

INTERNATIONAL STANDARD

NORME INTERNATIONALE



Fuel cell technologies –

**Part 8-101: 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**

Technologies des piles à combustible –

**Partie 8-101: Système de stockage de l'énergie utilisant des modules à piles
à combustible en mode inversé – Procédures d'essai pour la performance
des cellules élémentaires et des piles à oxyde solide, comprenant
le fonctionnement réversible**



THIS PUBLICATION IS COPYRIGHT PROTECTED

Copyright © 2020 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

Droits de reproduction réservés. Sauf indication contraire, aucune partie de cette publication ne peut être reproduite ni utilisée sous quelque forme que ce soit et par aucun procédé, électronique ou mécanique, y compris la photocopie et les microfilms, sans l'accord écrit de l'IEC ou du Comité national de l'IEC du pays du demandeur. Si vous avez des questions sur le copyright de l'IEC ou si vous désirez obtenir des droits supplémentaires sur cette publication, utilisez les coordonnées ci-après ou contactez le Comité national de l'IEC de votre pays de résidence.

IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee,...). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

Electropedia - www.electropedia.org

The world's leading online dictionary on electrotechnology, containing more than 22 000 terminological entries in English and French, with equivalent terms in 16 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

IEC Glossary - std.iec.ch/glossary

67 000 electrotechnical terminology entries in English and French extracted from the Terms and Definitions clause of IEC publications issued since 2002. Some entries have been collected from earlier publications of IEC TC 37, 77, 86 and CISPR.

A propos de l'IEC

La Commission Electrotechnique Internationale (IEC) est la première organisation mondiale qui élabore et publie des Normes internationales pour tout ce qui a trait à l'électricité, à l'électronique et aux technologies apparentées.

A propos des publications IEC

Le contenu technique des publications IEC est constamment revu. Veuillez vous assurer que vous possédez l'édition la plus récente, un corrigendum ou amendement peut avoir été publié.

Recherche de publications IEC -

webstore.iec.ch/advsearchform

La recherche avancée permet de trouver des publications IEC en utilisant différents critères (numéro de référence, texte, comité d'études,...). Elle donne aussi des informations sur les projets et les publications remplacées ou retirées.

IEC Just Published - webstore.iec.ch/justpublished

Restez informé sur les nouvelles publications IEC. Just Published détaille les nouvelles publications parues. Disponible en ligne et une fois par mois par email.

Service Clients - webstore.iec.ch/csc

Si vous désirez nous donner des commentaires sur cette publication ou si vous avez des questions contactez-nous: sales@iec.ch.

Electropedia - www.electropedia.org

Le premier dictionnaire d'électrotechnologie en ligne au monde, avec plus de 22 000 articles terminologiques en anglais et en français, ainsi que les termes équivalents dans 16 langues additionnelles. Egalement appelé Vocabulaire Electrotechnique International (IEV) en ligne.

Glossaire IEC - std.iec.ch/glossary

67 000 entrées terminologiques électrotechniques, en anglais et en français, extraites des articles Termes et Définitions des publications IEC parues depuis 2002. Plus certaines entrées antérieures extraites des publications des CE 37, 77, 86 et CISPR de l'IEC.

INTERNATIONAL STANDARD

NORME INTERNATIONALE



Fuel cell technologies –

**Part 8-101: 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**

Technologies des piles à combustible –

**Partie 8-101: Système de stockage de l'énergie utilisant des modules à piles
à combustible en mode inversé – Procédures d'essai pour la performance
des cellules élémentaires et des piles à oxyde solide, comprenant
le fonctionnement réversible**

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

COMMISSION
ELECTROTECHNIQUE
INTERNATIONALE

ICS 27.070

ISBN 978-2-8322-7705-8

Warning! Make sure that you obtained this publication from an authorized distributor.

Attention! Veuillez vous assurer que vous avez obtenu cette publication via un distributeur agréé.

CONTENTS

FOREWORD.....	7
INTRODUCTION.....	9
1 Scope.....	10
2 Normative references	10
3 Terms, definitions, abbreviated terms and symbols.....	11
3.1 Terms and definitions.....	11
3.2 Abbreviated terms and symbols	17
3.2.1 Abbreviated terms	17
3.2.2 Symbols	17
3.3 Flow rates.....	21
4 General safety conditions	21
5 Test environment.....	22
5.1 General.....	22
5.2 Cell.....	23
5.3 Stack	23
5.4 Experimental set-up	24
5.4.1 General	24
5.4.2 Electrode gas control equipment.....	25
5.4.3 Thermal management equipment.....	25
5.4.4 Electric power supply/load control equipment	25
5.4.5 Measurement and data acquisition equipment	25
5.4.6 Safety equipment.....	25
5.4.7 Compression force control equipment.....	25
5.4.8 Pressure control equipment	25
5.5 Interface between test object and experimental set-up.....	26
5.6 Parameter control and measurement	27
5.7 Measurement uncertainty of TIPs and TOPs	28
5.8 Mounting of the test object into the experimental set-up.....	28
5.9 Stability criteria	29
6 Measurement instruments and methods.....	29
6.1 General.....	29
6.2 Instrument uncertainty	29
6.3 Recommended measurement instruments and methods.....	30
6.3.1 Electrode inlet gas flow rate measurement	30
6.3.2 Electrode gas composition measurement.....	30
6.3.3 Electrode gas temperature measurement.....	31
6.3.4 Electrode gas pressure measurement.....	31
6.3.5 Electrode exhaust gas flow rate measurement.....	31
6.3.6 Cell/stack assembly unit voltage measurement.....	32
6.3.7 Cell/stack assembly unit current measurement	32
6.3.8 Cell/stack assembly unit temperature measurement	32
6.3.9 Compression force measurement.....	32
6.3.10 Total impedance measurement.....	32
6.3.11 Ambient condition measurement.....	32
6.4 Test conditions and manufacturer recommendations.....	33
6.4.1 Start-up and shut-down conditions.....	33

6.4.2	Range of test conditions	33
6.4.3	Stabilization, initialization conditions and stable state	33
6.4.4	Dwell time, equilibration time, acquisition time	33
6.5	Data acquisition method	34
7	Test procedures and computation of results	34
7.1	General	34
7.2	Current-voltage characteristics test	34
7.2.1	Objective of this test	34
7.2.2	Test method	34
7.2.3	Data post-processing	35
7.3	Effective reactant utilization test	35
7.3.1	Objective of this test	35
7.3.2	Test method	35
7.3.3	Data post-processing	36
7.4	Durability test	36
7.4.1	Objective of this test	36
7.4.2	Test method	37
7.4.3	Data post-processing	37
7.5	Temperature sensitivity test	37
7.5.1	Objective of this test	37
7.5.2	Test method	38
7.5.3	Data post-processing	38
7.6	Separation of resistance components test via electrochemical impedance spectroscopy	39
7.6.1	Objective of this test	39
7.6.2	Test method	39
7.6.3	Data post-processing	40
7.7	Current cycling durability test	40
7.7.1	Objective of this test	40
7.7.2	Test method	41
7.7.3	Data post-processing	41
7.8	Thermal cycling test	41
7.8.1	Objective	41
7.8.2	Test method	41
7.8.3	Data post-processing	42
7.9	Pressurized test	42
7.9.1	Objective of this test	42
7.9.2	Test method	42
7.9.3	Data post-processing	43
8	Test report	43
8.1	General	43
8.2	Report items	43
8.3	Test unit data description	43
8.4	Test condition description	44
8.5	Test data description	44
8.6	Uncertainty evaluation	44
Annex A (normative)	Detailed test procedures	45
A.1	Test objective	45
A.2	Test set-up	45

A.3	Current-voltage characteristics test (7.2)	46
A.3.1	Test input parameters (TIPs)	46
A.3.2	Test output parameters (TOPs)	46
A.3.3	Derived quantities	47
A.3.4	Measurement of current-voltage characteristics	47
A.4	Effective reactant utilization test (7.3)	49
A.4.1	Test input parameters (TIPs)	49
A.4.2	Test output parameters (TOPs)	51
A.4.3	Derived quantities	51
A.4.4	Measurement of effective reactant utilization	52
A.5	Durability test (7.4)	53
A.5.1	Test input parameters (TIPs)	53
A.5.2	Test output parameters (TOPs)	53
A.5.3	Derived quantities	54
A.5.4	Measurement of durability	54
A.6	Temperature sensitivity test (7.5)	55
A.6.1	Test input parameters (TIPs)	55
A.6.2	Test output parameters (TOPs)	56
A.6.3	Derived quantities	56
A.6.4	Measurement of temperature sensitivity	57
A.7	Separation of resistance components test via electrochemical impedance spectroscopy (7.6)	58
A.7.1	Test input parameters (TIPs)	58
A.7.2	Test output parameters (TOPs)	58
A.7.3	Derived quantities	59
A.7.4	Measurement of resistance components via EIS	59
A.7.5	Measuring range of frequencies	59
A.8	Current cycling durability test (7.7)	60
A.8.1	Test input parameters (TIPs)	60
A.8.2	Test output parameters (TOPs)	60
A.8.3	Derived quantities	61
A.8.4	Measurement of current cycling durability	61
A.9	Thermal cycling test (7.8)	64
A.9.1	Test input parameters (TIPs)	64
A.9.2	Test output parameters (TOPs)	65
A.9.3	Derived quantities	65
A.9.4	Measurement of thermal cycling	66
A.10	Pressurized test (7.9)	68
A.10.1	Test input parameters (TIPs)	68
A.10.2	Test output parameters (TOPs)	69
A.10.3	Derived quantities	69
A.10.4	Measurement of pressurized test	69
Annex B (informative)	Guidelines for electrochemical impedance spectroscopy (EIS)	71
B.1	General principles	71
B.2	EIS test equipment and set-up	72
B.3	Representation of results	73
B.4	Analysis and simulation of data	75
Annex C (normative)	Formulae for calculation of utilization values	76
C.1	Generic formulae	76

C.2	Degradation	76
C.3	Area-specific resistance (ASR)	77
C.4	Temperatures	77
Bibliography.....		78
Figure 1	– Exploded schematic representation of a planar-type single cell test object consisting of a SOC in a cell housing	23
Figure 2	– Schematic representation of a planar-geometry SOC stack test object with N RU including supporting structure (top and bottom plates)	24
Figure 3	– Schematic representation of a test environment for a SOC cell/stack assembly unit.....	24
Figure 4	– Test environment with interfaces between SOC cell and experimental set-up.....	26
Figure 5	– Test environment with interfaces between SOC stack and experimental set-up	27
Figure A.1	– Qualitative representation of TIPs when carrying out a current-voltage characteristics test for combined (SOFC and SOEC) operation	48
Figure A.2	– Schematic representation of the current-voltage characteristics test procedure for two consecutive set points k and $k + 1$	48
Figure A.3	– Schematic representation of a J - V curve in both electrolysis and fuel cell modes.....	49
Figure A.4	– Qualitative representation of TIPs when carrying out an effective reactant utilization test varying the negative electrode reactant flow rate ($q_{V,neg,in}$), consisting of hydrogen and nitrogen	52
Figure A.5	– Qualitative representation of TIPs when carrying out a durability test (in galvanostatic mode).....	55
Figure A.6	– Qualitative representation of TIPs when carrying out a temperature sensitivity test.....	57
Figure A.7	– Qualitative representation of TIPs when carrying out a current cycling durability test	63
Figure A.8	– Current profile of a SOEC system with fast switch on/off at thermoneutral conditions	64
Figure A.9	– Current profile of a SOEC system with fast switch on/off at exothermal conditions	64
Figure A.10	– Current profile of a load-following SOEC system and thermoneutral conditions	64
Figure A.11	– Current profile of a load-following SOEC system and exothermal conditions	64
Figure A.12	– General evolution of TIPs during test: continuous thermal cycling above 600 °C (in this case with zero electric current)	67
Figure A.13	– General evolution of TIPs during test: thermal cycling below 600 °C with gas and current changes (coupling with operation at constant current for instance)	68
Figure B.1	– Input/output signals during electrochemical impedance spectroscopy (EIS) of a solid oxide fuel/electrolysis cell	72
Figure B.2	– Test set-up for electrochemical impedance spectroscopy of a planar solid oxide fuel cell/electrolysis stack with 5 RUs	73
Figure B.3	– Bode plot representing the modulus of impedance and phase angle against excitation frequency	74
Figure B.4	– Nyquist plot, representing conjugate imaginary part against real part of impedance	75

Table 1 – Symbols	18
Table 2 – Stability criteria for TIPs and TOPs as a reference	29
Table 3 – Instrument uncertainty for each quantity to be measured	30
Table A.1 – Test input parameters (TIPs) for current-voltage characteristics test	46
Table A.2 – Test output parameters (TOPs) for current-voltage characteristics test	47
Table A.3 – Derived quantities for current-voltage characteristics test	47
Table A.4 – Test input parameters (TIPs) for negative electrode reactant utilization test	50
Table A.5 – Test input parameters (TIPs) for positive electrode reactant utilization test	50
Table A.6 – Test output parameters (TOPs) for effective reactant utilization test	51
Table A.7 – Derived quantities for effective reactant utilization test	52
Table A.8 – Test input parameters (TIPs) for durability test	53
Table A.9 – Test output parameters (TOPs) for durability test	54
Table A.10 – Derived quantities for constant load durability test	54
Table A.11 – Test input parameters (TIPs) for temperature sensitivity test	55
Table A.12 – Test output parameters (TOPs) for temperature sensitivity test	56
Table A.13 – Derived quantities for temperature sensitivity test	56
Table A.14 – Test input parameters (TIPs) for EIS test	58
Table A.15 – Test output parameters (TOPs) for EIS test	59
Table A.16 – Derived quantities for EIS test	59
Table A.17 – Test input parameters (TIPs) for current cycling durability test within a single operating mode (fuel cell or electrolysis)	60
Table A.18 – Test input parameters (TIPs) for current cycling durability test covering both operating modes (fuel cell and electrolysis)	60
Table A.19 – Test output parameters (TOPs) for current cycling durability test	61
Table A.20 – Derived quantities for current cycling durability test	61
Table A.21 – Test input parameters (TIPs) for thermal cycling	65
Table A.22 – Test output parameters (TOPs) for thermal cycling	65
Table A.23 – Derived quantities for thermal cycling test	66
Table A.24 – Test input parameters (TIPs) for pressurized testing	69
Table A.25 – Test output parameters (TOPs) for pressurized testing	69
Table A.26 – Derived quantities for pressurized test	69
Table C.1 – Generic formulae	76

INTERNATIONAL ELECTROTECHNICAL COMMISSION

FUEL CELL TECHNOLOGIES –

**Part 8-101: 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**

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 62282-8-101 has been prepared by IEC technical committee 105: Fuel cell technologies.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
105/765/FDIS	105/779/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 62282 series, published under the general title *Fuel cell technologies*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This document describes test methods for a single cell or stack (denoted as "cell/stack" hereafter) that are intended for application to energy storage systems using solid oxide fuel cells (SOFC) in combination with solid oxide electrolysis cells (SOEC), or directly using reversible solid oxide cells (Re-SOC, see Note in Clause 1). The test methods aim to provide guidelines for the characterization of real-time performance and durability of the cell/stack.

