) ..... | 7  |
| 5.1. TIP.....   | 7  |
| 5.2. TOP .....  | 8  |
| 6. Test procedure .....   | 10 |
| 7. Data processing and representation .....                         | 13 |
| Bibliography .....  | 16 |
| Appendix A .....  | 17 |
| Statistical analysis of test results .....                          | 17 |
| Appendix B .....  | 20 |
| Measurement statistics of TIPs & TOPs.....                          | 20 |
| Appendix C.....   | 26 |
| Measurement uncertainties of TIPs & TOPs.....                       | 26 |
| Appendix D .....  | 29 |
| Example of measurement data of Figure 1 .....                       | 29 |

---

## **ACKNOWLEDGMENTS**

We would like to express our sincere gratitude to all participants and their respective organisations for their contributions in developing the Polarisation Test Method document for low temperature water electrolysis applications.

We would also like to thank the “Fuel Cell and Hydrogen second Joint Undertaking” (FCH2JU) Programme Office and in particular Dr. Nikolaos Lymperopoulos for the continuous support and encouragement we received throughout the preparatory stages of this report.



## 1. Introduction

This report on “EU Harmonised Polarisation Curve Test Method for Low Temperature Water Electrolysis” was carried out under the Framework Contract between the Joint Research Centre and the Fuel Cells and Hydrogen second Joint Undertaking (FCH2JU), Rolling Plan 2017.

The polarization curve measurement is a basic test method used to characterize low temperature Water Electrolysis (WE) single cells and stacks at specified operating conditions (temperature,  $T$  and pressure,  $p$ ). The procedure is applicable to Polymer Electrolyte Membrane Water Electrolysis (PEMWE), Alkaline Water Electrolysis (AWE) and Anion Exchange Membrane Water Electrolysis (AEMWE) single cells and stacks.

A polarisation curve is the plot of the voltage,  $U$  expressed in Volt (V) or the power density,  $P_d$  expressed in Watts per square centimetre ( $W.cm^{-2}$ ) vs the current,  $I$  or the current density,  $j$  expressed in Ampere per square centimetre ( $A.cm^{-2}$ ) of the cell / stack.

It provides information on the **reaction kinetics**, **Ohmic resistance** and **mass transport resistance** of the cell / stack.

In almost every test campaign the testing protocol starts with a polarization curve test and ends with another polarization curve test. The comparison between both curves performed at Beginning of Life (BoL) and at End of Life (EoL) provides information on performance and on degradation.

The current procedure is a general characterization method and should be used in both research and development of low temperature Water Electrolysis single cells and stacks.

## 2. Objective and scope

The purpose of this generic testing procedure is to characterize the performance of a low temperature WE cell or stack in terms of polarisation curves at specified operating conditions.

The present procedure can be considered generic and useful to test low temperature WE for various applications whether single cells or stacks.

At ambient pressure, the performance is measured from lowest to the highest current density (**ascending part** of the polarisation curve) followed by a measurement in reverse order that is from highest to lowest current density (**descending part** of the polarisation curve) considering the specifications of the manufacturer and the objective of the test.

For operation at pressure, the performance is alternatively measured from the highest to the lowest current density (**descending part** of the polarisation curve) followed by a measurement in reverse order (**ascending part** of the polarisation curve).

### 3. Terminology, definitions, and symbols

#### 3.1 Terminology and definitions

All the terminology definitions used in this document are defined in [1].

#### 3.2 Used abbreviations

The abbreviations used in this document are given in Table 1.

**Table 1 Description of abbreviations**

| Abbreviation | Description   |
|--------------|---|
| Avg          | Average   |
| Cov          | Covariance  |
| CVM          | Cell voltage monitoring (and recording)                   |
| DAQ          | Data acquisition  |
| DC           | Direct current  |
| ERR          | Measurement error   |
| FM           | Flow meter  |
| FS           | Full scale  |
| MFC          | Mass flow controller                                      |
| QTY          | Quantity  |
| RMU          | Relative measurement uncertainty                          |
| RSD          | Relative standard deviation                               |
| STD          | Standard deviation  |
| STP          | Standard temperature and pressure (273.15 K, 101.325 kPa) |
| TIP          | Test input parameter                                      |
| TOP          | Test output parameter                                     |
| Var          | Variance  |
| WE           | Water electrolysis  |

### 3.3 Symbols

The symbols used in this document are given in Table 2.

**Table 2 Definition of symbols**

| Symbol                | Description   |
|-----------------------|---|
| $A$                   | Active cell area of the cell (geometric)  |
| $F$                   | Faraday's constant ( $F = 96,485.3 \text{ C/mol}$ )   |
| $j$                   | Current density ( $j = I / A$ ) of the cell / stack   |
| $j_0$                 | Exchange current density (rate of the electro-catalytic reaction at equilibrium, zero net current) for the for the anode, <sup>a</sup> and cathode, <sup>c</sup> of the WE cell |
| $I$                   | Electrical current of the cell / stack  |
| $k$                   | <i>Step (set point) of the polarisation curve measurement</i>   |
| $M$                   | Number of values of a quantity measured   |
| $N$                   | Total number of test conditions   |
| $p_A$                 | Ambient pressure (absolute)   |
| $p_{H_2}$             | Pressure (gauge) of hydrogen after the gas liquid separator   |
| $p_{O_2}$             | Pressure (gauge) of oxygen after the gas liquid separator   |
| $p_{x,y}$             | Pressure (gauge) of cell / stack fluid x at cell / stack location y   |
| $P_{d, cell / stack}$ | Electric power density of the cell /stack   |
| $Q_{in}$              | Heat supplied by an external source   |
| $Q_{rev}$             | Reversible heat in the overall liquid WE reaction   |
| $Q_{v,x,y}$           | Volumetric flow rate of cell / stack fluid x at cell / stack location y under STP conditions  |
| $R$                   | Universal gas constant ( $R = 8.31446 \text{ J.mol}^{-1}.K^{-1}$ )  |
| $R_{\Omega}$          | Total series resistance of components and their interface of the WE cell  |
| $T$                   | Temperature   |
| $T_{x,y}$             | Temperature of cell / stack fluid x at cell location y (either inlet=in or outlet=out)  |
| $T_a$                 | Ambient temperature   |
| $T_c$                 | Cell / stack temperature  |
| $u$                   | Measurement uncertainty   |
| $U_{cell}$            | Cell voltage  |
| $U_{on}$              | Onset voltage   |
| $U_{rev}$             | Reversible cell voltage   |
| $U_{stack}$           | Stack terminal voltage  |
| $U_{tn}$              | Thermal neutral voltage   |
| $X$                   | Placeholder for a quantity (test variable)  |
| $Y$                   | Placeholder for a function of test variable(s) X's (TIP or TOP)   |
| $z$                   | Number of electrons exchanged in the cell reaction for one mole of gas  |
| Subscripts            |   |
| $avg$                 | Average of a quantity (test variable)   |
| $err$                 | Measurement error   |

