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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



AS IEC 62282.8.101:2024

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- Australian Hydrogen Council
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- Engineers Australia
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Preface

This Standard was prepared by the Standards Australia Committee ME-093, Hydrogen Technologies.

The objective of this document is to address 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.

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”.

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.

This document is identical with, and has been reproduced from, IEC 62282-8-101:2020, *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*.

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The terms “normative” and “informative” are used in Standards to define the application of the appendices or annexes to which they apply. A “normative” appendix or annex is an integral part of a Standard, whereas an “informative” appendix or annex is only for information and guidance.

Contents

Preface	ii
FOREWORD	vii
INTRODUCTION	ix
1 Scope	1
2 Normative references	1
3 Terms, definitions, abbreviated terms and symbols	2
3.1 Terms and definitions	2
3.2 Abbreviated terms and symbols	8
3.2.1 Abbreviated terms	8
3.2.2 Symbols	8
3.3 Flow rates	12
4 General safety conditions	12
5 Test environment	13
5.1 General	13
5.2 Cell	13
5.3 Stack	14
5.4 Experimental set-up	15
5.4.1 General	15
5.4.2 Electrode gas control equipment	15
5.4.3 Thermal management equipment	15
5.4.4 Electric power supply/load control equipment	16
5.4.5 Measurement and data acquisition equipment	16
5.4.6 Safety equipment	16
5.4.7 Compression force control equipment	16
5.4.8 Pressure control equipment	16
5.5 Interface between test object and experimental set-up	16
5.6 Parameter control and measurement	18
5.7 Measurement uncertainty of TIPs and TOPs	19
5.8 Mounting of the test object into the experimental set-up	19
5.9 Stability criteria	20
6 Measurement instruments and methods	20
6.1 General	20
6.2 Instrument uncertainty	20
6.3 Recommended measurement instruments and methods	21
6.3.1 Electrode inlet gas flow rate measurement	21
6.3.2 Electrode gas composition measurement	21
6.3.3 Electrode gas temperature measurement	22
6.3.4 Electrode gas pressure measurement	22
6.3.5 Electrode exhaust gas flow rate measurement	22
6.3.6 Cell/stack assembly unit voltage measurement	23
6.3.7 Cell/stack assembly unit current measurement	23
6.3.8 Cell/stack assembly unit temperature measurement	23
6.3.9 Compression force measurement	23
6.3.10 Total impedance measurement	23
6.3.11 Ambient condition measurement	23
6.4 Test conditions and manufacturer recommendations	23
6.4.1 Start-up and shut-down conditions	23
6.4.2 Range of test conditions	24
6.4.3 Stabilization, initialization conditions and stable state	24
6.4.4 Dwell time, equilibration time, acquisition time	24
6.5 Data acquisition method	25
7 Test procedures and computation of results	

7.1	General.....	25
7.2	Current-voltage characteristics test.....	25
7.2.1	Objective of this test.....	25
7.2.2	Test method.....	25
7.2.3	Data post-processing.....	26
7.3	Effective reactant utilization test.....	26
7.3.1	Objective of this test.....	26
7.3.2	Test method.....	26
7.3.3	Data post-processing.....	27
7.4	Durability test.....	27
7.4.1	Objective of this test.....	27
7.4.2	Test method.....	27
7.4.3	Data post-processing.....	28
7.5	Temperature sensitivity test.....	28
7.5.1	Objective of this test.....	28
7.5.2	Test method.....	28
7.5.3	Data post-processing.....	29
7.6	Separation of resistance components test via electrochemical impedance spectroscopy	29
7.6.1	Objective of this test.....	29
7.6.2	Test method.....	29
7.6.3	Data post-processing.....	30
7.7	Current cycling durability test	31
7.7.1	Objective of this test.....	31
7.7.2	Test method.....	31
7.7.3	Data post-processing.....	31
7.8	Thermal cycling test.....	32
7.8.1	Objective.....	32
7.8.2	Test method.....	32
7.8.3	Data post-processing.....	32
7.9	Pressurized test	32
7.9.1	Objective of this test.....	32
7.9.2	Test method.....	33
7.9.3	Data post-processing.....	33
8	Test report.....	33
8.1	General.....	33
8.2	Report items.....	33
8.3	Test unit data description	34
8.4	Test condition description.....	34
8.5	Test data description.....	34
8.6	Uncertainty evaluation	35
Annex A	(normative) Detailed test procedures	36
Annex B	(informative) Guidelines for electrochemical impedance spectroscopy (EIS)	61
Annex C	(normative) Formulae for calculation of utilization values	66
Bibliography		68

List of Figures

Figure 1 — Exploded schematic representation of a planar-type single cell test object consisting of a SOC in a cell housing.....	14
Figure 2 — Schematic representation of a planar-geometry SOC stack test object with <i>N</i> RU including supporting structure (top and bottom plates).....	15
Figure 3 — Schematic representation of a test environment for a SOC cell/stack assembly unit	15
Figure 4 — Test environment with interfaces between SOC cell and experimental set-up	17
Figure 5 — Test environment with interfaces between SOC stack and experimental set-up	18
Figure A.1 — Qualitative representation of TIPs when carrying out a current-voltage characteristics test for combined (SOFC and SOEC) operation	20