SOFC, SOEC and Re-SOC have a broad range of geometries (e.g. planar, tubular and their variations) and size. As such, in general, peripherals like current collectors and gas manifolds are unique to each cell or stack and are often incorporated into a cell or stack to form one integrated unit. In addition, they tend to have a significant effect on the power generation characteristics of the cell or stack. This document therefore introduces as its subject "cell/stack assembly units", which are defined as those units containing not only a cell or a stack but also peripherals.

This document is generally applicable to all types or geometries of SOFC, SOEC and Re-SOC, unless where explicitly mentioned.

IEC 62282-8 (all parts) aims to develop performance test methods for power storage and buffering systems based on electrochemical modules (combining electrolysis and fuel cells, in particular reversible fuel cells), taking into consideration both options of re-electrification and substance (and heat) production for sustainable integration of renewable energy sources.

Under the general title "Energy storage systems using fuel cell modules in reverse mode", the IEC 62282-8 series will consist of the following parts:

- IEC 62282-8-101: *Test procedures for the performance of solid oxide single cells and stacks, including reversible operation*
- IEC 62282-8-102: *Test procedures for the performance of single cells and stacks with proton exchange membranes, including reversible operation*
- IEC 62282-8-103¹: *Alkaline single cell and stack performance including reversible operation*
- IEC 62282-8-201: *Test procedures for the performance of power-to-power systems*
- IEC 62282-8-202²: *Power-to-power systems – Safety*
- IEC 62282-8-300 series³: *Power-to-substance systems*

As a priority dictated by the emerging needs for industry and opportunities for technological development, IEC 62282-8-101, IEC 62282-8-102 and IEC 62282-8-201 have been initiated jointly and as a priority. These documents are presented as a package to highlight the need for an integrated approach as regards the system application (i.e. a solution for energy storage) and its fundamental constituent components (i.e. fuel cells operated in reverse or reversible mode).

IEC 62282-8-103, IEC 62282-8-202 and IEC 62282-8-300 (all parts) are suggested but are left for initiation at a later stage.

¹ Under consideration.

² Under consideration.

³ Under consideration.

FUEL CELL TECHNOLOGIES –

Part 8-101: 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

1 Scope

This part of IEC 62282 addresses solid oxide cell (SOC) and stack assembly unit(s). It provides for testing systems, instruments and measuring methods to test the performance of SOC cell/stack assembly units for energy storage purposes. It assesses performance in fuel cell mode, in electrolysis mode and/or in reversible operation.

This document is not applicable to small button cells that are designed for SOC material testing and provide no practical means of reactant utilization measurement, or to single-chamber SOC. This document is not intended to be applied to fuel cell/stack assembly units for power generation purposes only, since this is covered in IEC TS 62282-7-2. Therefore, test methods are not included in this document that are applicable to fuel cell mode only and that are already described in IEC TS 62282-7-2.

This document is intended for data exchanges in commercial transactions between cell/stack manufacturers and system developers or for acquiring data on a cell or stack in order to estimate the performance of a system based on it. Users of this document may selectively execute test items suitable for their purposes from those described in this document. Users can also substitute selected test methods of this document with equivalent test methods of IEC TS 62282-7-2 for SOC operation in fuel cell mode only.

NOTE 1 In the context of this document, the term "reversible" does not refer to the thermodynamic meaning of an ideal process. It is common practice in the fuel cell community to call the operation mode of a solid oxide cell that alternates between fuel cell mode and electrolysis mode "reversible".

NOTE 2 This document considers only steam electrolysis. Other reactants in electrolysis mode can be used, provided appropriate measures are taken for handling the specific reactants and products, and the guidelines as regards the measurement, control and post-test analysis of results are adapted accordingly.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-485, *International Electrotechnical Vocabulary – Part 485: Fuel cell technologies* (available at www.electropedia.org)

IEC 61515:2016, *Mineral insulated metal-sheathed thermocouple cables and thermocouples*

IEC 60584-1, *Thermocouples – Part 1: EMF specifications and tolerances*

IEC 60584-3, *Thermocouples – Part 3: Extension and compensating cables – Tolerances and identification system*

ISO 5168, *Measurement of fluid flow – Procedures for the evaluation of uncertainties*

ISO 6141, *Gas analysis – Contents of certificates for calibration gas mixtures*



ISO 6142-1, *Gas analysis – Preparation of calibration gas mixtures – Part 1: Gravimetric method for Class I mixtures*

ISO 6143, *Gas analysis – Comparison methods for determining and checking the composition of calibration gas mixtures*

ISO 6145-7, *Gas analysis – Preparation of calibration gas mixtures using dynamic volumetric methods – Part 7: Thermal mass-flow controllers*

ISO 6974 (all parts), *Natural gas – Determination of composition with defined uncertainty by gas chromatography*

ISO 7066-2, *Assessment of uncertainty in the calibration and use of flow measurement devices – Part 2: Non-linear calibration relationships*

ISO 8756, *Air quality – Handling of temperature, pressure and humidity data*

3 Terms, definitions, abbreviated terms and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-485 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia available at: <http://www.electropedia.org/>
- ISO Online browsing platform available at: <http://www.iso.org/obp>

3.1.1

active electrode area

effective electrode area

geometric area of the electrode where the electrochemical reaction takes place

Note 1 to entry: Usually this corresponds to the smaller of the two areas of negative electrode or positive electrode.

Note 2 to entry: Area perpendicular to the ionic current flow, usually expressed in m^2 or cm^2 .

[SOURCE: IEC TS 62282-7-2:2014, 3.1.2, modified – Definition and Note 1 to entry reworded and Note 2 to entry added.]

3.1.2

area-specific resistance

ASR

R_{ASR}

internal resistivity of any component of a cell or a stack, including the change of potential due to the electrochemical reaction

Note 1 to entry: It is normalized by the active electrode area and is expressed in $\Omega \text{ m}^2$ or $\Omega \text{ cm}^2$.

Note 2 to entry: This note applies to the French language only.

3.1.3

average repeating unit voltage

average RU voltage

cell/stack assembly unit voltage divided by the number of the cells in a series connection in the unit

Note 1 to entry: Average voltage is expressed in V.

[SOURCE: IEC TS 62282-7-2:2014, 3.1.4 modified – In the term, word "cell" replaced by "repeating unit", and Note 1 to entry added.]

3.1.4

interconnector

interconnect

conductive and gas-tight component connecting single cells in a stack

Note 1 to entry: Gas tightness is relevant for planar-type geometries of SOC.

Note 2 to entry: This item is only applicable to planar-type geometries of SOC, as opposed to tubular geometries (see IEC 60050-485:—, 485-06-04).

[SOURCE: IEC 60050-485:—, 485-06-05, modified – Words "fuel cell stack" replaced by "stack", and Notes 1 and 2 to entry added.]

3.1.5

catalyst

substance that accelerates (increases the rate of) a reaction without being consumed itself

Note 1 to entry: The catalyst lowers the activation energy of the reaction, allowing for an increase in the reaction rate.

[SOURCE: IEC 60050-485:—, 485-01-01, modified – Definition reworded, and Note 2 to entry removed.]

3.1.6

single cell

cell

basic unit of a solid oxide cell

3.1.7

axial load

compression force

compressive load applied to the single cell or the end plates of a planar SOC stack to ensure electric contact and/or gas tightness

Note 1 to entry: The compression force is in practice expressed in N.

[SOURCE: IEC 60050-485:—, 485-06-14, modified – Words "end plates of a fuel cell" replaced by "single cell or the end plates of a planar SOC", "electric" added, and Note to entry replaced.]

3.1.8

conditioning

preliminary step of treatment that is required to properly operate a SOC and is usually realized by following a protocol specified by the manufacturer

Note 1 to entry: The conditioning may include reversible and/or irreversible processes depending on the cell technology.

[SOURCE: IEC 60050-485:—, 485-11-08, modified – Words "of treatment" added, "fuel cell" replaced by "SOC", and "to achieve a desired performance" replaced by "and is usually realized by".]

3.1.9**contact layer**

layer applied between the interconnect and the cell to minimize the contact resistance

3.1.10**current collector**

electronically conductive material in a cell/stack assembly unit that collects/conducts electrons from/to the electrodes

[SOURCE: IEC 60050-485:—, 485-06-07, modified – Word "electronically" added, "fuel cell" replaced with "cell/stack assembly unit", and "anode/cathode" replaced with "electrodes".]

3.1.11**current density**

current per unit active area

Note 1 to entry: The current density is expressed in A/m² or A/cm².

[SOURCE: IEC 60050-485:—, 485-12-01, modified – Word "electric" deleted before "current".]

3.1.12**derived quantities**

quantities that can be derived or calculated from test input parameters, and/or test output parameters (e.g. current density, reactant utilization, electric efficiency)

Note 1 to entry: In comparison to test output parameters, derived quantities are not directly measurable.

3.1.13**dwelt time**

time between changes in the setting of operating conditions

3.1.14**electrode gas**

gas present at the positive or negative electrode

Note 1 to entry: Electrode gases can be reactants, products or inert gas.

3.1.15**reactant utilization**

effective reactant utilization

ratio of converted substance flow through a given electrode of the cell/stack assembly unit to the input substance flow of the same electrode

Note 1 to entry: The three types of reactant utilization are:

- fuel utilization (negative electrode in SOFC mode);
- oxygen utilization (positive electrode in SOFC mode);
- steam conversion (negative electrode in SOEC mode).

Note 2 to entry: In SOFC mode, the effective reactant utilization can also be calculated as the ratio of actual output current of the cell/stack assembly unit to the theoretical Faradaic current.

Note 3 to entry: Under the assumption that the electrolyte has neither leak nor electronic conductivity, the reactant utilization is equivalent to the effective reactant utilization and can be calculated according to IEC TS 62282-7-2:2014, Annex B and Annex C.

3.1.16

exhaust gas

gas which is exhausted from the electrodes of the SOC

Note 1 to entry: The exhaust gas is a mixture of the reaction products of the electrochemical reaction, not converted reactant gas and inert gases, which is supplied to the electrodes.

3.1.17

minimum voltage

<in SOFC mode> lowest cell/stack assembly unit voltage specified by the manufacturer

Note 1 to entry: Minimum voltage is expressed in V.

3.1.18

maximum voltage

<in SOEC mode> highest cell/stack assembly unit voltage specified by the manufacturer

Note 1 to entry: Maximum voltage is expressed in V.

3.1.19

negative electrode

electrode at which fuel gas is consumed or produced

Note 1 to entry: It may also be called fuel electrode. In fuel cell mode, it is called the anode, where the fuel is oxidized. In electrolysis mode, it is called the cathode, where steam is reduced producing hydrogen.

Note 2 to entry: In fuel cell mode, the negative electrode gas is usually hydrogen or a mixture which contains hydrogen as a principal component mixed with water vapour and/or inert gas.

Note 3 to entry: In electrolysis mode, the negative electrode gas is usually water vapour mixed with hydrogen and/or inert gas.

3.1.20

open-circuit voltage

OCV

voltage across the terminals of a SOC with positive and negative electrode gases present and in the absence of external current flow

Note 1 to entry: Open-circuit voltage is expressed in V.

Note 2 to entry: This note applies to the French language only.

[SOURCE: IEC 60050-485:—, 485-13-02, modified – Words "fuel cell" replaced by "SOC", and "fuel and oxidant" replaced with "positive and negative electrode gases".]

3.1.21

positive electrode

electrode at which oxygen is consumed or produced

Note 1 to entry: Oxygen and nitrogen are the main components of positive electrode gases.

Note 2 to entry: In the case of a proton-conducting SOC, the mechanisms at electrodes, the ions crossing the electrolyte and the atmosphere at the electrodes will be different.

Note 3 to entry: It may also be called oxidant electrode. In fuel cell mode, it is called cathode where oxygen is reduced producing oxide ions going through the electrolyte. In electrolysis mode, it is called anode where two oxide ions are recombined to form one molecule of oxygen.

3.1.22

power density

ratio of power to the active electrode area of the cell/stack assembly unit electrodes

Note 1 to entry: Power density is calculated from the voltage multiplied by the current density ($P_d = V \times J$, where J is current density). It is expressed in $W \cdot m^{-2}$ or $W \cdot cm^{-2}$.

[SOURCE: IEC TS 62282-7-2:2014, 3.1.16, modified – Word "electrodes" added, and second sentence in the note to entry added.]

3.1.23

protection gas

mixture of hydrogen and inert gas (usually argon or nitrogen)

Note 1 to entry: It is often used to protect transition metal-containing negative electrodes of the SOC from being re-oxidized in the case of abnormal operating conditions (e.g. fuel interruption, emergency stop of the test station).

3.1.24

rated current

recommended continuous electric current as specified by the manufacturer, at which the SOC power system has been designed to operate

Note 1 to entry: The rated current is expressed in A.

[SOURCE: IEC 60050-485:—, 485-12-02, modified – Word "maximum" replaced by "recommended", and "fuel cell" replaced by "SOC".]

3.1.25

reactant gas

gas which is fed to the electrodes of the SOC where it reacts in an electrochemical reaction

Note 1 to entry: The reactant gases are the fuel and the oxidant in fuel cell mode and steam in electrolysis mode.

3.1.26

reversible mode

regenerative mode

operation mode of a solid oxide cell which alternates between fuel cell mode and electrolysis mode (Re-SOC)

Note 1 to entry: The term "reversible" in this context does not refer to the thermodynamic principle of an ideal process.

3.1.27

repeating unit

RU

elementary unit which periodically repeats itself to form a stack

Note 1 to entry: For planar-geometry SOCs, it is composed of one single cell and two half interconnects on both sides of the single cell and usually also of a sealant to ensure gas-tightness and contact layers to minimize contact resistances between cells and interconnects.

Note 2 to entry: This note applies to the French language only.

3.1.28

solid oxide cell

SOC

electrochemical cell composed of three functional elements (negative electrode, electrolyte and positive electrode) based on ceramic oxide materials

Note 1 to entry: A SOC can consist of a single cell or of an assembly unit of multiple cells, called a stack.

Note 2 to entry: The two electrodes are made of electronic and possibly ionic conducting ceramics and are attached to one ionic conducting solid oxide ceramic electrolyte. Furthermore, the cell may contain a support layer which may be a ceramic

Note 3 to entry: SOCs can be used in fuel cell mode (SOFC) or in electrolysis mode (SOEC) with a layer or a non-ceramic layer as is the case for metal-supported cells.

Note 4 to entry: This note applies to the French language only.

3.1.29

solid oxide electrolysis cell

SOEC

SOC operated in electrolysis mode, i.e. reversed fuel cell mode

Note 1 to entry: Electricity is required as energy input. Where possible, heat may be used as additional energy input to reduce the amount of electrical work needed.

Note 2 to entry: It can be used to produce hydrogen from steam and, alternatively, to produce carbon monoxide from carbon dioxide, or syngas, a mixture of hydrogen and carbon monoxide from water vapour and carbon dioxide

Note 3 to entry: This note applies to the French language only.