| Symbol               | Description   |
|----------------------|---|
| $H_2$                | Reference to hydrogen or the hydrogen evolution electrode   |
| $k$                  | Quantity at step (set point) $k$ of the polarisation curve measurement  |
| $max$                | Maximum of a quantity   |
| $O_2$                | Reference to oxygen or the oxygen evolution electrode   |
| $rmu$                | Relative measurement error  |
| $rsd$                | Relative standard deviation   |
| $std$                | Standard deviation  |
| $sterr$              | Standard error  |
| $X$                  | Reference to quantity $X$   |
| <i>Superscripts</i>  |   |
| $a$                  | Reference to the oxygen evolution electrode (anode) of the WE cell  |
| $c$                  | Reference to the hydrogen evolution electrode (cathode) of the WE cell  |
| <i>Greek symbols</i> |   |
| $\alpha$             | Charge transfer coefficient   |
| $\eta$               | Overtoltage of the electrode of the WE cell   |
| $\Delta G$           | Gibbs free energy in the overall liquid water electrolysis reaction   |
| $\Delta G^0$         | Gibbs free energy in the overall liquid water electrolysis reaction at 101.325 kPa absolute pressure and 25 °C (298.15 K) temperature |
| $\Delta H$           | Enthalpy change in the overall liquid WE reaction   |
| $\Delta S$           | Entropy change in the overall liquid WE reaction  |
| $\rho_x$             | Density of cell / stack fluid $x$ under STP conditions  |

## 4. Test equipment and setup

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 will have to be described in the test report to meet the test objective.

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

The test bench is controlled by a computer which also acts as 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) |
| Adjustable FM 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)        | Minimum 1    |

| Description  | Specification   | QTY |
|--|---|-----|
|  | control)  |     |
| Water treatment device   | -   | 1   |
| Water conductivity meter   | Minimum range: 0.1-10 <sup>-6</sup> S.cm  | 1   |
| DC power supply  | Dependent on maximum reachable current density $\geq 2\text{A.cm}^{-2}$ (galvanostatic control);<br><br>Dependent on maximum cut-off voltage $\geq 2\text{ V/cell}$ (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 as to best represent the temperature of the cell / stack taking account of the control equipment used in the test and the internal configuration and dimension of the cell / stack; see the recommendation of  $T_c$  in Sec. 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 (0.84 Vol-% H<sub>2</sub> in O<sub>2</sub>) 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 trigger appropriate safety measures in case a specified threshold is approached. A threshold value of 10% of the upper explosive limit (UEL) of oxygen in hydrogen (5.25 Vol-% O<sub>2</sub> in H<sub>2</sub>) is advised.

## 5. Test Input parameter (TIP) and Test Output parameter (TOP)

**Test input parameter (TIP)** is a physical quantity which sets the testing conditions. There are variable TIP which are varied during testing and static TIP which are kept constant during testing.

**Test output parameter (TOP)** is a physical quantity resulting from carrying out the tests.

Note, the control accuracy of the TIPs (see Table 4 & Table 5 below) and of the measurement uncertainty of the TOPs (see Table 6 below) will for stacks (with large cell area) depend on respectively the control equipment and the measurement equipment used in the test.

It is recommended to measure the cell / stack temperature,  $T_c$  (**set point**) directly at the cell / stack water outlet,  $T_{\text{water, out}}$  of the oxygen evolution electrode. For a cell / stack with liquid on both the oxygen evolution electrode and the hydrogen evolution electrode, it is recommended to measure the cell / stack temperature directly at the cell / stack water / liquid outlet,  $T_{\text{water / liquid, out}}$  of the hydrogen evolution electrode.

This implies that the regulation of the cell / stack temperature which is monitored at the cell / stack outlet, is at the cell / stack inlet of the oxygen evolution electrode and/or hydrogen evolution electrode where the fluid flows and/or fluid temperatures are controlled.

Where the monitoring and regulation of the cell / stack temperature is different from this recommendation, it should be mentioned in the test report.

### 5.1. TIP

The static TIPs applied during the test are given in Table 4.

**Table 4 Static TIPs**

| TIP  | Control accuracy | Sampling rate |
|--|------------------|---------------|
| $p_{\text{H}_2}$ (gauge) ( <b>set point</b> )                          | $\pm 2\%$        | $\geq 1$ Hz   |
| $p_{\text{O}_2}$ (gauge) ( <b>set point</b> )                          | $\pm 2\%$        | $\geq 1$ Hz   |
| $p_{\text{water / liquid, in}}$ (gauge) (hydrogen evolution electrode) | $\pm 2\%$        | $\geq 1$ Hz   |
| $p_{\text{water / liquid, in}}$ (gauge) (oxygen evolution electrode)   | $\pm 2\%$        | $\geq 1$ Hz   |
| $p_{\text{N}_2, \text{ in}}$ (gauge)                                   | $\pm 2\%$        | $\geq 1$ Hz   |
| $Q_{v, \text{N}_2, \text{ in}}$ (hydrogen evolution electrode)         | $\pm 1\%$ FS     | $\geq 1$ Hz   |
| $Q_{v, \text{water / liquid, in}}$ (hydrogen evolution electrode)      | $\pm 1\%$ FS     | $\geq 1$ Hz   |
| $Q_{v, \text{water / liquid, in}}$ (oxygen evolution electrode)        | $\pm 1\%$ FS     | $\geq 1$ Hz   |
| $T_c$ ( <b>set point</b> )   | $\pm 2$ K        | $\geq 1$ Hz   |
| $T_{\text{water / liquid, out}}$ (hydrogen evolution electrode)        | $\pm 2$ K        | $\geq 1$ Hz   |
| $T_{\text{water / liquid, out}}$ (oxygen evolution electrode)          | $\pm 2$ K        | $\geq 1$ Hz   |

\* Commonly, these inlet flows are kept constant during the entire test. Usually, the digital flow controllers are provided with an accuracy level of 1% of full scale (FS) or maximum flow and in general, a minimum measurable flow of 10% of FS. It means that the measurement uncertainty decreases with the flow rate and so decreases while increasing the current density.

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

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

\*\*\*\* Usually, the water inlet flow is kept constant during the entire test. The flow rate should be select to be high enough to replenish the water. Also, the flow rate can greatly influence the water temperature. When the flow rate is variable as a result of the regulation of the cell / stack temperature, this should be mentioned in the test report.

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

\*\*\*\*\* The sensor location and method of regulation of the cell / stack water / liquid temperature should be mentioned in the test report.