3.1.30

solid oxide fuel cell

SOFC

SOC operated in fuel cell mode

Note 1 to entry: In this mode, it cogenerates electricity and heat using fuels such as hydrogen.

Note 2 to entry: This note applies to the French language only.

3.1.31

stable state

condition of a cell/stack assembly unit stable enough for any controlling parameter and the output voltage or output current of the unit to remain within its tolerance range of variation

[SOURCE: IEC TS 62282-7-2:2014, 3.1.9]

3.1.32

fuel cell stack

stack

assembly of cells, interconnectors, cooling plates, manifolds and a supporting structure that electrochemically converts, typically hydrogen-rich gas and air reactants to DC power, heat and other reaction products

Note 1 to entry: For planar geometry SOC's, the supporting structure consists of two endplates ("top plate" and "bottom plate") to facilitate applying a compression force to all RUs.

[SOURCE: IEC 60050-485:—, 485-06-01, modified – Word "separators" replaced by "interconnectors", and note to entry added.]

3.1.33

test input parameter

TIP

parameter whose values can be set in order to define the test conditions of the test system including the operating conditions of the test object

Note 1 to entry: TIPs have to be controllable and measurable. Values of TIPs are known before conducting the test. TIPs can be either static or variable. Static TIPs stay constant and variable TIPs are varied during the test.

Note 2 to entry: This note applies to the French language only.

3.1.34

test output parameter

TOP

parameter that indicates the response of the test system/test object as a result of variation of TIPs

Note 1 to entry: Values of TOPs are unknown before conducting the test and will be measured during the test. TOPs need to be measurable.

Note 2 to entry: This note applies to the French language only.

3.1.35**theoretical current**

current when the supplied positive and negative electrode gases are completely consumed in electrochemical reactions divided by the number of cells in a series connection

Note 1 to entry: Theoretical current is expressed in A.

3.1.36**total impedance**

frequency-dependent losses due to ohmic, activation, diffusion, concentration effects, stray (parasitic) capacitance and inductances

Note 1 to entry: Total impedance is expressed in $\Omega \cdot \text{m}^2$ or $\Omega \cdot \text{cm}^2$.

[SOURCE: IEC TS 62282-7-2:2014, 3.1.17, modified – Words "stray (parasitic) capacitance and inductances" added, and note to entry added.]

3.1.37**total resistance**

real part of low-frequency limit of total impedance

Note 1 to entry: Total resistance is expressed in $\Omega \cdot \text{m}^2$ or $\Omega \cdot \text{cm}^2$.

[SOURCE: IEC TS 62282-7-2:2014, 3.1.18, modified – Removed reference to slope of I - V curve, and addition of note to entry.]

3.2 Abbreviated terms and symbols**3.2.1 Abbreviated terms**

BOP	balance of plant
EIS	electrochemical impedance spectroscopy
LHV	lower heating value
HHV	higher heating value
OCV	open circuit voltage
SOC	solid oxide cell
SOEC	solid oxide electrolysis cell
SOFC	solid oxide fuel cell
Re-SOC	regenerative solid oxide cell
RU	repeating unit
SPT	standard pressure and temperature
TIP	test input parameter
TOP	test output parameter

3.2.2 Symbols

Table 1 lists the symbols and units that are used in this document.

Table 1 – Symbols

Symbol	Definition	Unit
A_{active}	Active (surface) area of the cell/stack electrode(s)	m ² , cm ²
c	Concentration	
c_i	Molar concentration of component i	mol/m ³
F	Faraday constant, force	
F	Faraday constant (96485,3)	C/mol
F_{comp}	Compression force applied onto the cell/stack	N
f	Frequency	
f	Excitation frequency	Hz
f_{char}	Characteristic frequency	Hz
I, J	Current, current density	
I_{cell}	Cell current	A
I_{n}	Nominal current	A
I_{stack}	Stack current	A
I_{RU}	Repeating unit current	A
$\underline{I}$	Fourier transform of excitation current	A
I_{pk}	Amplitude of alternating current	A
i	Excitation current (galvanostatic mode), current response (potentionstatic mode)	A
J	Current density	A/m ² , A/cm ²
J_{rr}	Current density ramp rate	A/(m ² ·s), A/(cm ² ·s)
$\mathbf{i}$	Imaginary unit	
N, n	Number of items	
N_{cycles}	Number of cycles	
N_{periods}	Number of measuring periods	
N_{points}	Number of measuring points	
n	Number of transferred electrons	
P	Power	
P_{el}	Electric power	W
P_{d}	Electric power density	W/m ² , W/cm ²
p	Pressure	
p_{vessel}	Pressure inside containment vessel	kPa
$p_{\text{neg,in}}$	Pressure of negative electrode gas at cell/stack inlet	kPa
$p_{\text{neg,out}}$	Pressure of negative electrode gas at cell/stack outlet	kPa
$p_{\text{pos,in}}$	Pressure of positive electrode gas at cell/stack inlet	kPa
$p_{\text{pos,out}}$	Pressure of positive electrode gas at cell/stack outlet	kPa
p_0	Standard pressure (101,325)	kPa
q_V	Volumetric flow rate	
$q_{V,\text{neg,in}}$	Total volumetric flow rate at negative electrode inlet (at STP)	m ³ /s, l/min
$q_{V,\text{pos,in}}$	Total volumetric flow rate at positive electrode inlet (at STP)	m ³ /s, l/min

Symbol	Definition	Unit
$q_{V,neg,out}$	Total volumetric flow rate at negative electrode outlet (at STP)	m ³ /s, l/min
$q_{V,pos,out}$	Total volumetric flow rate at positive electrode outlet (at STP)	m ³ /s, l/min
$q_{V,i,neg,in}$	Volumetric flow rate of gas component i at negative electrode inlet (at STP)	m ³ /s, l/min
$q_{V,i,pos,in}$	Volumetric flow rate of gas component i at positive electrode inlet (at STP)	m ³ /s, l/min
$q_{V,i,neg,out}$	Volumetric flow rate of gas component i at negative electrode outlet (at STP)	m ³ /s, l/min
$q_{V,i,pos,out}$	Volumetric flow rate of gas component i at positive electrode outlet (at STP)	m ³ /s, l/min
R	Resistance, universal gas constant	
R	Resistance	Ω
R_{ASR}	Area-specific resistance	$\Omega \cdot m^2$, $\Omega \cdot cm^2$
R_{LF}	Low frequency resistance	Ω
R_{HF}	High frequency resistance	Ω
R_{ohm}	Ohmic resistance	Ω
$R_{non-ohm}$	Non-ohmic resistance	Ω
R_g	Universal gas constant (8,3145)	J/(mol·K)
T	Temperature	
$T_{cell/stack}$	Temperature of the cell or stack	°C, K
$T_{stack,av}$	Average temperature of the stack	°C, K
$T_{stack,intern}$	Internal stack temperature	°C, K
T_{BP}	Temperature of bottom plate	°C, K
T_{TP}	Temperature of top plate	°C, K
$T_{furnace}$	Temperature of the furnace	°C, K
T_{min}	Minimum temperature during cycling	°C, K
$T_{neg,in}$	Temperature of negative electrode gas stream at cell/stack inlet	°C, K
$T_{pos,in}$	Temperature of positive electrode gas stream at cell/stack inlet	°C, K
$T_{neg,out}$	Temperature of negative electrode gas stream at cell/stack outlet	°C, K
$T_{pos,out}$	Temperature of positive electrode gas stream at cell/stack outlet	°C, K
$T_{PH,neg}$	Temperature of the pre-heater for preheating the negative electrode gas stream	°C, K
$T_{PH,pos}$	Temperature of the pre-heater for preheating the positive electrode gas stream	°C, K
T_0	Standard temperature (273,15)	K
ΔT_{max}	Maximum temperature difference between reactants and the stack temperature during start-up	K
t	Time	s, min, h
t_{acq}	Data acquisition time	s, min, h
t_{dwell}	Dwell time	s, min, h
t_{eq}	Equilibration time	s, min, h
t_{op}	Duration time of operation at given conditions	s, min, h
t_0	Initial time	
t_1	End time	

Symbol	Definition	Unit
U	Utilization	
$U_{\text{gas,neg}}$	Reactant utilization at the negative electrode (fuel utilization in fuel cell mode, steam conversion in electrolysis mode)	
$U_{\text{gas,pos}}$	Reactant utilization at the positive electrode (air utilization or oxygen utilization, valid only in fuel cell mode)	
V	Voltage	
V_{cell}	Voltage of the cell	V
V_{stack}	Voltage of the stack	V
$V_{\text{RU},i}$	Voltage of repeating unit (RU) i in the stack	V
$V_{\text{RU,av}}$	Average RU voltage of all RU in the stack	V
$\underline{V}$	Fourier transform of AC part of cell/stack voltage response	V
V_{pk}	Amplitude of alternating voltage	V
v	Excitation voltage (potentiostatic mode), voltage response (galvanostatic mode)	V
x	Fraction	
x_i	Molar fraction of component i	mol/mol
$x_{i,\text{neg,in}}$	Molar fraction of component i in the negative electrode gas stream inlet at cell/stack	mol/mol
$x_{i,\text{neg,out}}$	Molar fraction of component i in the negative electrode gas stream outlet at cell/stack	mol/mol
$x_{i,\text{pos,in}}$	Molar fraction of component i in the positive electrode gas stream inlet at cell/stack	mol/mol
$x_{i,\text{pos,out}}$	Molar fraction of component i in the positive electrode gas stream outlet at cell/stack	mol/mol
$x_{\text{H}_2\text{O}}$	Steam molar fraction	mol/mol
x_{O_2}	Oxygen molar fraction	mol/mol
$\underline{Y}, \underline{Z}$	Admittance, impedance	
$\underline{Y}$	Admittance	S
	Specific admittance	$\text{S}\cdot\text{m}^{-2}$, S cm^{-2}
$\underline{Y}'$	Real part of admittance (conductance)	S
	Real part of specific admittance	$\text{S}\cdot\text{m}^{-2}$, S cm^{-2}
$\underline{Y}''$	Imaginary part of admittance (susceptance)	S
	Imaginary part of specific admittance	$\text{S}\cdot\text{m}^{-2}$, S cm^{-2}
$\underline{Z}$	Impedance	Ω
	Specific impedance	$\Omega\cdot\text{cm}^2$, $\Omega\cdot\text{m}^2$
$ \underline{Z} $	Modulus of impedance	Ω
	Modulus of specific impedance	$\Omega\cdot\text{cm}^2$, $\Omega\cdot\text{m}^2$
$\underline{Z}'$	Real part of impedance (resistance)	Ω
	Real part of specific impedance	$\Omega\cdot\text{cm}^2$, $\Omega\cdot\text{m}^2$
$\underline{Z}''$	Imaginary part of impedance (reactance)	Ω
	Imaginary part of specific impedance	$\Omega\cdot\text{cm}^2$, $\Omega\cdot\text{m}^2$
$\Delta\alpha$	Degradation rate	
$\Delta\alpha_{\text{rel}}$	Relative degradation rate	
ω, φ	Angular frequency, phase angle	
ω	Angular perturbation frequency	

Symbol	Definition	Unit
$\omega_{\min}$	Minimum frequency for EIS spectra	rad/s
$\omega_{\max}$	Maximum frequency for EIS spectra	rad/s
φ	Phase angle	rad, °
NOTE 1 The standard temperature and pressure (STP) values for gas temperature and pressure are specified as follows: $T_0 = 273,15 \text{ K}$ $p_0 = 101,325 \text{ kPa}$ NOTE 2 To express the rate of change of a certain parameter x, a dot above the parameter symbol can be used. For instance, $\dot{T}$ can be used to express the temperature ramp with a unit of K/s, $\dot{q}_v$ used to express the speed of variation of the gas flow rate with a unit of (m³/s)/s. Alternatively, $(\Delta x/\Delta t)$ can be used. For instance, the temperature ramp can be expressed by $(\Delta T/\Delta t)$ and the speed of current density variation can be expressed by $(\Delta j/\Delta t)$. NOTE 3 About the amplitude of alternating current/voltage with a sine waveform for electrochemical impedance spectroscopy (EIS) measurement: it refers here to the peak amplitude. It amounts to half of the peak-to-peak amplitude and $\sqrt{2}$ times the root mean square (RMS) amplitude. NOTE 4 The real part of impedance (resistance) and imaginary part of impedance (reactance) can also be represented by $Re(\underline{Z})$ and $Im(\underline{Z})$, respectively. NOTE 5 The quantity $\Delta\alpha$ chosen for calculating the degradation rate can be the cell or stack voltage, current, power density or ASR, each with their own unit.		

3.3 Flow rates

In this document, volumetric flow rates are used, following common practice. Volumetric flow rate can however be replaced in principle by mass flow rate, taking into consideration the molar mass and density of the species considered.

4 General safety conditions

An operating SOC cell/stack assembly unit uses oxidizing and reducing, combustible gases. Typically, these gases are stored in high-pressure containers. The SOC cell/stack assembly unit itself may be operated at pressure greater than atmospheric pressure.

The solid oxide cell/stack in particular operates at high temperatures, typically above 600 °C, which are higher than the spontaneous ignition temperatures of both hydrogen (565 °C) and methane (537 °C). Those who carry out cell/stack assembly unit testing shall be trained and experienced in the operation of test systems and specifically in safety procedures involving electrical equipment, hot surfaces and fluids (e.g. steam), and (reactive) compressed gases handling.

The test personnel are responsible for obtaining and following all applicable safety codes and generally accepted engineering practices related to their test system, facility, fuels (with particular attention to compressed gases), and exhaust products.

Materials which are compatible with the use and storage of the reactant gases shall be used during testing. Local safety codes and standards for working with hydrogen, hydrocarbons and carbon monoxide, shall be followed.

In summary, safely operating a test station requires appropriate technical training and experience as well as safe facilities and equipment, all of which are outside the scope of this document.

Nevertheless, a number of empirical guidelines can be given for good practice while carrying out the experimental tests, which can help identify potentially hazardous situations. Operating conditions of the SOC cell/stack assembly unit have to be carefully monitored as a means of securing safety through an appropriate emergency shutdown system.

- Gas sensors: It is recommended to have gas sensors in close proximity to the test station (in particular for H_2), which are connected to an automated emergency shutdown system that cuts off negative electrode gas feed to the test station if hazardous concentrations of said gases are measured.
- Protection gas supply: In the case of emergency shutdown, it is recommended that a line containing an inert, reducing gas ("protection gas") be employed for the flushing of the negative electrode side of the SOC cell/stack assembly unit. The hydrogen fraction in the protection gas shall be low enough (usually 3 % to 5 %) to avoid the formation of an explosive atmosphere. It shall be high enough to keep a reducing atmosphere at the negative electrode of the SOC cell/stack assembly unit to avoid the re-oxidation of the constituent transition metal. This also helps to expel flammable reactants from the system.
- Care shall be taken that exhausted hydrogen is adequately dealt with. For small hydrogen flow rates (relative to the confined space where testing takes place), it can be sufficient to dilute the exhaust gas from the negative electrode with air or inert gas before venting. If large stacks are used, it is advised to adopt a (catalytic) afterburner before venting.
- Care shall be taken that oxygen produced in electrolysis mode is adequately dealt with. This shall be ventilated to the exterior in order to avoid accumulation of oxygen-enriched air especially in confined spaces.
- In fuel cell mode, care shall be taken that the positive electrode exhaust gas will be air depleted in oxygen, and therefore shall be adequately dealt with.
- In all cases, an adequate risk assessment considering the place of testing and operating conditions shall be conducted and appropriate risk reduction measures taken.