\*\*\*\*\* The regulation of the cell / stack (water / liquid) outlet temperature **set point** is assumed to take place by the variation of the cell /stack (water / liquid) inlet temperature. In case 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 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 $j < 0.1\text{A/cm}^2$<br>$\pm 1\%$ for $j \geq 0.1\text{A/cm}^2$ | $\geq 1\text{ Hz}$ |
| $P_{N_2, in}$ (gauge)                                   | $\pm 2\%$   | $\geq 1\text{ Hz}$ |
| $T_{N_2, in}$ (hydrogen evolution electrode)            | $\pm 2\text{ K}$  | $\geq 1\text{ Hz}$ |
| $T_{water / liquid, in}$ (hydrogen evolution electrode) | $\pm 2\text{ K}$  | $\geq 1\text{ Hz}$ |
| $T_{water / liquid, in}$ (oxygen evolution electrode)   | $\pm 2\text{ K}$  | $\geq 1\text{ Hz}$ |
| $U$ (potentiostatic control)                            | $\pm 1\text{ mV / cell}$  | $\geq 1\text{ Hz}$ |

\* 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. In case 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.

## 5.2. TOP

Table 6 below lists the TOPs.

**Table 6 TOPs**

| TOP  | Measurement uncertainty | Sampling rate      |
|--|-------------------------|--------------------|
| $j$ (potentiostatic control)               | calculated*             | $\geq 1\text{ Hz}$ |
| $P_d$                                      | calculated*             | -                  |
| $p_{H_2 \text{ or } H_2/N_2, out}$ (gauge) | calculated*             | $\geq 1\text{ Hz}$ |
| $p_{O_2, out}$ (gauge)                     | calculated*             | $\geq 1\text{ Hz}$ |
| $T_{H_2 \text{ or } H_2/N_2, out}$         | calculated*             | $\geq 1\text{ Hz}$ |
| $U$ (galvanostatic control)                | calculated*             | $\geq 1\text{ Hz}$ |





## EU Harmonised Polarisation Curve Test Method for Low Temperature Water Electrolysis



---

\* see Appendices B & C for the calculations of the statics of the test results and the measurement errors of the quantity concerned.

\*\* Calculated according to Equation (5) when applying method B. For method A, the measurement uncertainty results from the uncertainty of the measurement equipment used in the test.

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

## 6. Test procedure

**The main objective of the polarisation curve measurement is to determine the change in the cell / stack voltage (and consequently in supplied power or power density) generated by the variation in the supplied current under steady-state conditions and in particular at constant cell / stack temperature and constant hydrogen (and/or oxygen) pressure.**

The complete testing procedure is composed of the following steps:

- Leak test (not part of this procedure).
- Break-in (not part of this procedure) and cell / stack conditioning.
- Polarization curve test.
- Break-out (not part of this procedure).

Upon break-in of the MEA following manufacturer instructions, it is recommended to operate the cell / stack for a specified duration to ensure the MEA has / all MEA have reached steady state.

It is recommended to keep the cell / stack current density at  $0.1 \text{ A.cm}^{-2}$  for 5 minutes to ensure the catalysts are in the proper oxidation state. This is followed by setting lowest current value (Table 7) in steps of  $25 \text{ mA.cm}^{-2}$  per minute prior to the actual polarisation curve measurement. The variation in cell voltage at the lowest current should not be more than 1% during one hour of hold at this condition.

The polarisation curve measurement is performed under galvanostatic control. The measurement should be aborted when the cell voltage is 2 V or above (cut-off voltage). Note a higher cut-off voltage, for example, 2.4 V may be applied where EoL testing is aimed at.

At ambient pressure, it is recommended to perform a polarisation curve measurement from lowest to highest current density (ascending polarisation curve) followed by a polarisation curve measurement in reverse order (descending polarisation curve).

For operation of the cell / stack at pressure above ambient, the cell / stack should be operated at the highest current density for the specified pressure until a stable voltage and pressure is established for a specified duration prior to measuring the performance from the highest to the lowest current density (descending part of the polarisation curve) followed by a measurement in reverse order (ascending part of the polarisation curve).

As the hydrogen concentration in the gas stream from the oxygen evolution electrode could increase significantly especially under high hydrogen-to-oxygen differential pressure operation for low current densities, e. g.  $0.3\text{-}0.5 \text{ A.cm}^{-2}$ , the hydrogen pressure as a precautionary measure may be reduced where the electrical load is lower than 20% of the nominal load or where the current density is lower than  $0.5 \text{ A.cm}^{-2}$ .

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 & 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. per minute 80 mA/cm<sup>2</sup> (PEMWE) and 16 mA/cm<sup>2</sup> (AWE & AEMWE).

Note 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 $k^*$ | Current density (A.cm <sup>-2</sup> ) |             |        | 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                  |
| 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                  |

| Set point $k^*$ | Current density ( $A \cdot cm^{-2}$ ) |             |        | Step duration (s) |                     |
|-----------------|---------------------------------------|-------------|--------|-------------------|---------------------|
|                 | PEMWE                                 | Alkaline WE | AEMWE  | Dwell time**      | Data acquisition*** |
| 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  $100 \text{ mA} \cdot \text{cm}^{-2}$ .

\*\* Generally, the dwell time should be chosen so that the cell voltage does not deviate by more than  $\pm 5 \text{ mV}$  during 30 s duration. 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 resultant mean cell voltage. Particularly for stacks (with large cell area), the dwell time should be chosen 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) during a specified duration (depending on the control equipment used in the test) following the application of a set point. Once thermal equilibrium is obtained in this way, the deviation in the cell voltage should be checked. The temperature range and duration of check on thermal equilibrium should be mentioned in the test report along with any greater than specified deviation.

\*\*\* The period of data acquisition is preceded by the dwell time.

\*\*\*\* Any possible increase beyond the given maximum current density should be made in steps consisting of the difference between this maximum value and its preceding value.

When the polarisation curve measurement cannot be performed under galvanostatic control or when the cell / stack need to be protected from high voltages, the measurement should be performed under potentiostatic control by varying the voltage of the cell / stack between two specified voltages (lowest cell voltage and highest cell voltage) either at a specified rate (**Method A**) or by specified voltage steps (**Method B**).

Under potentiostatic control, it is recommended to apply a cell voltage above the thermal neutral voltage as the lowest cell voltage and 2 V or more as the highest cell voltage.

Upon performing the polarisation curve measurement and depending on the objective of the test, a break-out procedure may be applied following manufacturer instructions. Such procedure is to purge the hydrogen evolution electrode compartment (cathode) of the cell / stack with an inert gas to avoid cathode aging and to prevent mixing of hydrogen and air upon long exposures as well as to inhibit possible reactions in the presence of electrode catalyst.

## 7. Data processing and representation

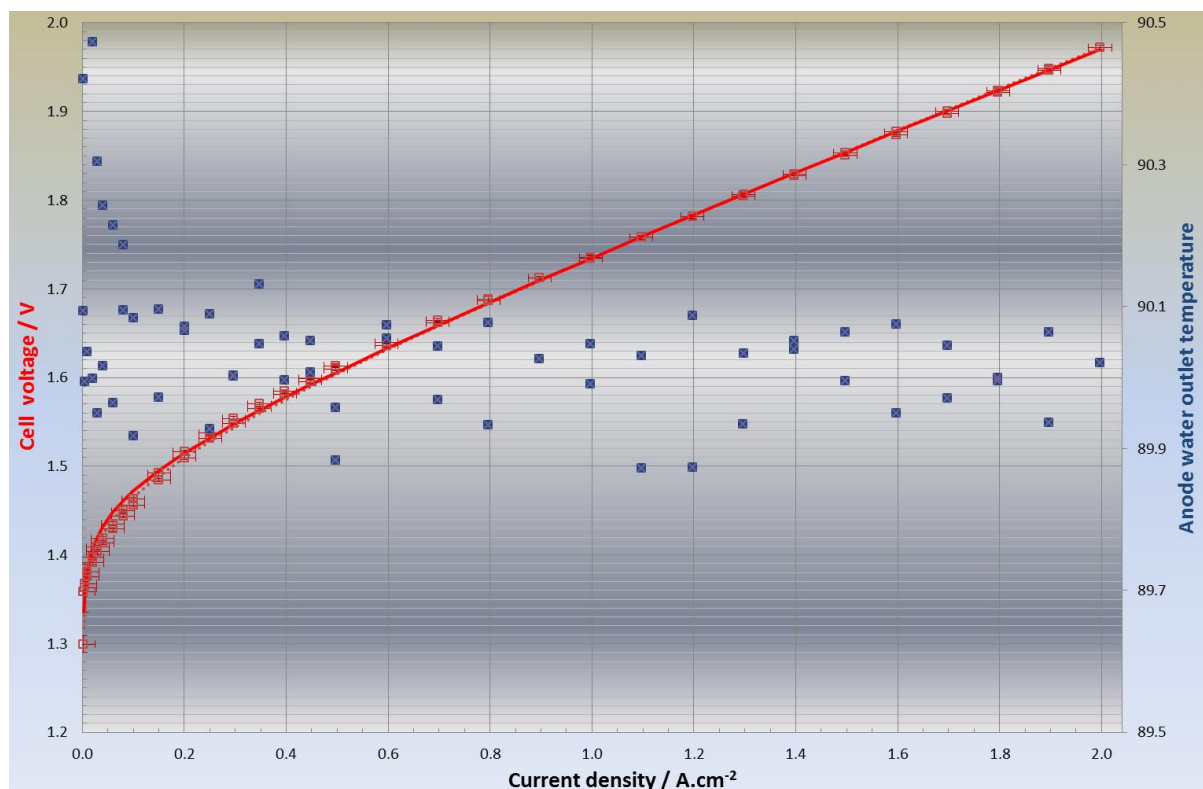
For method A, the TIPs (pressure, temperature and flow) are averaged.

For method B, the TIPs and TOPs are averaged for a sufficient number of data points, for example, minimum 10 data points recorded during the period of data acquisition at each current density step.

Along with the average the standard deviation (STD) should be calculated according to GUM [2] (see Appendix A).

For method A, the instantaneous voltage of the cell / stack,  $U$  versus that of the current density,  $j$  is the polarisation curve in the ascending and descending parts for a given cell / cell / stack temperature,  $T_c$  and pressure,  $p$ .

For method B, the average of  $U$  versus  $j$  (see Appendix B for their calculation) is the polarisation in either part (Figure 1).



**Figure 1 Example of the polarisation curve (ascending and descending) measurement of a WE single cell at 90°C cell temperature.**

The displayed error bars in the graphs in Figure 1 constitute the measurement uncertainty (see Appendix C) of the cell voltage and current density expanded two fold (expansion factor  $k=2$  according to GUM [2]). The dotted line and the solid line are the NLLS fits with positivity constrains (for  $R_\Omega$ ,  $\alpha^a$ ,  $\alpha^c=1-\alpha^a$ ,  $j_0^a$  &  $j_0^c$ ) of equation (1) to the average of the measured values of respectively the ascending part ( $R_\Omega = 26.8 \text{ m}\Omega$ ,  $\alpha^a= 0.29$ ,  $j_0^a= 24.1 \text{ mA/cm}^2$  &  $j_0^c= 24.6 \text{ mA/cm}^2$ ) and descending part of the polarisation curve ( $R_\Omega = 26.8 \text{ m}\Omega$ ,  $\alpha^a= 0.34$ ,  $j_0^a=$

15.6 mA/cm<sup>2</sup> &  $j_0^c = 19.7$  mA/cm<sup>2</sup>; see Appendix D for the tabulation of the averaged measurement data. In this example, the anode water inlet temperature constituting the cell temperature is kept constant in the test while the anode water outlet temperature was monitored (see Figure 1).

Further analysis of the polarization curve for given operating conditions (i.e. temperature, pressure) may provide additional insight into MEA performance. Assuming

- i. no mass transport limitations,
- ii. homogenous current distribution over the active area (1D model),
- iii. neglecting the reverse term in the Butler-Volmer reaction corresponding to assuming a very low reaction rate for oxygen reduction and
- iv. provided that all the reversible heat,  $Q_{rev}(T_c, p) = T_c \Delta S$  in the endothermic WE operation is supplied by an external source,

the cell / stack voltage  $U(j, T, p)$  at a given cell / stack temperature,  $T$  expressed in Kelvin (K) and pressure,  $p$  expressed in kilo Pascal (kPa) as a function of current density,  $j$  can be fit by the non-linear least square (NLLS) method [4,5] with positivity constrain to the model [3]

$$U(j, T_c, p) = U_{rev}(T_c, p) + IR_{\Omega} + \eta_{H_2}(j, T_c) + \eta_{O_2}(j, T_c) \quad (1)$$

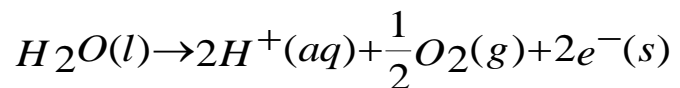
with the cell / stack temperature expressed in degree Celsius (°C), the cell / stack current,  $I = A \cdot j$  expressed in Ampere (A) where  $A$  is the active area (geometric) of the cell / stack expressed in squared centimetre (cm<sup>2</sup>) and the reversible cell voltage,  $U_{rev}(T_c, p) = \frac{\Delta G(T_c, p)}{zF}$ , e. g.  $U_{rev}(25 \text{ }^\circ\text{C}, 1 \text{ atm}) \approx 1.23 \text{ V}$  [1,6],<sup>1</sup>

$$U_{rev}(T_c, 1 \text{ atm}) = 1.5184 - 1.5421 \cdot 10^{-3} \cdot T_c + 9.523 \cdot 10^{-5} \cdot T_c \log_e T_c + 9.84 \cdot 10^{-8} \cdot T_c^2, \quad (2)$$