This by no means claims to be an exhaustive or even sufficient list for safe operation during testing. However, it is recommended to consult ISO/TR 15916 and the safety measures have to be mandatorily designed following local legal requirements.

5 Test environment

5.1 General

The test environment consists of the test object (a SOC cell/stack assembly unit) mounted within the experimental set-up. The SOC cell/stack assembly unit consists of a cell or stack, gas supply, current leads and such other peripherals as required for tests in fuel cell and electrolysis modes. It shall be provided with single or multiple measuring points for temperature and voltage and one set of current lead points, all to be specified by the manufacturer.

The boundary of a cell/stack assembly unit goes through the negative electrode gas supply port, positive electrode gas supply port, negative electrode gas exhaust port, positive electrode gas exhaust port, the temperature measuring points, current lead points, voltage measuring points and compression force application points.

Some cell/stack assembly units may have no supply port or exhaust port for the electrode gases because of the configuration of their cell(s). In such cases, the gas flow field pattern and its material shall be determined by the method recommended by the manufacturer. The compression force application method shall be also based on the recommendation of the manufacturer.

If the components of a cell/stack assembly unit other than a cell/stack are not specified by the manufacturer, the following shall be described in the test report:

- a) materials and geometry of the peripheral components to be used for testing;

- b) flow patterns and directions of negative electrode and positive electrode gas;
- c) locations of temperature measurement, compression force application, voltage measurement and current extraction;
- d) magnitude of the compression force;
- e) configuration of assembly unit and its assembling method.

5.2 Cell

Figure 1 shows a single cell test object (for explanatory purposes, planar geometry is shown, but the principle applies to tubular geometries as well), as an assembly of two electrodes (with contact layers) and the electrolyte which is integrated in a cell housing. For testing a cell ideally, the cell housing design and materials are optimized in such a way so as not to have an influence on cell performance measurement. Therefore, usually the electrical contact resistances of the electrodes in the cell housing are negligible and the supply of the electrodes with gases in the cell housing is presumed ideal.

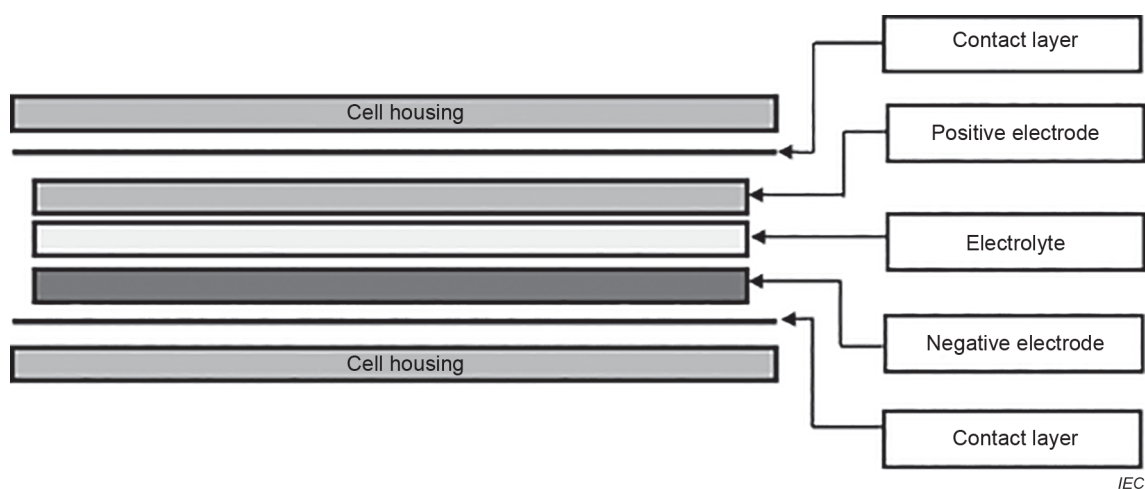
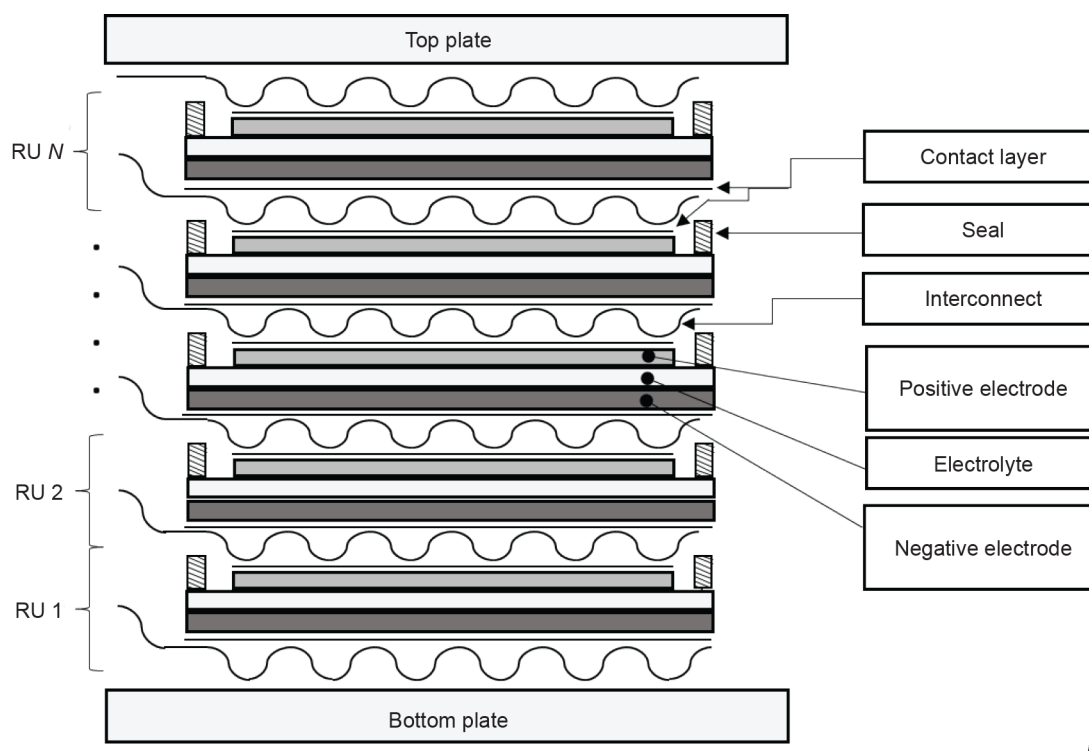


Figure 1 – Exploded schematic representation of a planar-type single cell test object consisting of a SOC in a cell housing

5.3 Stack

Figure 2 shows the schematic representation of a SOC stack test object, consisting of multiple repeating units (RUs) which are assembled in series (for explanatory purposes, planar geometry is shown, but the principle applies as well to tubular geometries). Electrical contacts and the gas distribution are provided by interconnects and the top/bottom plates. The stack results are generated by the repeating units, which can be influenced by electrical contact and gas flow conditions.



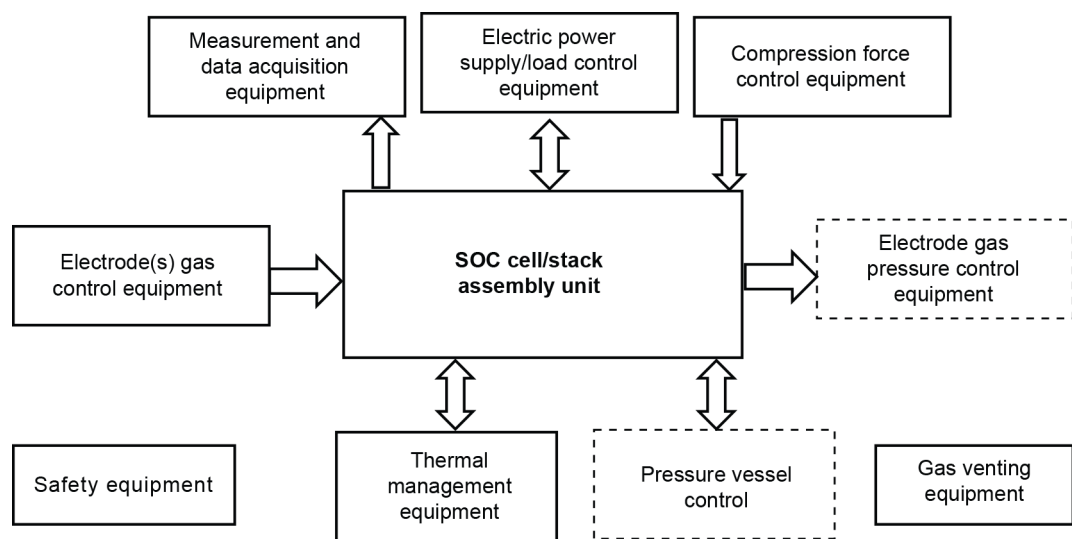
IEC

Figure 2 – Schematic representation of a planar-geometry SOC stack test object with N RU including supporting structure (top and bottom plates)

5.4 Experimental set-up

5.4.1 General

Figure 3 shows a schematic representation of a test environment which consists of the SOC cell/stack assembly unit (test object) and the corresponding test and control equipment, divided into different subsystems. All equipment is considered mandatory in Figure 3. In the case of pressurized operation, the equipment in dashed lines is required in addition. The test object is exposed to test inputs or operational conditions and delivers test outputs or object test results.



IEC

Figure 3 – Schematic representation of a test environment for a SOC cell/stack assembly unit

The equipment can be classified according to the physical properties controlled, which are of media, electrical, thermal, mechanical and data type. Especially for high temperature solid oxide systems, the temperature control equipment and the gas control equipment (flow rate, pressure) play an important role for the test output results. Moreover, the complexity of the test environment is significantly increased when the operation mode is changed from steady state operation to dynamic operating conditions.

5.4.2 Electrode gas control equipment

The electrode gas control equipment controls the flow rate, composition, and temperature of reactant gas supplied to the cell/stack assembly unit. If the gas composition is to be maintained throughout the piping, then attention shall be paid to the materials, temperature, inner diameter and length of the piping. Where necessary, the piping shall be heated and/or thermally insulated in order to prevent condensation of water vapour.

5.4.3 Thermal management equipment

The thermal management equipment controls at least the electric furnace and, usually indirectly, additional temperature control can be carried out on reactant gas preheating. Its objective is to set the unit temperature at the operating temperature. The electric furnace shall be selected to maintain the temperature distribution within the specified tolerance level. Efforts shall be made to minimize the electrical noise that the electric furnace generates while providing heat. It is assumed that all the test systems will use an electric furnace for simplicity and safety reasons.

5.4.4 Electric power supply/load control equipment

The electric power supply/demand control equipment subsystem controls the output/input current or output/input voltage of the cell/stack assembly unit.

5.4.5 Measurement and data acquisition equipment

The measurement and data acquisition equipment acquires and records the cell/stack assembly unit temperature, current, voltage, electrode gas flow rate, reactant gas composition, electrode gas temperature and pressure, and optionally environmental conditions (ambient temperature, relative humidity and atmospheric pressure) by the specified methods. If necessary, it also acquires and records the compression force applied to the cell/stack assembly unit, impedance data etc., by the specified method. The gas composition shall be recorded, but does not have to be measured in real time.

5.4.6 Safety equipment

The safety equipment shall consist of detectors, actuators and an alarm system for alerting malfunctioning of the test system based on predefined parameters and criteria. If it detects a serious fault, then it shall automatically establish a safe state in the test system. The electrode compartments should be purged with an inert gas, such as nitrogen which, in the negative electrode compartment, could also contain hydrogen below the lower flammability limit, to avoid oxidation of the negative electrode.

5.4.7 Compression force control equipment

The optional, compression force control equipment regulates the compression force that is applied to increase the contact among components and to obtain gas-tightness in the cell/stack assembly unit. The equipment shall be strong enough to apply the required compression force under the test condition and to maintain the load for long term operation.

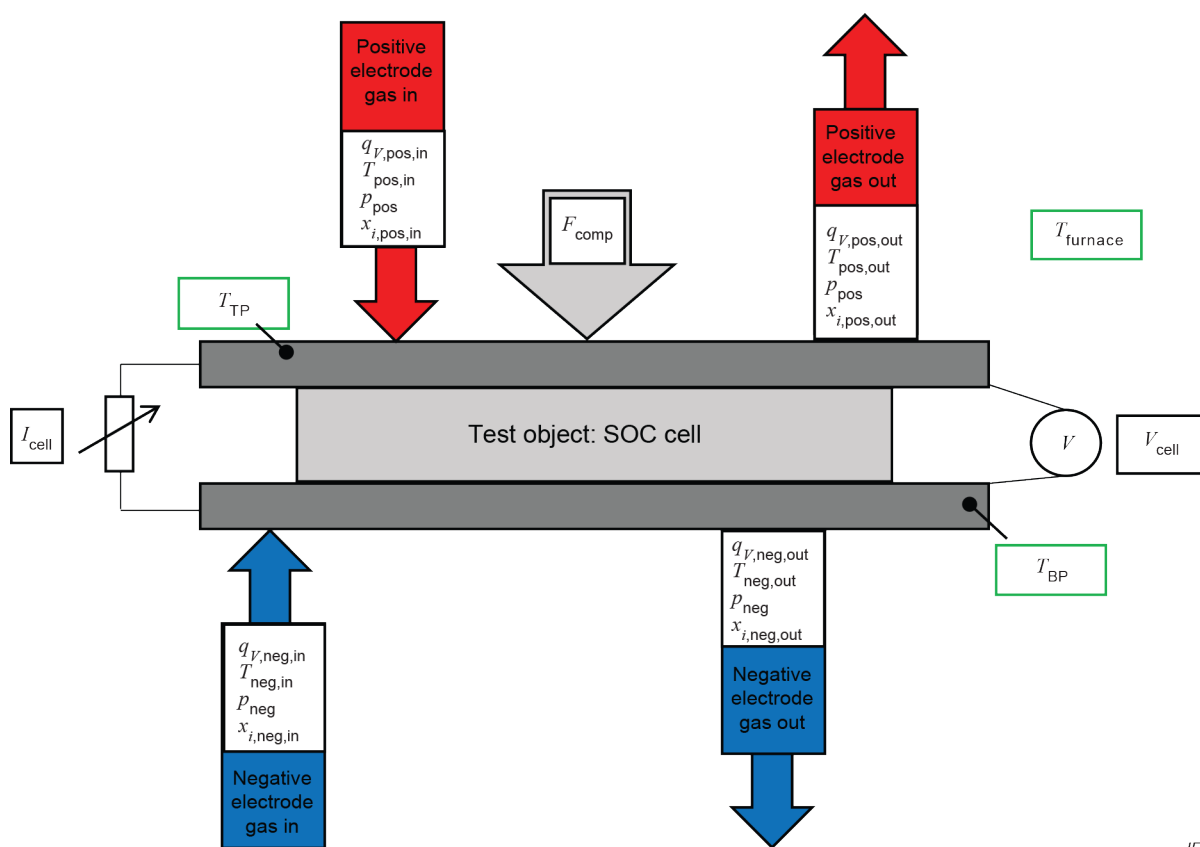
5.4.8 Pressure control equipment

The optional, gas pressure control equipment for electrode gases regulates the pressure of these gases by the use of a backpressure control valve, etc.