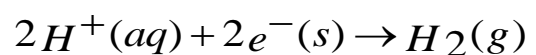
$\Delta S$  is the change in entropy ( $\Delta S(25^\circ\text{C}, 1 \text{ atm}) = \Delta S^0 \approx 0.16 \text{ kJ}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$  at 101.325 kPa absolute pressure),  $\Delta G$  is the change in Gibbs free energy ( $\Delta G(25^\circ\text{C}, 1 \text{ atm}) = \Delta G^0 \approx 237.21 \text{ kJ}\cdot\text{mol}^{-1}$  at 298.15 K absolute temperature and 101.325 kPa absolute pressure) [1,6],  $F = 96,485.3 \text{ C}\cdot\text{mol}^{-1}$  is Faraday's constant and  $z = 2$  is the number of exchanged electrons in the liquid WE reaction:

#### PEMWE cells

anode (oxygen electrode)

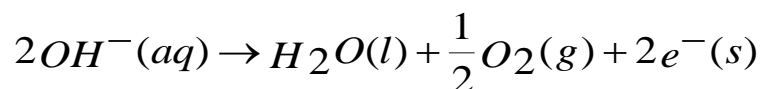


cathode (hydrogen electrode)



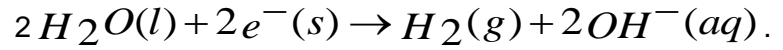
#### AWE cells & AEMWE cells

anode (oxygen electrode)



<sup>1</sup> Equation (2) applies up to 18 bar pressure.

cathode (hydrogen electrode)



Note,  $U_{rev}(T_c, 1 atm)$  in equation (1) is to be replaced by the thermal neutral voltage,

$$U_{tn}(T_c, 1 atm) = U_{rev}(T_c, 1 atm) + \frac{T_c \Delta S}{z F} \quad (3)$$

in case heat is not supplied by an external source, e. g.  $U_{tn}(25 \text{ }^{\circ}\text{C}, 1 atm) \approx 1.48 \text{ V}$ . For a partial heat supply,  $U_{rev}(T_c, 1 atm)$  in equation (1) is to be replaced by the onset voltage,

$$U_{on}(T_c, 1 atm) = U_{rev}(T_c, 1 atm) + \frac{T_c \Delta S - Q_{in}}{z F} \quad (4)$$

where  $Q_{in}$  is the heat supplied by the external source.

The total ionic / electronic cell resistance (bulk and surface / interface),  $R_{\Omega}$  is expressed in Ohm ( $\Omega$ ).

$$\eta_{H_2}(j, T_c) = \frac{RT_c}{\alpha^c n^c F} \ln \left( \frac{j}{j_0^c} \right) \quad (5)$$

and

$$\eta_{O_2}(j, T_c) = \frac{RT_c}{\alpha^a n^a F} \ln \left( \frac{j}{j_0^a} \right) \quad (6)$$

are expressed in Volt (V) the respective overvoltage for the Hydrogen Evolution Reaction (HER) at the cathode (c) and the Oxygen Evolution Reaction (OER) at the anode (a) with their charge transfer coefficients and exchange current densities,  $j_0$ ,  $R = 8.31446 \text{ J}\cdot\text{mol}^{-1}\cdot\text{K}^{-1}$  is the universal gas constant;  $n^c$  and  $n^a$  are the number of electrons involved in the rate determining step (rds) of respectively the hydrogen (c) and oxygen evolution processes (a) while the transfer coefficient,  $\alpha = -\frac{RT_c}{nF} \frac{d \ln k}{dU}$  is related to the symmetry of the activation (energy) barrier in these processes which proceed with reaction rate,  $k$ . Usually,  $\alpha$  assumes a value of between zero and unity.

An output which can directly be derived from a polarisation curve measurement without any need for additional measurement is the power density,

$$P_d(j, T_c, p) = U(j, T_c, p) \cdot j \quad (7)$$

as the product of the measured cell voltage and the current density.

The calculation of the statistics of the TIPs & TOPs and of their measurement errors is outlined in respectively Appendix B and Appendix C.

Due to the nonlinearities in equation (5) and equation (6), the value and error in the fit parameter  $R_{\Omega}$ ,  $\alpha^{a,c}$  and  $j_0^{a,c}$  should be determined through fitting of equation (1) or as appropriate equation (3) or equation (4) using the average and the error of  $U$ ,  $j$  and  $T_c$ .

## Bibliography

- [1] G Tsotridis, A Pilenga, EU harmonised terminology for low temperature water electrolysis for energy storage applications, European Commission, Report EUR EN (2018).
- [2] *JCGM 100:2008 GUM 1995 with minor corrections, Evaluation of measurement data - Guide to the expression of uncertainty in measurement*, First edition September 2008, corrected version 2010; *JCGM 104:2009, Evaluation of measurement data — An introduction to the Guide to the expression of uncertainty in measurement and related documents*, First edition July 2009; *JCGM 102:2011, Evaluation of measurement data – Supplement 2 to the Guide to the expression of uncertainty in measurement – Extension to any number of output quantities*, October 2011.
- [3] P Millet, Characterization Tools for Polymer Electrolyte Membrane (PEM) Water Electrolysis. In: *PEM Electrolysis for Hydrogen Production Principles and Applications*. D Bessarabov, H Wang, H Li, N Zhao (editors), CRC Press, Boca Raton, London, New York, 2016, pp. 179-217.
- [4] P C Hansen, V Pereyra, G Scherer, *Least Squares Data Fitting with Applications*, Johns Hopkins University Press, Baltimore, MD, 2012.
- [5] D C Harris, Nonlinear Least-Squares Curve Fitting with Microsoft Excel Solver. *J Chem Educ* 75, 1 (1998) 119-121.
- [6] RL LeRoy, CT Bowen, DJ LeRoy. *The Thermodynamics of Aqueous Water Electrolysis*. *J Electrochem Soc* 127, 9 (1980) 1954-1962.



## Appendix A

### Statistical analysis of test results

From  $M$  sampled data under  $N$  sets of test conditions, the statistical values such as sample average (avg), sample variance (Var), sample covariance (Cov), sample standard deviation, relative standard deviation (RSD) and sample standard error values for test variable (TIP or TOP),  $X_k$  ( $0 < k \leq M$ ) and  $Y_k(X^1 \pm X_{stdev}^1, \dots, X^i \pm X_{stdev}^i, \dots, X^N \pm X_{stdev}^N)$  ( $0 < i \leq N$ ) are calculated according to GUM [2].

Also, the calculation of the measurement uncertainty,  $u(X_k)$  considering the instrument uncertainty,  $u_x$  of the measurand  $X$  is analogous to GUM [2].

These calculations are commonly performed by a spreadsheet program but due attention should be paid to the calculations involving combined quantities such as electric power density.