If the SOC cell/stack assembly unit is operated at an elevated pressure, adequate control equipment controls the pressure in the pressurized vessel.

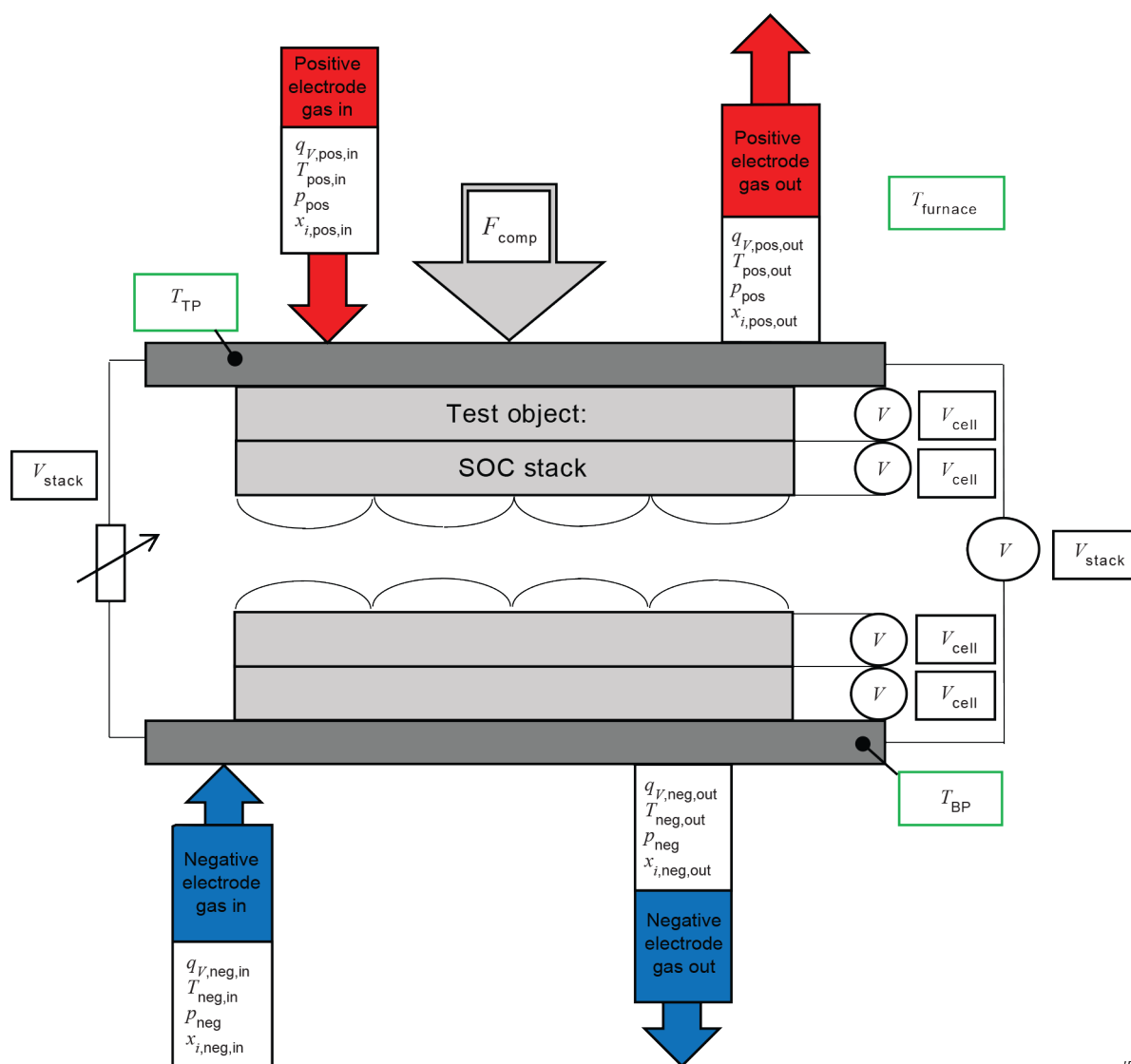
5.5 Interface between test object and experimental set-up

Figure 4 and Figure 5 show the physical interfaces between the SOC cell/stack test object and the experimental set-up (for explanatory purposes, planar geometry is shown, but the principle applies to tubular geometries as well). The physical interfaces between the experimental set-up (test station) and the SOC cell/stack test object can be separated in media, electric, heat and mechanic interfaces. Media interfaces are the reactants inlet and outlet; electric interfaces are the load and power supply and voltage wiring; heat interface is the furnace and the mechanic interface is to mount the cell/stack on the test station which may supply compression force to the cell/stack. These interfaces will be defined by different physical parameters. Depending on the test objective these physical parameters can be either of input nature (test input parameter, or TIP) or of output nature (test output parameter, or TOP).



IEC

Figure 4 – Test environment with interfaces between SOC cell and experimental set-up



IEC

Figure 5 – Test environment with interfaces between SOC stack and experimental set-up

5.6 Parameter control and measurement

For the fluids at cell/stack inlet and/or outlet the relevant parameters are:

- Temperature, $T_{neg,in}$, $T_{pos,in}$, $T_{neg,out}$ and $T_{pos,out}$
- Volumetric flow, $q_{V,neg,in}$, $q_{V,pos,in}$, $q_{V,neg,out}$, $q_{V,pos,out}$
- Pressure, $p_{neg,in}$, $p_{pos,in}$, $p_{neg,out}$ and $p_{pos,out}$
- Molar fraction of component i , $x_{i,neg,in}$, $x_{i,pos,in}$, $x_{i,neg,out}$ and $x_{i,pos,out}$

The electric interface parameters are:

- Cell/stack current (a common synonym is stack load), I
- Stack voltage, V_{stack}
- Voltage of cell or the individual repeating units, V_{cell} or $V_{RU,i}$

As regards the current, if necessary, for example when operating in reversible mode, by convention, the current is taken to be negative in electrolysis mode, and positive in fuel cell mode.

The thermal interface parameters are:

- Furnace temperature, T_{furnace}
- Stack top plate temperature, T_{TP}
- Stack bottom plate temperature, T_{BP}
- Any other temperature measurement points aimed to quantify cell/stack temperature $T_{\text{cell/stack}}$ or $T_{\text{stack,intern}}$

The mechanical interface parameter is:

- Cell or stack compression force, F_{comp}

5.7 Measurement uncertainty of TIPs and TOPs

The process of determining the uncertainty of TIPs and TOPs measurement is an extensive process beyond the scope of this document. Details can be found in ISO/IEC Guide 98-3.

5.8 Mounting of the test object into the experimental set-up

When mounting the test object into the test system some test-related factors shall be considered in addition to the general safety precautions of the test system.

When testing a single solid oxide cell, the cell is mounted within a cell housing system, which provides gas connections and possible sensory connections similar to a stack assembly. When mounting a cell within a cell housing, some general considerations have to be made to ensure that the influence of the test set-up on the results is minimized:

- electrical contact to both the negative and positive electrodes has to be ensured; this is done by ensuring actual mechanical contact of the cell to the contact components, and by having sufficient contact points to avoid current restrictions.
- the cell has to be sufficiently leak-tight to avoid significant mixing of the test gases with other gases, before and after passing the negative or positive electrodes.
- the impact of potential contaminants (sulphur, phosphorous, halides, etc.) from components used in the cell housing shall be limited.
- mechanical stresses transferred to the tested cell from the cell housing components have to be avoided, to prevent any potential cracking of the cell during testing.
- furthermore, flow fields at the electrodes have to distribute the gas evenly, and without a potential turbulent flow, to avoid gas starvation and mass transport limitations at the electrodes.

When the above mentioned considerations are adequately taken care of, the cell test fixture can be handled similar to a stack assembly.

When the cell/stack assembly has to be mounted in the test set-up, it has to be securely positioned, to avoid accidental movement during testing. Electrical connections have to be properly done and gas connections securely tightened, while sharp bends of the gas tubes shall be avoided. Furthermore, the gases fed into the cell test system have to be preheated to the ambient furnace temperature, to avoid a significant temperature difference at the gas inlet. Any additional weight on the cell test fixture/stack assembly has to be levelled off to avoid uneven weight distribution.

5.9 Stability criteria

To evaluate the influence of operating conditions on the cell/stack performance, a certain degree of stability of both TIPs and TOPs is required. One simple option to evaluate stability is to record a parameter with a desired sampling rate for a desired sampling duration. The parameter is considered stable if the maximum variation (difference between the maximum value and the minimum value recorded) does not exceed a pre-defined threshold value.

Nevertheless, the following stability criteria can be taken as recommendations and can be adapted according to the test object, test system and test objective. The judgement criteria for a stable state shall be determined through preliminary testing and shall be described in the test report.

NOTE The voltage stability criterion in SOEC mode is less strict, since it is difficult to maintain stable steam supply at laboratory scale.

Table 2 – Stability criteria for TIPs and TOPs as a reference

Parameter	Sampling rate	Sampling duration	Variation threshold
$V_{\text{cell}}, V_{\text{RU},i}$	1 Hz	3 min	±5 mV (SOFC mode) ±10 mV (SOEC mode)
J	1 Hz	3 min	±5 mA/cm ² (or 1 % of rated current density)
T	1 Hz	3 min	±3 K
$q_{V,\text{neg/pos,in/out}}$	1 Hz	3 min	±3 % full scale
$p_{\text{neg/pos,in/out}}$	1 Hz	3 min	±3 % full scale
x_i	1 Hz	3 min	±0,02 mol/mol for each gas component
$x_{\text{H}_2\text{O}}$	1 Hz	3 min	±0,05 mol/mol for steam

6 Measurement instruments and methods

6.1 General

Measuring instruments shall meet the requirement of 6.2 as a minimum: the flow rate and composition of the electrode gases, cell/stack assembly unit temperature, voltage and current shall be measured. Additional measurements shall be taken based on the test parameters and/or test conditions.

6.2 Instrument uncertainty

The measuring parameters listed in Table 3 shall be recorded and stored with a sampling rate fast enough to ensure that all relevant changes in the parameters are recorded for later data analyses. The sampling rate frequency is recommended to be 1 Hz or higher.

The expanded uncertainty of each measuring instrument (coverage factor $k = 2$) at the time of calibration or that estimated from the class of instrument shall be as specified in Table 3.

NOTE The stated values for instrument uncertainty are derived from the European pre-normative research project SOCTESQA (see Bibliography).

Table 3 – Instrument uncertainty for each quantity to be measured

Symbol	Quantity	Instrument uncertainty
I	Current	± 1 % relative to rated
V	Voltage	$\pm 0,5$ % relative to OCV
T	Temperature	$\pm 2,5$ K or 0,75 % of reading
$q_{V,neg,pos,in/out}$	Volumetric flow rate at STP	± 2 % of rated
x_i	Molar fraction	$\pm 0,02$ mol/mol
x_{O_2}	Oxygen molar fraction	$\pm 0,003$ mol/mol relative to O_2 concentration (balance in N_2)
$p_{neg,pos,in/out}$	Pressure	± 1 % of reading

Each measuring instrument shall be checked for its last calibration, the uncertainty under the calibration conditions, or estimated from the class of the instrument, and its dependency on the environmental conditions in order to estimate the uncertainty of the instrument.

6.3 Recommended measurement instruments and methods

6.3.1 Electrode inlet gas flow rate measurement

The gas flow rate at the positive and negative electrode inlets shall be measured using mass flow meters, volumetric flow meters or turbine-type flow meters. The flow meter shall be selected in consideration of the expected range of flow rates and the allowable uncertainty, and of the species in the supplied gas. The flow rates shall be converted to volumetric flow rate at STP. The flow meter shall be selected considering the expected range of flow rates and the allowable uncertainty of the flow meter. Uncertainty shall be evaluated in accordance with ISO 5168 or ISO 7066-2.

6.3.2 Electrode gas composition measurement

Depending on whether the objective is to measure inlet or outlet composition, the electrode gas composition shall be sampled near the electrode gas supply or exit port, respectively, of the cell/stack assembly unit and analysed using an infrared spectroscopy, mass spectrometer, gas chromatograph or similar device. At the positive electrode specifically, oxidant concentration can be measured using an oxidant concentration meter.

The gas sample shall be transported from its origin to the point of analysis in a manner which minimizes changes in composition. Thus, the material temperature, diameter and the length of the tubing shall be carefully chosen to minimize the compositional change in the sampling tubing. When it is necessary to measure humidity, a dew point meter, water content meter, or gas chromatograph shall be used, while controlling gas temperature to prevent condensation of water vapour. On the other hand, if water vapour may negatively affect measurement, remove water from the gas sample or dilute the gas sample with argon or similar inert gas.

The result of the analysis for gas component i shall be normalized to obtain a normalized concentration of component i , using the following equation:

$$x_i = \frac{c_i}{\sum_i c_i} \quad (1)$$

where

x_i is the molar fraction of component i (mol/mol);

c_i is the concentration (result of the analysis) of gas component i (mol/m³);

$\sum_i c_i$ is the sum of concentrations of all component gases in the analysis.

Considering that the ideal gas law applies for the operating conditions commonly encountered in SOC, the gas analyzer shall be calibrated using a standard gas of known mass ratio.

The measurement uncertainty shall be evaluated in accordance with ISO 6974 (all parts), ISO 6141, ISO 6142-1 or ISO 6143.

The electrode gas composition shall be measured when the performance of the cell/stack assembly unit is measured. If this is not possible, however, the electrode gas composition shall be measured during the preparation of the performance test under the same conditions as those of the cell/stack performance test.

When negative electrode gas is supplied in one of the following methods and if the gas supply line has no reactors (such as a reformer for example) and it is confirmed that insignificant changes in gas composition occur, composition may be calculated based on the composition table published by the gas supplier and values obtained from each flow meter, in accordance with ISO 6145-7:

- a) if a single-constituent gas such as hydrogen is supplied;
- b) if a mixed gas of known composition is supplied;
- c) if electrode gas is supplied by mixing gases in a controlled manner using multiple flow meters;
- d) if gases under b) and c) above are supplied in combination.

6.3.3 Electrode gas temperature measurement

Gas temperature shall be measured at the inlet and outlet of the cell/stack by using thermocouples placed in the gas stream line near the electrode gas supply/exit port of the cell/stack assembly unit by using thermocouples or sheathed thermocouples, and an extension leadwire of the type and class in accordance with IEC 61515, IEC 60584-1, or IEC 60584-3. When there is a reactor in the reactant supply line, such as a reformer, gas temperature at the exit of the reactor shall also be measured. If it is difficult to measure the gas temperature during the cell performance test, the electrode gas temperature shall be measured during the preparation of the performance test under the same conditions as those of the performance test.