#### A.1. Statistics on test variables

Sample average or arithmetic mean (measure of central tendency):

$$X_{k,avg} = \frac{1}{M} \sum_{l=0}^{M-1} X_{k,l} \quad (8)$$

Sample variance:

$$Var(X_k) = \frac{1}{M-1} \sum_{l=0}^{M-1} (X_{k,l} - X_{k,avg})^2 \quad (9)$$

Sample standard deviation (measure for absolute variability):

$$X_{k,std} = \sqrt{Var(X_k)} \quad (10)$$

Sample covariance:

$$Cov(X_k^i, X_k^j) = \frac{1}{M(M-1)} \sum_{l=0}^{M-1} (X_{k,l}^i - X_{k,avg}^i) \cdot (X_{k,l}^j - X_{k,avg}^j) \quad (11)$$

Combined standard deviation:

$$Y_{k,std} = \sqrt{\sum_{i=1}^N \left( \frac{\partial Y_k}{\partial X_k^i} \Big|_{X_{k,avg}^i} \right)^2 \cdot Var(X_k^i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial Y_k}{\partial X_k^i} \frac{\partial Y_k}{\partial X_k^j} \Big|_{X_{k,avg}^{i,j}} \cdot Cov(X_k^i, X_k^j)} \quad (12)$$

Sample RSD (measure of relative variability):

$$X_{k,rsd} = \frac{X_{k,std}}{|X_{k,avg}|} \cdot 100\% \quad (13)$$

Note the RSD provides a means to compare the variability of the measurand  $X$  at the different steps  $k$  of the polarisation curve for the same number of measurements  $M$ .

Sample standard error (measure for normalized variability):

$$X_{k,sterr} = \frac{X_{k,std}}{\sqrt{M}} \quad (14)$$

Note the standard error provides a means to compare the variability of the measurand  $X$  for different number of measurements  $M$  at step  $k$  of the polarisation curve.

The significant figures of a test variable to be reported should be consistent with its measurement uncertainty.

For a calculated test variable, the lesser number of significant figures of all of the involved test variables should determine the significant figure.

The standard deviation and standard error should be expressed with at least one more figure than the value of the test variable and the RSD should be reported with two significant digits.

## A.2. Calculation of measurement uncertainties

Measurement uncertainty:

$$u(X_k) = \sqrt{Var(X_k) + u_X^2} \quad (15)$$

Combined measurement uncertainty:

$$u(Y_k) = \sqrt{\sum_{i=1}^N \left( \frac{\partial Y_k}{\partial X_k^i} \Big|_{X_{k,avg}^i} \right)^2 \left[ \text{Var}(X_k^i) + u_{X^i}^2 \right] + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{\partial Y_k}{\partial X_k^i} \frac{\partial Y_k}{\partial X_k^j} \Big|_{X_{k,avg}^{i,j}} \left[ \text{Cov}(X_k^i, X_k^j) + u_{X^i} u_{X^j} \right]} \quad (16)$$

Relative measurement uncertainty (RMU):

$$u_{rmu}(X_k) = \frac{u(X_k)}{|X_{k,avg}|} \cdot 100\% \quad (17)$$

Note the RMU provides a means to compare the variability of the measurand  $X$  at the different steps  $k$  of the polarisation curve for the same number of measurements  $M$ .

Measurement error:

$$u_{err}(X_k) = \frac{X_{k,std}}{\sqrt{M}} \quad (18)$$

Note the measurement error provides a means to compare the variability of the measurand  $X$  for different number of measurements  $M$  at step  $k$  of the polarisation curve.

The significant figures of a test variable to be reported should be consistent with its measurement uncertainty.

For a calculated test variable, the lesser number of significant figures of all of the involved test variables should determine the significant figure.

The standard deviation and standard error should be expressed with at least one more figure than the value of the test variable and the RSD should be reported with two significant digits.

## Appendix B

### Measurement statistics of TIPs & TOPs

#### B.1. Statistics of current density

The average of the current density of the cell / stack from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve (see Table 7) is

$$j_{k,avg} = \frac{1}{M} \sum_{l=0}^{M-1} j_{k,l} \quad (19)$$

with standard deviation,

$$j_{k,std} = \sqrt{\text{Var}(j_k)} \quad (20)$$

and variance,

$$\text{Var}(j_k) = \frac{1}{M-1} \sum_{l=0}^{M-1} (j_{k,l} - j_{k,avg})^2. \quad (21)$$

The RSD is

$$j_{k,rstd} = \frac{j_{k,std}}{|j_{k,avg}|} \cdot 100\% \quad (22)$$

and the standard error is

$$j_{k,sterr} = \frac{j_{k,std}}{\sqrt{M}}. \quad (23)$$

#### B.2. Statistics of voltage

The average of the cell / stack voltage from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$U_{k,avg} = \frac{1}{M} \sum_{l=0}^{M-1} U_{k,l} \quad (24)$$

with standard deviation,

$$U_{k,std} = \sqrt{\text{Var}(U_k)} \quad (25)$$

and variance,

$$\text{Var}(U_k) = \frac{1}{M-1} \sum_{l=0}^{M-1} (U_{k,l} - U_{k,avg})^2. \quad (26)$$

The RSD is

$$U_{k,rsd} = \frac{U_{k,std}}{|U_{k,avg}|} \cdot 100\% \quad (27)$$

and the standard error is

$$U_{k,sterr} = \frac{U_{k,std}}{\sqrt{M}} \quad (28)$$

### B.3. Statistics of electric power density

The average electric power density of the cell / stack at step  $k$  of the polarisation curve is

$$P_{d,k,avg} = U_{k,avg} \cdot j_{k,avg} \quad (29)$$

with standard deviation,

$$P_{d,k,std} = P_{d,k,avg} \sqrt{\frac{\text{Var}(j_k)}{j_{k,avg}^2} + \frac{\text{Var}(U_k)}{U_{k,avg}^2} + 2 \frac{\text{Cov}(j_k, U_k)}{P_{d,k,avg}}} \quad (30)$$

and covariance,

$$\text{Cov}(j_k, U_k) = \frac{1}{M(M-1)} \sum_{l=0}^{M-1} (j_{k,l} - j_{k,avg}) \cdot (U_{k,l} - U_{k,avg}) \quad (31)$$

Note, power density has a combined standard deviation as voltage and current are correlated to each other in the WE reaction.