6.3.4 Electrode gas pressure measurement

Electrode gas pressure shall be measured upstream of the gas supply port of the cell/stack assembly unit by using a pressure sensor, manometer, Bourdon tube, or similar instrument. The measuring instrument shall be located in such a manner that the uncertainty is minimized in consideration of any pressure loss within the piping, of piping temperature, and other factors. Condensation of water vapour shall be prevented during measurement. A good example may be to measure the pressure by injecting a very small amount of dry nitrogen gas or similar into the pipe close to the measuring instrument.

6.3.5 Electrode exhaust gas flow rate measurement

The electrode product gas flow rate shall be measured using a mass flow meter, volumetric flow meter or turbine-type flow meter after cooling the gas and – specifically for the negative electrode flow – implementing a means to prevent water condensation from affecting the stability of gas flow or after removing water from the gas flow. Alternatively, the product gas flow rate may be calculated from the constituent concentrations of the exhaust gas, tracer concentration, and tracer flow rate by precisely adding a minute amount of a gas that is not contained in the product gas as tracer. The gas analyser shall be calibrated using a standard gas of known mass ratio. The measurement uncertainty shall be evaluated in accordance with ISO 6974 (all parts), ISO 6141, ISO 6142-1, or ISO 6143.

The negative electrode exhaust gas shall be handled with caution for safety and the environment since it may still contain significant amounts of hydrogen, and other hazardous gases.

The flow rates shall be converted to volumetric flow rate at STP. The flow meter shall be selected considering the expected range of flow rates and the allowable uncertainty of the instrument. The uncertainty of the instrument shall be evaluated in accordance with ISO 6974 (all parts), ISO 6141, ISO 6142-1, ISO 6143, or ISO 6145-7.

6.3.6 Cell/stack assembly unit voltage measurement

A voltage meter shall be connected to the voltage measuring points described in Clause 5. The voltage thus measured shall be deemed to be the voltage of the cell/stack assembly unit. In the case of a series connection of repeating units (RUs), this voltage corresponds to the sum of the voltages of all RUs in the stack. The connecting cable shall be durable enough for the test conditions. Attention should be paid to the thermal electromotive force at the connection.

Voltage probes shall be placed as close as possible to the cell/stack terminals to prevent the measure from being affected by losses on the cables. Voltage losses can be relevant at high temperature.

6.3.7 Cell/stack assembly unit current measurement

A galvanostat or electric load connected to the current drawing points, as described in Clause 5, and/or a current sensor, such as a shunt resistor, located within the current circuit shall be used to measure the current by sending its output to a measuring/recording instrument. The connecting cable shall be selected for appropriate materials and geometry considering the test conditions and possible voltage drop within the cable.

Electric current shall be measured directly by the electrical load in fuel cell mode or by the power supply in electrolysis mode. Current can also be measured by using a shunt resistor on the power cables.

6.3.8 Cell/stack assembly unit temperature measurement

A thermocouple or sheathed thermocouple, and an extension leadwire of the type and class that are appropriate shall be selected in accordance with IEC 61515, IEC 60584-1, or IEC 60584-3. They shall be placed at the temperature measuring point as described in Clause 5 and connected with a recorder or similar for measurement. When there is more than one temperature measuring point, the unit temperature and its distribution shall be obtained by the calculation method recommended by the manufacturer.

6.3.9 Compression force measurement

A compression force applied as recommended by the manufacturer shall be measured.

6.3.10 Total impedance measurement

The overall impedance of the cell/stack assembly unit shall be measured by either the electrochemical impedance spectroscopy (EIS) or the current interruption method. An appropriate measuring line shall be used in order to ensure high-quality data over the entire frequency range investigated. Care should be taken in the set-up and execution of the measurement to minimize stray capacitance and/or inductances of the measured impedance not originating in the cell/stack unit assembly.

NOTE For guidelines for the EIS method, see 7.6. For guidelines for the current interruption method, see IEC TS 62282-7-2:2014.

6.3.11 Ambient condition measurement

The ambient temperature, pressure, and relative humidity of the laboratory environment may be measured during testing. Sampling interval shall be the value specified in ISO 8756 or less.

6.4 Test conditions and manufacturer recommendations

6.4.1 Start-up and shut-down conditions

The start-up conditions, such as heating rate and test environment conditions during the heating ramp, the condition of the negative electrode (that is, for example, the extent of reduction of the nickel oxide to nickel), and the shut-down conditions, such as cooling rate and test environment conditions during the cooling ramp, shall be based on those recommended by the manufacturer or the results of preliminary tests.

6.4.2 Range of test conditions

The test conditions and the typical test ranges that are recommended by the cell/stack assembly unit manufacturer shall be reviewed in the following parameters in order to determine the test conditions and ranges:

- a) cell/stack assembly unit temperature;
- b) allowable cell/stack assembly unit temperature distribution (if multiple measuring points);
- c) negative electrode gas flow rate;
- d) negative electrode gas composition;
- e) negative electrode gas pressure;
- f) negative electrode gas temperature;
- g) positive electrode gas flow rate;
- h) positive electrode gas composition;
- i) positive electrode gas pressure;
- j) positive electrode gas temperature;
- k) effective reactant utilization at the negative electrode (also called fuel utilization in fuel cell mode, or steam conversion in electrolysis mode);
- l) effective oxygen utilization;
- m) current or current density;
- n) minimum/maximum cell/stack assembly unit voltage;
- o) compression force.

Within these ranges of test conditions, a reference condition shall be defined which acts as a baseline for the assessment of test results.

6.4.3 Stabilization, initialization conditions and stable state

After start-up, the manufacturer may recommend a period of stabilization, or initialization before the cell/stack assembly unit is ready for characterization. Alternatively, this can be based on preliminary tests, to ensure that the output drift at the time of measurement – due to on-going stabilization or initialization of the cell/stack assembly unit – is insignificant.

Once the cell/stack assembly unit is initialized, the tolerance level shall be determined as variation of the output current or output voltage of the cell/stack assembly unit, and the resulting acceptance criteria for stable state shall be defined.

6.4.4 Dwell time, equilibration time, acquisition time

During a test, the operating conditions are held constant for a specific time t_{dwell} (see Figure A.2), where t_{dwell} comprises the period of equilibration time (t_{eq}) and of data acquisition time (t_{acq}). The equilibration times starts with t_{dwell} and ends with the starting of t_{acq} , as illustrated in Figure A.2, which is when the readings meet the stability requirements as in 5.9.

6.5 Data acquisition method

Preliminary tests shall be conducted while taking into consideration the variation of each test parameter and the sampling rate of each measuring instrument, amongst other things, to determine the sampling interval and the number of samplings and measurements. The sampling interval (e.g. 1 s) shall be short enough to observe the variation for a single measurement parameter with sufficient time resolution. The number of samplings and repetitions for a single measurement shall be decided so that the total measurement period becomes sufficiently longer than the dominant variation cycle of each test parameter.

7 Test procedures and computation of results

7.1 General

Due to the intrinsic functionality of a solid oxide cell (SOC), the following test procedures may address different operation modes: fuel cell mode (SOFC), electrolysis mode (SOEC) and reversible or regenerative mode (Re-SOC). Each of these cases will investigate performance and durability, and can be tailored to fit a specific test objective, reflecting for example a typical application, such as wind power peak shaving or others. In the frame of this document, the objective is to align the following test procedures as much as possible with the requirements of systems for power storage and buffering (see IEC 62282-8-201). Test procedures already described in IEC TS 62282-7-2 and that are directly applicable to SOCs operated in fuel cell or reversible mode are not repeated in this document.

For all the following tests, it is recommended that a benchmark test is carried out at reference conditions (see 6.4.2).

NOTE More details on the following tests are provided in Annex A.

7.2 Current-voltage characteristics test

7.2.1 Objective of this test

The objective of this test is to characterize the response of a SOC while operating at different current densities either in fuel cell mode, in electrolysis mode or in reversible mode. The test aims to measure the voltage of the SOC as a function of the current density (current-voltage characteristics or J - V curve) either at constant flow or at constant reactant utilization. From the J - V curve resulting from this test and the active surface area, the area-specific resistance (ASR) can be computed.

7.2.2 Test method

The main action of the test is to determine the cell/stack assembly unit voltage at specified settings of current. The duration of the test depends on the measurement method (number of steps, current increasing/decreasing rate) and whether a specified current or voltage is obtained. The unit shall be operated until the stable state is reached under open-circuit conditions, after which the current-voltage characteristics can be measured.

The test shall be carried out by changing the current stepwise, and recording the cell/stack assembly unit voltage. Measurements shall be taken when the cell/stack assembly unit reaches the stable state in each step, and at each step measurements are taken over the duration of time at the sampling intervals as specified in 5.9.

Alternatively, the voltage can be controlled and the current recorded (in which case the open circuit voltage shall be recorded, since it cannot be controlled). In both cases, instead of stepwise measurements, a sweep of the controlling parameter can be carried out at a constant speed. When a sweep is used, the sweep speed shall be determined such that the maximum width of the recorded parameter's hysteresis does not exceed the parameter variation in the stable state.

7.2.3 Data post-processing

The raw data post processing consists in calculating the average of the measured values from the data sampled during the respective acquisition time of each step (t_{acq}). The calculated averages of voltage and current at each step constitute the current-voltage characteristics of the cell/stack assembly unit.

Furthermore, the following results shall be computed and presented.

The electric power P_{el} and/or the power density P_{d} will be calculated, according to Annex C.

The area-specific resistance, R_{ASR} , is defined by the slope of the current-voltage characteristic curve (dV/dJ) at a specified SOC voltage or current density, depending on the test objective and test conditions. It is determined by linear regression of at least three data points around the target voltage or current density value, obtained during the current density ascending part of the curve. It is recommended that the selected voltage or current density values should lie within the apparent linear regime of the polarization curve. If they do not, then the selected voltage values should lie in a very small window (typically less than 10 mV) for which the voltage response to the current density change may be considered as linear.

In electrolysis mode, large uncertainty can arise due to fluctuation of voltages (in galvanostatic mode) due to the difficulty of maintaining sufficiently stable steam supply in small-scale systems. See Table 2 for acceptable fluctuations.

NOTE 1 This definition of ASR includes the change of potential due to the electrochemical reaction.

The ASR shall be reported along with the voltage and current density values that were used for the calculation and the polarization curve diagram.

The results shall be plotted as SOC voltage, power density and SOC temperature(s) against current density. In addition, reactant utilization, and/or exhaust gas evolution may be plotted. In general, the reported plots shall be representative of the targeted application/test objective.

All relevant test input parameters (TIPs), test output parameters (TOPs) and derived quantities for this test are provided in Clause A.3.

7.3 Effective reactant utilization test

7.3.1 Objective of this test

The objective of this test is to characterize the influence of the reactant utilization on the performance of a SOC cell/stack assembly unit either in fuel cell mode, in electrolysis mode or in reversible mode. The parameters governing the reactant utilization are the current generated (fuel cell) or consumed (electrolysis) by the cell/stack, the fuel/oxidant stream composition and the flow rate of the latter. As an example, in fuel cell mode the reactants are hydrogen (negative electrode) and oxygen (positive electrode) while the product is steam (negative electrode). In electrolysis mode the reactant is steam (negative electrode) and the products are hydrogen (negative electrode) and oxygen (positive electrode).

7.3.2 Test method

The main action of the test is to determine the cell/stack assembly unit voltage at specified settings of reactant utilization. The duration of the test depends on the number of measurement steps and whether a specified voltage is obtained. The unit shall be operated until the stable state is reached under operating conditions specified by the manufacturer (reference condition), after which the flow rate of the targeted electrode is changed to evaluate the voltage response, keeping the current load constant.

In order to evaluate the effect of the flow rate of the (negative or positive) electrode gas stream at the cell/stack inlet, the molar fraction of the reactant shall be kept constant. Hence, in the case of the negative electrode for example, the gas composition shall be kept constant, i.e. the molar composition shall be kept constant. Measurements shall be taken when the cell/stack assembly unit reaches the stable state in each step, and at each step measurements are taken over the duration of time at the sampling intervals as specified in 5.9.

In order to avoid reactant starvation, the reactant flow has to be increased prior to an increase of the current density while the current density has to be decreased prior to reactant flow reduction. Thereby the test stand dynamics have to be taken into consideration, especially if large dead volumes (e.g. long pipes, vessels in series) are present in the test system.

When operating in fuel cell mode, a modification of the reactant utilization in one electrode when varying the current density implies the modification of reactant utilization in the opposite electrode if the volumetric flow and molar fractions of the latter remain unaltered. Therefore, if throughout a part of the test a particular reactant utilization shall remain constant, for instance the positive reactant utilization ($U_{\text{gas,pos}}$), the individual flow rates of the components of the positive electrode gas stream ($q_{V,i,\text{pos,in}}$) taking part in the reaction need to be modified accordingly. It is essential to not alter significantly the volumetric flow as this can induce significant alterations in the operating conditions as this parameter has a strong influence on the thermal and fluid dynamics of the system.

Finally, it is recommended that the test campaign begin with the most benign operating conditions (low utilization) and shift towards harsher conditions (high utilization).

7.3.3 Data post-processing

The raw data post processing consists in calculating the average of the response values from all data sampled during acquisition time of each step (t_{acq}). Furthermore, the following results shall be computed and presented.

The electric power P_{el} and/or the power density P_{d} will be calculated, and reported together with the utilization values calculated according to Annex C.

All relevant test input parameters (TIPs), test output parameters (TOPs) and derived quantities for this test are provided in Clause A.4.

7.4 Durability test

7.4.1 Objective of this test

The objective of this test is to characterize the response of a SOC under constant current (i.e. galvanostatic conditions) or constant voltage (i.e. potentiostatic conditions) either as a fuel cell or as an electrolyser, or in reversible mode. The test aims to measure the long-term endurance of the cell/stack assembly at a given operating condition. Under constant current, from the voltage profile over time resulting from this test the degradation rate can be computed. Under constant voltage, from the current profile over time resulting from this test the degradation rate can be computed.

7.4.2 Test method

The main action of the test is to record the evolution of the cell/stack assembly unit voltage (under constant current operation) or current (under constant voltage operation) in steady-state operation, at constant operating conditions, for either conditioning/standby treatment or long-term endurance tests. Particular attention should be paid to the stability of the operating conditions (temperature, pressure, gas flows and current density) when constant. Also noise on the voltage or current measurement needs to be below a threshold of 1 % of the voltage or current signal to allow degradation rate determination during long-term operation.

Durability tests shall be long enough (at least above 500 h, preferably above 1 000 h) to allow a valid computation of the degradation rate expressed in %/kh.

For significantly long operation times under constant current, it is recommended to carry out current-voltage characteristics tests (7.2) and/or separation of resistance components tests (see 7.6) at regular intervals to monitor the evolution of the ASR.