The RSD is

$$P_{d,k,rsd} = \frac{P_{d,k,std}}{|P_{d,k,avg}|} \cdot 100\% \quad (32)$$

and the standard error is

$$P_{d,k,sterr} = \frac{P_{d,k,std}}{\sqrt{M}} \quad (33)$$

### B.4. Statistics of temperatures

The average water inlet temperature of the cell / stack from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$T_{water,in,k,avg} = \frac{1}{M} \sum_{l=0}^{M-1} T_{water,in,k,l} \quad (34)$$

with standard deviation,

$$T_{water,in,k,stdev} = \sqrt{Var(T_{water,in,k})} \quad (35)$$

and variance,

$$Var(T_{water,in,k}) = \frac{1}{M-1} \sum_{l=0}^{M-1} (T_{water,in,k,l} - T_{water,in,k,avg})^2. \quad (36)$$

The average water outlet temperature of the cell / stack from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$T_{water,out,k,avg} = \frac{1}{M} \sum_{l=0}^{M-1} T_{water,out,k,l} \quad (37)$$

with standard deviation,

$$T_{water,out,k,stdev} = \sqrt{Var(T_{water,out,k})} \quad (38)$$

and variance,

$$Var(T_{water,out,k}) = \frac{1}{M-1} \sum_{l=0}^{M-1} (T_{water,out,k,l} - T_{water,out,k,avg})^2. \quad (39)$$

The temperature of the cell / stack at the oxygen evolution electrode is

$$T_c = T_{water,in} + \frac{T_{water,out} - T_{water}}{2}. \quad (40)$$

The average temperature of the cell / stack at step  $k$  of the polarisation curve is

$$T_{c,k,avg} = T_{water,in,k,avg} + \frac{T_{water,out,k,avg} - T_{water,in,k,avg}}{2} \quad (41)$$

with standard deviation,

$$T_{c,k,std} = \frac{\sqrt{(Var(T_{water,in,k}) + Var(T_{water,out,k}))}}{2}. \quad (42)$$

The RSD is

$$T_{c,k,rsd} = \frac{T_{c,k,std}}{|T_{c,k,avg}|} \cdot 100\% \quad (43)$$

and the standard error is

$$T_{c,k,sterr} = \frac{T_{c,k,std}}{\sqrt{M}}. \quad (44)$$

The average hydrogen outlet temperature of the cell / stack from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$T_{H2,out,k,avg} = \frac{1}{M} \sum_{l=0}^{M-1} T_{H2,out,k,l} \quad (45)$$

with standard deviation,

$$T_{H2,out,k,std} = \sqrt{\text{Var}(T_{H2,out,k})} \quad (46)$$

and variance,

$$\text{Var}(T_{H2,out,k}) = \frac{1}{M-1} \sum_{l=0}^{M-1} (T_{H2,out,k,l} - T_{H2,out,k,avg})^2. \quad (47)$$

The RSD is

$$T_{H2,out,k,rsd} = \frac{T_{H2,out,k,std}}{|T_{H2,out,k,avg}|} \cdot 100\% \quad (48)$$

and the standard error is

$$T_{H2,out,k,sterr} = \frac{T_{H2,out,k,std}}{\sqrt{M}}. \quad (49)$$

### B.5. Statistics of pressures

The average water inlet pressure of the cell / stack from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$P_{water,in,k,avg} = \frac{1}{M} \sum_{l=0}^{M-1} P_{water,in,k,l} \quad (50)$$

with standard deviation,

$$P_{water,in,k,std} = \sqrt{\text{Var}(p_{water,in,k})} \quad (51)$$

and variance,

$$\text{Var}(p_{water,in,k}) = \frac{1}{M-1} \sum_{l=0}^{M-1} (P_{water,in,k,l} - P_{water,in,k,avg})^2. \quad (52)$$

The RSD is

$$P_{water,in,k,rsd} = \frac{P_{water,in,k,std}}{|P_{water,in,k,avg}|} \cdot 100\% \quad (53)$$

and the standard error is

$$P_{water,in,k,sterr} = \frac{P_{water,in,k,std}}{\sqrt{M}}. \quad (54)$$

The average hydrogen outlet pressure of the cell / stack from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$P_{H2,out,k,avg} = \frac{1}{M} \sum_{l=0}^{M-1} P_{H2,out,k,l} \quad (55)$$

with standard deviation,

$$P_{H2,out,k,std} = \sqrt{\text{Var}(P_{H2,out,k})} \quad (56)$$

and variance,

$$\text{Var}(P_{H2,out,k}) = \frac{1}{M-1} \sum_{l=0}^{M-1} (P_{H2,out,k,l} - P_{H2,out,k,avg})^2. \quad (57)$$

The RSD is

$$P_{H2,out,k,rsd} = \frac{P_{H2,out,k,std}}{P_{H2,out,k,avg}} \cdot 100\% \quad (58)$$

and the standard error is

$$P_{H2,out,k,sterr} = \frac{P_{H2,out,k,std}}{\sqrt{M}}. \quad (59)$$

The average oxygen outlet pressure of the cell / stack from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$P_{O2,out,k,avg} = \frac{1}{M} \sum_{l=0}^{M-1} P_{O2,out,k,l} \quad (60)$$

with standard deviation,

$$P_{O2,out,k,std} = \sqrt{\text{Var}(P_{O2,out,k})} \quad (61)$$

and variance,

$$\text{Var}(P_{O2,out,k}) = \frac{1}{M-1} \sum_{l=0}^{M-1} (P_{O2,out,k,l} - P_{O2,out,k,avg})^2. \quad (62)$$

The RSD is

$$P_{O2,out,k,rsd} = \frac{P_{O2,out,k,std}}{P_{O2,out,k,avg}} \cdot 100\% \quad (63)$$

and the standard error is



$$P_{O_2,out,k,stderr} = \frac{P_{O_2,out,k,std}}{\sqrt{M}}. \quad (64)$$

## Appendix C

### Measurement uncertainties of TIPs & TOPs

#### C.1. Uncertainty of current density

The measurement uncertainty of the current density of the cell / stack from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$u(j_k) = \sqrt{\text{Var}(j_k) + u_j^2}. \quad (65)$$

The RMU is

$$u_{rmu}(j_k) = \frac{u(j_k)}{|j_{k,avg}|} \cdot 100\% \quad (66)$$

and the measurement error is

$$u_{err}(j_k) = \frac{u(j_k)}{\sqrt{M}}. \quad (67)$$

#### C.2. Uncertainty of voltage

The measurement uncertainty of the cell / stack voltage from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$u(U_k) = \sqrt{\text{Var}(U_k) + u_U^2}. \quad (68)$$

The RMU is

$$u_{rmu}(U_k) = \frac{u(U_k)}{|U_{k,avg}|} \cdot 100\% \quad (69)$$

and the measurement error is

$$u_{err}(U_k) = \frac{u(U_k)}{\sqrt{M}}. \quad (70)$$

#### C.3. Uncertainty of electric power density

The measurement uncertainty of the electric power density of the cell / stack voltage from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$u(P_{d,k}) = P_{d,k,avg} \sqrt{\frac{\text{Var}(j_k) + u^2(j_k)}{j_{k,avg}^2} + \frac{\text{Var}(U_k) + u^2(U_k)}{U_{k,avg}^2} + 2 \frac{\text{Cov}(j_k, U_k)}{P_{d,k,avg}}}. \quad (71)$$