7.4.3 Data post-processing

A graph presenting the evolution of the cell/stack assembly voltages (V_{stack} , V_{cell} and $V_{\text{RU},i}$) in galvanostatic mode or current (I_{stack} , I_{cell} or I_{RU}) in potentiostatic mode as a function of time shall be reported. It is highly recommended to also provide a graph with the time-evolution of the unit temperatures ($T_{\text{cell/stack}}$).

For a long-term endurance test, the degradation rate is reported as the change in area-specific resistance (ΔR_{ASR}), power density (ΔP_{d}) and voltage (ΔV_{cell} , ΔV_{stack} and $\Delta V_{\text{RU},i}$) or current (ΔI_{cell} , ΔI_{stack} and ΔI_{RU}) over a given duration (Δt) which has to be clearly mentioned. For instance, the first hundred hours are generally disregarded because the cell/stack assembly unit goes through a stabilization phase. Degradation rates are expressed in $\text{m}\Omega \cdot \text{cm}^2$, mW/cm^2 and mV per kh (μV per h) respectively and additionally can be expressed in % of the initial value (per kh or h) for each of the parameters. It is necessary to provide at least those three mutually dependent representations of degradation in order to give a comprehensive representation of the cell/stack assembly unit durability.

The degradation rate can be used to measure both recoverable and permanent losses in cell/stack performance. Depending on the operating mode, the degradation rate can be expressed by the rate of evolution of any quantity of interest, which serves as an indicator of cell/stack performance, for instance electric current, fuel production rate, voltage, electrical power or area-specific resistance. It is recommended to use always a sign before the number to indicate univocally the variation direction of the quantity. A positive sign means that the quantity is increasing with time and a negative sign means that the quantity is decreasing with time. Usually the degradation rate of a cell/stack is a function of time. Therefore, the time frame under which degradation rate is evaluated shall always be indicated.

All relevant test input parameters (TIPs), test output parameters (TOPs) and derived quantities for this test are provided in Clause A.5.

7.5 Temperature sensitivity test

7.5.1 Objective of this test

The objective of this test is to investigate the influence of operating temperature on the cell/stack performance. The parameters that have a predominant role in this test are: furnace temperature, reactant preheating temperatures, current and, optionally, the flow rate of the positive electrode gas stream at the cell/stack inlet. The latter is often used in real-life systems for the thermal management of the stack. To have a complete assessment of the cell/stack assembly unit response, it is recommended to carry out the current-voltage characteristics test (7.2) at the different operating temperatures.

7.5.2 Test method

The main action of the test is to record the cell/stack assembly unit voltage in steady-state operation, at specific conditions, as a function of different unit operating temperature levels. It is recommended to measure the cell/stack temperature at a fixed location which shall be as close as possible to the geometric centre of the cell/stack. Since usually it will not be possible to place a thermocouple (or similar temperature sensor) in the core of a stack, it is suggested to measure the temperature in direct contact with the centre of the end plate(s) of the cell/stack assembly. If direct measurement of the cell/stack temperature is not possible, the oxidant outlet temperature shall be taken as reference, measured as close as possible to the cell/stack outlet.

The stability of the cell/stack temperature during the measurement has to be ensured. Minor temperature variations are acceptable as long as the cell/stack voltage is not notably affected. Since the objective of the test is to determine the influence of cell/stack temperature on performance, changes in the cell/stack temperature caused by electric power variation have to be taken into consideration. In electrolysis mode, this determines the change from a net heat deficit to a net heat surplus of the SOC cell/stack assembly unit (which takes place at the theoretical value of the so-called thermoneutral voltage).

7.5.3 Data post-processing

The raw data post processing consists in calculating the average of the response values from all data sampled during the acquisition time of each step (t_{acq}).

Attending to the difficulties of measuring the temperature in the middle of the stack, a mean stack temperature can be approximated by calculating the average temperature between the top and bottom plates, for example the arithmetic average of the top and bottom plate temperatures:

$$T_{stack,av} = \frac{T_{TP} + T_{BP}}{2} \quad (2)$$

where

$T_{stack,av}$ is the average cell/stack assembly unit temperature;

T_{TP} is the top plate temperature;

T_{BP} is the bottom plate temperature.

or the arithmetic average of all temperatures around the cell/stack assembly unit, for example including those of top and bottom plates, inlet and outlet gases at the negative and positive electrode:

$$T_{stack,av} = \frac{T_{TP} + T_{BP} + T_{neg,in} + T_{neg,out} + T_{pos,in} + T_{pos,out}}{6} \quad (3)$$

where

$T_{neg,in}$ is the temperature of negative electrode gas stream at cell/stack inlet;

$T_{neg,out}$ is the temperature of negative electrode gas stream at cell/stack outlet;

$T_{pos,in}$ is the temperature of positive electrode gas stream at cell/stack inlet;

$T_{pos,out}$ is the temperature of positive electrode gas stream at cell/stack outlet.

The main recorded data – temperatures, voltage and current (optionally the positive electrode reactant flow rate) – shall be reported and shall be represented in one single graph as a function of time.

All relevant test input parameters (TIPs), test output parameters (TOPs) and derived quantities for this test are provided in Clause A.6.

7.6 Separation of resistance components test via electrochemical impedance spectroscopy

7.6.1 Objective of this test

The main objective of this test is to identify and evaluate ohmic and non-ohmic components of the total resistance of the cell/stack assembly unit. This test is already partly defined in IEC TS 62282-7-2:2014, 10.7, but in this document remarks on electrolysis operation are added. More details on the basic principles of EIS and interpretation of EIS spectra are given in Annex B.

7.6.2 Test method

The main action of the test is to determine the dynamic response of the cell/stack assembly unit to oscillating electric perturbations at the reference state, allowing to determine the ohmic resistance and the total polarization of the unit. This method is known as electrochemical impedance spectroscopy (EIS).

The following recommendations are given for this test method.

a) Direct current (DC)

EIS can be carried out at open-circuit voltage or under electric load. It is recommended to carry out measurements in direct current to understand the different processes occurring under load. For electrolysis measurements the external current shall be negative (see Clause 5.6). Therefore, a DC source is needed. In electrolysis mode, attention shall be paid to the fact that EIS measurements performed under direct current may require EIS equipment able to apply high DC values (several tens or even hundreds of A), or able to interact with DC loads applying said current.

b) Amplitude of excitation signal

The recommended perturbation amplitude for an AC signal is about 1 % to 3 % depending on the system noise. For example, an AC voltage excitation signal is 10 mV to 30 mV per cell, and an AC current excitation signal is 3 mA/cm² to 30 mA/cm² at a DC current density of 1 A/cm².

c) Sweep mode

It is recommended to start the measurements with high frequencies to get output quickly and see directly if the measurement is giving reasonable results. Afterwards sweep to lower frequencies.

d) Number of measuring points

Four to twenty points per decade of frequencies (to be distributed evenly as logarithms, if possible) are required; they shall be numerous enough to identify clearly the geometry of impedance plots. If possible, avoid the fundamental and harmonics of the electrical grid frequency.

e) Number of measuring periods

The measurement of the input signal is the average over more than one sine period. If the number of periods chosen is very high the measurement needs a lot of time. It is recommended to find a compromise between acceptable measuring time and precision (4 to 20 periods are feasible).

In electrolysis mode, special attention shall be paid to the noise of voltage signals caused by insufficient stability in steam supply, especially in small, low-power test environments. The operation parameters of the steam generator shall be optimized to reduce the noise resulting in the impedance measurement.

7.6.3 Data post-processing

For EIS measurement the directly achieved output parameters are the voltage (galvanostatic mode) or the current (potentiostatic mode). Both are sinusoidal signals. Moreover, the phase shift between the excitation signal and corresponding response signal is measured directly as an output parameter. It is possible to obtain an electrochemical impedance spectrum by calculation of the corresponding impedances (see Equation (B.2)). The most commonly employed method is to divide the total impedance into the imaginary part and the real part. State-of-the-art impedance analysers contain powerful software packages, which directly supply these derived values as output parameters. Therefore, these impedance values can also be treated as direct output parameters.

The electrochemical processes taking place in a fuel/electrolysis cell or stack repeating unit can be modelled as an equivalent electric circuit consisting of elements such as resistors, capacitors, constant phase elements. Individual processes taking place in the cell layers and/or the corresponding stack components may be assigned to these equivalent circuit elements. There are many different circuit models possible, as the scientific literature shows. Each element of the equivalent circuit represents a physicochemical or electrochemical process taking place in the cell/stack layer and is excited at a particular frequency (range).

After choosing a proper (Kramers-Kronig (KK) compliant, see A.7.4) equivalent electric circuit model, initial values may be assigned to the elements in the model. These values can be determined in different ways. The starting values for the model can be read out from the Nyquist or Bode plot. The initial values are provided as input to the simulation model. Using for example a complex nonlinear least squares (CNLS) algorithm, software can generate a curve (which is referred as a "FIT") for simulating the experimental result. At the end of the simulation, the values for the various resistors, capacitors and inductors are identified.

Results from impedance spectra fitting shall be analysed with caution. Firstly, they represent complicated electrochemical phenomena taking place inside the layers of the cell/stack unit, which have not been completely understood. Secondly, the spectra were observed to be very sensitive to measuring conditions especially temperature, current and gas composition. Thirdly, disturbances such as high frequency disturbance from measuring lines influence or handicap the measurement. Fourthly, fitting of the spectra to the model is not error free – the nature of the curve with the overlap between the different impedance arcs (i.e. the frequency overlap between different electrochemical processes) as well as human induced error can give different results even when a single curve is being fitted twice by the same person. Because of these reasons, it is sometimes more advisable to use the direct results from the EIS spectra to analyse the impedance changes in relation to the different cell/stack layers, to different operating conditions or as a function of time.

All relevant test input parameters (TIPs), test output parameters (TOPs) and derived quantities for this test are provided in Clause A.7.

7.7 Current cycling durability test

7.7.1 Objective of this test

The objective of this test is to evaluate the capability of a SOC cell/stack assembly unit to modulate its power according to application-specific load profiles, that can cover either fuel cell or electrolysis operation or both, for example in connection with peak shaving associated to fluctuating renewable electricity generation. The test aims to measure the response of the cell/stack assembly unit under quasi-dynamic operation, i.e. under varying current levels but in locally galvanostatic conditions (at a constant current for a given operating point).

7.7.2 Test method

The main action of the test is to record the evolution of the cell/stack assembly unit voltage at various current levels, that can cover both fuel cell operation (current generated), electrolysis operation (current stored into hydrogen) or reversible operation. A cycle can comprise several plateaus at different current values or continuous current ramps and can be repeated a number of times. The reactant utilization shall be kept constant throughout the test.

For the test, realistic currents, plateau durations and ramp rates for switching from one current to the other shall be defined, reflecting the target application selected for the test though also taking into account manufacturer recommendations.

For cycling tests comprising reversing operation, switching between fuel cell and electrolysis operation shall ensure suitable gas atmosphere at the electrodes at all times.

7.7.3 Data post-processing

A graph presenting the evolution of the cell/stack assembly voltages (V_{stack} , V_{cell} and $V_{\text{RU},i}$) as a function of time and the applied current load shall be reported. A graph with the time-evolution of the unit temperatures ($T_{\text{cell/stack}}$) shall be provided.

Detailed test guidelines and all relevant test input parameters (TIPs), test output parameters (TOPs) and derived quantities for this test are provided in Clause A.8.

7.8 Thermal cycling test

7.8.1 Objective

SOC assembly units, whether in fuel cell, electrolysis reversible or regenerative modes, are expected to bear thermal cycling during service, which implies sequential start-ups and shut-downs of varying periods, depending on the application. The objective of this test is to evaluate the stability of a SOC cell/stack assembly unit when thermally cycled. This test is carried out by cooling the cell/stack from the operating temperature ($T_{\text{cell/stack}}$), to a lower value T_{min} at a constant rate of temperature change during a number of cycles n . The dwell times at the operating and minimum temperatures respectively shall be defined beforehand.

7.8.2 Test method

Thermal cycling may lead to increasing leakage rates, therefore particular attention shall be paid to the measurement of gas-tightness. The main action of the test is to record the parameters related to SOC cell/stack assembly unit gas-tightness, like temperature, OCV and outlet flow rates. Also performance parameters like voltages at operating current shall be recorded, which allow the evaluation of the SOC cell/stack assembly unit thermal stability and the calculation of its degradation rates. It is recommended to record current-voltage characteristics (see 7.2) before and after a defined cycling programme. Particular attention shall be paid to the accuracy of the temperature read-outs and their rate of change in order to follow the thermal response of the system as closely as possible. The voltage has to be continuously measured, whether at open circuit or under current, in order to monitor SOC cell/stack assembly unit tightness during thermal cycling. The compression force on the cell/stack assembly shall be kept constant during thermal cycling to maintain reproducible parameters as regards electrical contact and gas-tightness. For safety reasons, when the cell/stack assembly is shut down, hydrogen composition on the negative electrode side has to be kept below 4 % to avoid the coming about of a potentially explosive atmosphere.

7.8.3 Data post-processing

Data post-processing consists in the analysis of the evolution of output parameters during the test. A graph presenting the evolution of the cell/stack assembly voltages (V_{stack} , V_{cell} and $V_{\text{RU},i}$) and the applied temperature variation as a function of time shall be reported. If a reference current is applied during operation at the operating cell/stack temperature, this shall also be plotted.

The cell/stack voltages V_{stack} , V_{cell} and/or $V_{\text{RU},i}$ at zero current load shall be recorded and indicated after each thermal cycle in order to determine possible degradation of the OCV as a result of the cycling periods. This gives an indication of the change of gas-tightness of the cell/stack assembly unit during thermal cycling.

All relevant test input parameters (TIPs), test output parameters (TOPs) and derived quantities for this test are provided in Clause A.9.

7.9 Pressurized test

7.9.1 Objective of this test

The objective of this test is to evaluate the capability of a SOC cell/stack assembly unit to operate in pressurized conditions, either in electrolysis mode, or in fuel cell mode, or in reversible mode. The test aims to measure the response of the cell/stack assembly unit under pressurized operation, i.e. under varying pressure from the atmospheric pressure up to a defined value (which can be several times the atmospheric pressure). To have a complete assessment of the cell/stack assembly unit response, it is recommended to carry out the current-voltage characteristics test (7.2) at the different operating pressures. Other measurements such as the durability test (7.4) also apply to this test mode.

7.9.2 Test method

The main action of this test is to pressurize the SOC cell/stack assembly unit for subsequent evaluation of its properties in electrolysis mode, in fuel cell mode or in reversible mode, according to procedures defined in all previous sub-clauses of Clause 7 (7.2 to 7.8). In most cases, the pressure is controlled by pressure valves.

If pressurized testing starts with electrolysis mode, pressurization of the SOC cell/stack assembly unit is performed at zero current, with gas composition defined at the negative and the positive electrode.

If pressurized test starts with fuel cell mode, pressurization of the SOC cell/stack assembly unit is performed at zero current, with gas composition defined at the negative and the positive electrode.

Starting from atmospheric pressure (1 bar), pressure is increased gradually. The pressure ramp rate shall be between 1 bar/h and 30 bar/h. The value shall be adjusted depending on the installation (valves capacities and volume to be pressurized).

The pressure difference between the pressure vessel and each electrode compartment shall be controlled by a pressure control system and kept in a range specified by the stack manufacturer to protect the sealing and the stack itself. For cell tests, it shall be consistent with the sealing solution selected.

The pressure difference between the negative and positive electrode compartments shall be kept in a range specified by the stack manufacturer to protect the sealing. For cell tests, it shall be consistent with the sealing solution selected.

Compression force on the cell/stack shall be adjusted at each step of pressure increase to compensate the pressure increase inside the cell/stack.

The switch from electrolysis mode to fuel cell mode and the reverse is done at constant pressure. If a different pressure value is targeted in electrolysis and fuel cell mode, the pressure modification can be done either in electrolysis or fuel cell mode.

7.9.3 Data post-processing

A graph presenting the SOC voltage, power density and SOC temperature against current density for the various pressures tested shall be reported in the case of current-voltage characteristics tests.

A graph presenting the evolution of the cell/stack assembly voltages (V_{stack} , V_{cell} and $V_{\text{RU},i}$) as a function of time and the applied current load for the various pressures tested shall be reported in the case of a constant load durability test. It is highly recommended to also provide a graph with the time-evolution of the unit temperatures ($T_{\text{cell/stack}}$).

All relevant test input parameters (TIPs), test output parameters (TOPs) and derived quantities for this test are provided in Clause A.10.

8 Test report

8.1 General

Test reports shall accurately, clearly and objectively present sufficient information to demonstrate whether the objectives of the tests have or have not been achieved.

8.2 Report items

The report shall present the following information, at a minimum:

- a) title of report;
- b) authors of the report;
- c) date of the report;
- d) test report reference/identification number;
- e) location and (start) date/time of the test;
- f) test bench used;
- g) test unit data (see 8.3 for details);
- h) test conditions (see 8.4 for details);
- i) test data (see 8.5 for details).

8.3 Test unit data description

Test unit data shall include the following information, at a minimum:

- a) product name and brand name of the unit;
- b) active electrode area;
- c) number of cells (total, series, parallel);
- d) cell materials and thicknesses, if known, and cell identification number(s);
- e) stacking materials, if known;
- f) geometry of the unit;
- g) temperature measurement and compression force application positions.

8.4 Test condition description

The test condition description shall include the following information, at a minimum:

- a) name of person(s) conducting the test;
- b) instruments and calibration record;
- c) test procedure;
- d) cell/stack assembly unit history (e.g. operating time in hours and number of cycles carried out) at the time of test;
- e) criteria of stable state;
- f) data acquisition method;
- g) gas purity and impurities;
- h) test bench layout.

8.5 Test data description

Test data shall include the following information:

- a) title of the test(s);
- b) test operating conditions;
- c) test results;
- d) ambient conditions;
- e) uncertainty evaluation (see 8.6 for details).

8.6 Uncertainty evaluation

Uncertainties of instruments shall be reported. If necessary, variation of measurements and/or measurement uncertainties calculated from the variation of measurements and uncertainties of instruments shall be reported.

Annex A (normative)

Detailed test procedures

NOTE The guidelines given in Annex A are taken from, and fully elaborated in the test modules and test programmes developed in the EU project SOCTESQA (see Bibliography).

A.1 Test objective

The determination of the objective of a test is the initial part of planning the procedure for testing a ceramic solid oxide cell/stack. The objectives could be:

- evaluation of the performance;
- stability over time at given (constant) conditions.

With the objective of the test in mind, the test can be planned by first choosing the relevant scope, the relevant test operating conditions (depending on type of application), operation mode, and whether cell or stack testing is most suitable.

A.2 Test set-up

The test set-up procedure shall be as follows.

- a) Check control and measurement equipment for possible leakage. There are many methods for leak-checking, such as pressure hold and helium leak detectors. The choice of method will depend on the equipment in use. The proper operation of the test equipment shall be verified by comparing its performance with the parameters specified in 6.2.
- a) Prepare a cell/stack assembly unit consisting of cell(s), gas passage, interconnectors, current collectors, insulation, and other components in accordance with the assembly method and procedure recommended by the manufacturer. Before connecting the cell/stack to the test bench, measure the resistance between positive electrode and negative electrode current lead points to see if it is not short circuited. Measure the resistance between cell voltage sense lead points to determine if they are electrically insulated. Measure the cell-to-cell resistances. These values shall not indicate a short circuit, but, rather, shall be similar to those specified by the manufacturer.
- b) Set up the cell/stack assembly unit in a temperature-controlled environment and install:
 - the wiring for the voltage measurement line,
 - the electric power connections,
 - the compression force equipment
 - the thermocouples,
 - the piping for the gas supply and exhaust.
- c) Connect items shown in c) with the corresponding subsystems.
- d) Ensure proper insulation between thermocouples and the cell/stack. There shall also be electrical insulation between the compression force equipment and the cell/stack. Check all piping and the test set-up for gas leakage.
- e) Verify the insulation-to-the-earth of wiring and others. It is recommended to check the insulation before the output control equipment or measurement equipment is connected. In addition, proper wiring shall be verified at joint connections.
- f) When the above are all completed, the measurement equipment is checked for its proper operation.

A.3 Current-voltage characteristics test (7.2)

A.3.1 Test input parameters (TIPs)

For this test procedure, there are two types of test input parameters (TIPs or test conditions): variable and static. The variable and static test inputs applied during the test are given in Table A.1. Depending on the test objective, the current set point profile (number of steps, levels and rate of change) is to be specified.

Table A.1 – Test input parameters (TIPs) for current-voltage characteristics test

Static TIPs		Variable TIPs	
Quantity	Symbol	Quantity	Symbol
Total volumetric gas flow rate at negative electrode inlet	$q_{V,neg,in}$	Cell/stack current (in the case of galvanostatic control)	I
Total volumetric gas flow rate at positive electrode inlet	$q_{V,pos,in}$	Dwell time at a given operating point	t_{dwell}
Volumetric flow rate of gas component i at negative electrode inlet	$q_{V,i,neg,in}$	Equilibration time at a given operating point	t_{eq}
Volumetric flow rate of gas component i at positive electrode inlet	$q_{V,i,pos,in}$	Acquisition time at a given operating point	t_{acq}
Molar fraction of component i in the negative electrode gas stream at cell/stack	$x_{i,neg,in}$	Cell/stack voltage (in the case of potentiostatic control)	V
Molar fraction of component i in the positive electrode gas stream at cell/stack	$x_{i,pos,in}$		
Inlet temperature of negative electrode gas	$T_{neg,in}$		
Inlet temperature of positive electrode gas	$T_{pos,in}$		
Furnace temperature	$T_{furnace}$		
Gas pressure at negative electrode inlet	$p_{neg,in}$		
Gas pressure at positive electrode inlet	$p_{pos,in}$		

The J - V curve is performed under galvanostatic control for a given working point. The step starts by bringing the TIPs to their specified values followed by a stabilization or equilibration period during which the specified TIP stability criterion (criteria) is (are) to be met.

A.3.2 Test output parameters (TOPs)

Table A.2 lists the test output parameters (TOPs) that are determined in the application of this test. The most important TOP is the cell/stack voltage. The other TOPs may be measured and recorded as motivated by the test objective.

Table A.2 – Test output parameters (TOPs) for current-voltage characteristics test

Quantity	Symbol
Cell/stack voltage (in the case of galvanostatic control)	V
Cell/stack current (in the case of potentiostatic control)	I
Negative electrode gas temperature	$T_{\text{neg,in}}$
Positive electrode gas temperature	$T_{\text{pos,in}}$
Negative electrode exhaust gas temperature	$T_{\text{neg,out}}$
Positive electrode exhaust gas temperature	$T_{\text{pos,out}}$
Top-plate temperature of the stack	T_{TP}
Bottom-plate temperature of the stack	T_{BP}
Cell temperature	T_{cell}

A.3.3 Derived quantities

Table A.3 below lists the relevant quantities that can be derived or calculated from the test input parameters and/or test output parameters.

Table A.3 – Derived quantities for current-voltage characteristics test

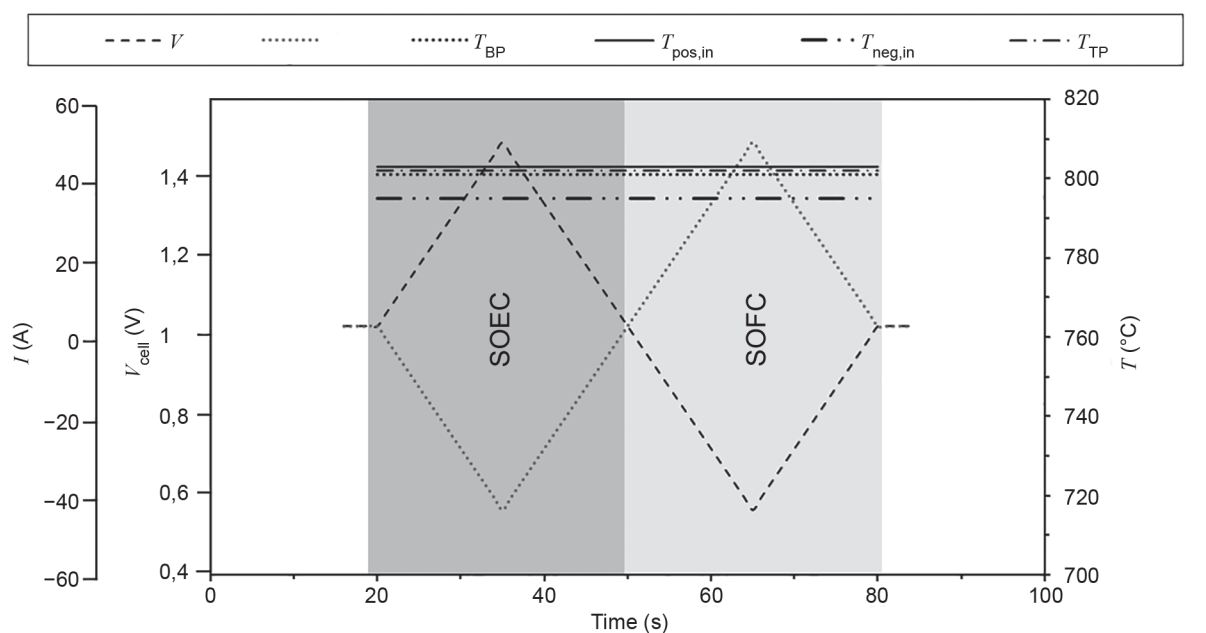
Quantity	Symbol	Formula
Current density	J	$\frac{I}{A_{\text{active}}}$
Area-specific resistance	R_{ASR}	$\frac{\Delta V(J)}{\Delta J}$
Electric power	P_{el}	$V_{\text{stack}} \cdot I$
Average stack temperature	$T_{\text{stack,av}}$	See examples in 7.5.3
Positive electrode reactant utilization	$U_{\text{gas,pos}}$	$\frac{R_g \cdot T_0}{p_0} \cdot \frac{I}{n \cdot F \cdot \sum (x_{i,\text{pos}} \cdot q_{V,\text{pos,in}})}$
Negative electrode reactant utilization	$U_{\text{gas,neg}}$	$\frac{R_g \cdot T_0}{p_0} \cdot \frac{I}{n \cdot F \cdot \sum (x_{i,\text{neg}} \cdot q_{V,\text{neg,in}})}$

The SOC voltage is measured as described either upon TIP stability or when the cell/stack temperature is within a specified limit. During the test, all TIPs and TOPs shall be measured and recorded as described.

A.3.4 Measurement of current-voltage characteristics

The test starts at open circuit voltage (OCV) conditions (zero current) up to the specified current or voltage and back to OCV. The current is changed stepwise or using a ramp with a defined rate. The total number of steps and each step size shall be the same in both the ascending part and the descending part.

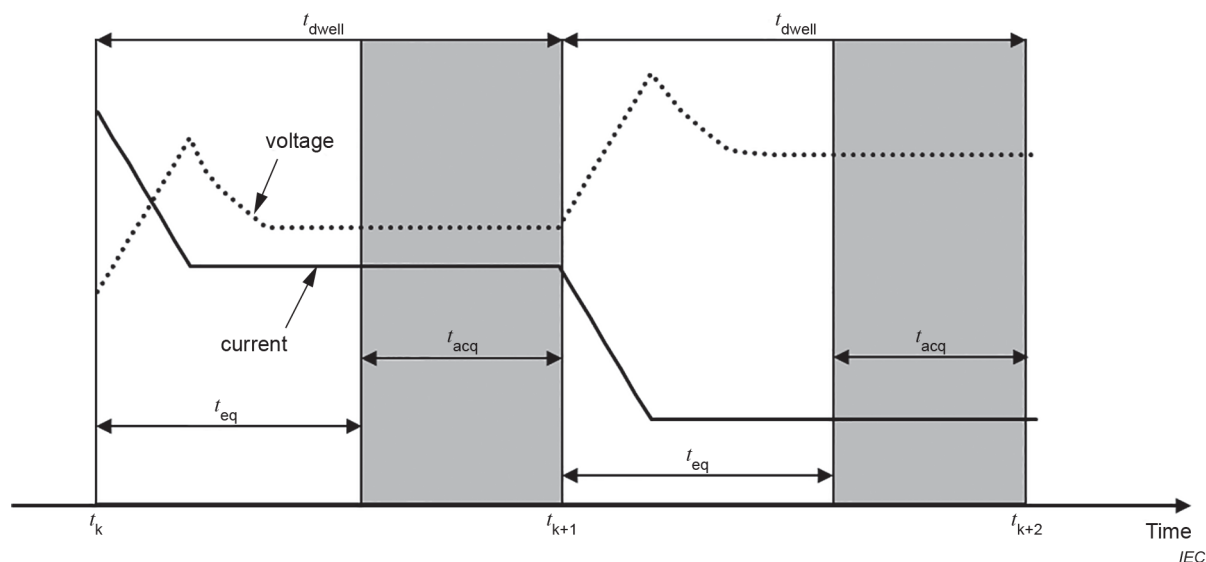
A typical measurement profile for combined SOFC and SOEC operating mode is given in Figure A.1.



IEC

Figure A.1 – Qualitative representation of TIPs when carrying out a current-voltage characteristics test for combined (SOFC and SOEC) operation

At each step, the current is held constant for a specific time t_{dwell} (Figure A.2). For each current step k , t_{dwell} comprises the period of equilibration time (t_{eq}) and of data acquisition time (t_{acq}). The equilibration time starts with t_{dwell} and ends with the starting of t_{acq} .



IEC

Figure A.2 – Schematic representation of the current-voltage characteristics test procedure for two consecutive set points k and $k + 1$

By convention, the current density J is considered positive in fuel cell mode and negative in electrolysis mode. The fuel utilization is proportional to the current density since the inlet reactant flow rates and compositions remain constant over the duration of the plot of the J - V curve. Therefore, it can be plotted as a secondary x-axis.