The RMU is

$$u_{rmu}(P_{d,k}) = \frac{u(P_{d,k})}{|P_{d,k,avg}|} \cdot 100\% \quad (72)$$

and the measurement error is

$$u_{err}(P_{d,k}) = \frac{u(P_{d,k})}{\sqrt{M}}. \quad (73)$$

#### C.4. Uncertainty of cell / stack temperature

The measurement uncertainty of the temperature of the cell / stack voltage from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$u(T_{c,k}) = \frac{\sqrt{\text{Var}(T_{water,in,k}) + \text{Var}(T_{water,out,k}) + 2u^2(T)}}{2}. \quad (74)$$

The RMU is

$$u_{rmu}(T_{c,k}) = \frac{u(T_{c,k})}{|T_{c,k,avg}|} \cdot 100\% \quad (75)$$

and the measurement error is

$$u_{err}(T_{c,k}) = \frac{u(T_{c,k})}{\sqrt{M}}. \quad (76)$$

#### C.5. Uncertainty of pressures

The measurement uncertainty of the hydrogen pressure of the cell / stack voltage from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$u(p_{H2,k}) = \sqrt{\text{Var}(p_{H2,out,k}) + u^2(p)}. \quad (77)$$

The RMU is

$$u_{rmu}(p_{H2,k}) = \frac{u(p_{H2,k})}{|p_{H2,k}|} \cdot 100\% \quad (78)$$

and the measurement error is

$$u_{err}(p_{H2,k}) = \frac{u(p_{H2,k})}{\sqrt{M}}. \quad (79)$$

The measurement uncertainty of the oxygen pressure of the cell / stack voltage from the  $M$  measurements during the acquisition period at step  $k$  of the polarisation curve is

$$u(p_{O_2,k}) = \sqrt{\text{Var}(p_{O_2,out,k}) + u^2(p)}. \quad (80)$$

The RMU is

$$u_{rmu}(p_{O_2,k}) = \frac{u(p_{O_2,k})}{|p_{O_2,k}|} \cdot 100\% \quad (81)$$

and the measurement error is

$$u_{err}(p_{O_2,k}) = \frac{u(p_{O_2,k})}{\sqrt{M}}. \quad (82)$$

## Appendix D

### Example of measurement data of Figure 1

Table 8 provides the average data of measurement of the ascending part and the descending part of the polarisation curve of the example given in Figure 1.

**Table 8 Example of polarisation curve measurement data**

| Ascending                             |                 | Descending                            |                 |
|---------------------------------------|-----------------|---------------------------------------|-----------------|
| Current density (A.cm <sup>-2</sup> ) | Cell voltage, V | Current density (A.cm <sup>-2</sup> ) | Cell voltage, V |
| 0.002196                              | 1.320659        | 1.997028                              | 1.971923        |
| 0.005037                              | 1.36234         | 1.897006                              | 1.945978        |
| 0.010062                              | 1.375311        | 1.797147                              | 1.921179        |
| 0.020117                              | 1.392194        | 1.696957                              | 1.897333        |
| 0.030138                              | 1.403544        | 1.597124                              | 1.873583        |
| 0.040142                              | 1.412891        | 1.497197                              | 1.851072        |
| 0.060187                              | 1.429582        | 1.397212                              | 1.827036        |
| 0.080224                              | 1.444366        | 1.297258                              | 1.804812        |
| 0.100238                              | 1.456766        | 1.197299                              | 1.781062        |
| 0.150326                              | 1.485284        | 1.097249                              | 1.759601        |
| 0.200385                              | 1.509416        | 0.997313                              | 1.735278        |
| 0.250495                              | 1.531258        | 0.897482                              | 1.712101        |
| 0.297237                              | 1.548522        | 0.797049                              | 1.689114        |
| 0.347374                              | 1.565118        | 0.697107                              | 1.664982        |
| 0.397259                              | 1.580856        | 0.597099                              | 1.640373        |
| 0.447324                              | 1.596021        | 0.497116                              | 1.612904        |
| 0.497136                              | 1.60947         | 0.447302                              | 1.599169        |
| 0.597415                              | 1.636368        | 0.397207                              | 1.584576        |
| 0.697348                              | 1.660976        | 0.347321                              | 1.570555        |
| 0.79707                               | 1.686156        | 0.297202                              | 1.553672        |
| 0.99733                               | 1.734229        | 0.250492                              | 1.537553        |
| 1.097498                              | 1.758361        | 0.200378                              | 1.516188        |
| 1.197311                              | 1.782015        | 0.150317                              | 1.492438        |
| 1.297265                              | 1.806052        | 0.100234                              | 1.463251        |
| 1.397199                              | 1.829134        | 0.080205                              | 1.449898        |
| 1.497192                              | 1.853552        | 0.060172                              | 1.435019        |
| 1.597162                              | 1.875967        | 0.040124                              | 1.418232        |
| 1.696959                              | 1.899622        | 0.030118                              | 1.40898         |
| 1.79709                               | 1.924231        | 0.020112                              | 1.397249        |
| 1.896997                              | 1.948363        | 0.01006                               | 1.380557        |
| 1.997028                              | 1.971923        | 0.005034                              | 1.368348        |



**EU Harmonised Polarisation Curve Test Method for Low Temperature Water Electrolysis**



---

THIS PAGE IS LEFT BLANK INTENTIONALLY

Europe Direct is a service to help you find answers to your questions about the European Union  
Freephone number (\*): 00 800 6 7 8 9 10 11

(\*): Certain mobile telephone operators do not allow access to 00 800 numbers or these calls may be billed.

A great deal of additional information on the European Union is available on the Internet.  
It can be accessed through the Europa server <http://europa.eu>.

How to obtain EU publications

Our publications are available from EU Bookshop (<http://bookshop.europa.eu>),  
where you can place an order with the sales agent of your choice.

The Publications Office has a worldwide network of sales agents.  
You can obtain their contact details by sending a fax to (352) 29 29-42758.

European Commission  
EUR xxxxx EN – Joint Research Centre

Title: EU Harmonised Polarisation Curve Test Method for Low Temperature Water Electrolysis

Authors: T Malkow, A Pilenga, G Tsotridis, G De Marco

Luxembourg: Publications Office of the European Union

2018 –36 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN xxxx-xxxx (print), ISSN xxxx-xxxx (online)

ISBN xxx-xx-xx-xxxxx-x (print)

ISBN xxx-xx-xx-xxxxx-x (PDF)

doi:xx.xxxx/xxxxx

## JRC Mission

As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new methods, tools and standards, and sharing its know-how with the Member States, the scientific community and international partners.

*Serving society*  
*Stimulating innovation*  
*Supporting legislation*

doi:xx.xxxx/xxxxx

ISBN xxx-xx-xx-xxxx-x