Figure A.2 — Schematic representation of the current-voltage characteristics test procedure for two consecutive set points k and $k + 1$	39
Figure A.3 — Schematic representation of a J - V curve in both electrolysis and fuel cell modes	40
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	43
Figure A.5 — Qualitative representation of TIPs when carrying out a durability test (in galvanostatic mode)	46
Figure A.6 — Qualitative representation of TIPs when carrying out a temperature sensitivity test	48
Figure A.7 — Qualitative representation of TIPs when carrying out a current cycling durability test	54
Figure A.8 — Current profile of a SOEC system with fast switch on/off at thermoneutral conditions	54
Figure A.9 — Current profile of a SOEC system with fast switch on/off at exothermal conditions	54
Figure A.10 — Current profile of a load-following SOEC system and thermoneutral conditions	54
Figure A.11 — Current profile of a load-following SOEC system and exothermal conditions	55
Figure A.12 — General evolution of TIPs during test: continuous thermal cycling above 600 °C (in this case with zero electric current)	57
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)	58
Figure B.1 — Input/output signals during electrochemical impedance spectroscopy (EIS) of a solid oxide fuel/electrolysis cell	62
Figure B.2 — Test set-up for electrochemical impedance spectroscopy of a planar solid oxide fuel cell/electrolysis stack with 5 RUs	63
Figure B.3 — Bode plot representing the modulus of impedance and phase angle against excitation frequency	64
Figure B.4 — Nyquist plot, representing conjugate imaginary part against real part of impedance	65

List of Tables

Table 1 — Symbols	8
Table 2 — Stability criteria for TIPs and TOPs as a reference	20
Table 3 — Instrument uncertainty for each quantity to be measured	20
Table A.1 — Test input parameters (TIPs) for current-voltage characteristics test	37
Table A.2 — Test output parameters (TOPs) for current-voltage characteristics test	37
Table A.3 — Derived quantities for current-voltage characteristics test	38
Table A.4 — Test input parameters (TIPs) for negative electrode reactant utilization test	41
Table A.5 — Test input parameters (TIPs) for positive electrode reactant utilization test	41
Table A.6 — Test output parameters (TOPs) for effective reactant utilization test	42
Table A.7 — Derived quantities for effective reactant utilization test	42
Table A.8 — Test input parameters (TIPs) for durability test	44
Table A.9 — Test output parameters (TOPs) for durability test	44
Table A.10 — Derived quantities for constant load durability test	45
Table A.11 — Test input parameters (TIPs) for temperature sensitivity test	46
Table A.12 — Test output parameters (TOPs) for temperature sensitivity test	47
Table A.13 — Derived quantities for temperature sensitivity test	47
Table A.14 — Test input parameters (TIPs) for EIS test	49
Table A.15 — Test output parameters (TOPs) for EIS test	49
Table A.16 — Derived quantities for EIS test	50
Table A.17 — Test input parameters (TIPs) for current cycling durability test within a single operating mode (fuel cell or electrolysis)	51
Table A.18 — Test input parameters (TIPs) for current cycling durability test covering both operating modes (fuel cell and electrolysis)	51
Table A.19 — Test output parameters (TOPs) for current cycling durability test	51
Table A.20 — Derived quantities for current cycling durability test	52
Table A.21 — Test input parameters (TIPs) for thermal cycling	55
Table A.22 — Test output parameters (TOPs) for thermal cycling	55
Table A.23 — Derived quantities for thermal cycling test	56
Table A.24 — Test input parameters (TIPs) for pressurized testing	59
Table A.25 — Test output parameters (TOPs) for pressurized testing	59

Table A.26 — Derived quantities for pressurized test..... 59

Table C.1 — Generic formulae..... 66

FOREWORD

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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.

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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.

NOTES

Australian Standard®

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

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

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 m² or cm².

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 Ω m² or Ω cm².

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

[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.]

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

3.1.4**interconnector****interconnect**

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

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

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).

3.1.5**catalyst**

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

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

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

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

[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.]

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

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

[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".]

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

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

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

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

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

[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".]

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

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

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

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

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 $W \cdot cm^{-2}$.

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

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

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

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

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

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

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

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

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

3.1.37**total resistance**

real part of low-frequency limit of total impedance

[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.]

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

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	

Table 1 (continued)

Symbol	Definition	Unit
I_{cell}	Cell current	A
I_{n}	Nominal current	A
I_{stack}	Stack current	A
I_{RU}	Repeating unit current	A
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)
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
$q_{V,\text{neg,out}}$	Total volumetric flow rate at negative electrode outlet (at STP)	m ³ /s, l/min
$q_{V,\text{pos,out}}$	Total volumetric flow rate at positive electrode outlet (at STP)	m ³ /s, l/min
$q_{V,i,\text{neg,in}}$	Volumetric flow rate of gas component i at negative electrode inlet (at STP)	m ³ /s, l/min
$q_{V,i,\text{pos,in}}$	Volumetric flow rate of gas component i at positive electrode inlet (at STP)	m ³ /s, l/min
$q_{V,i,\text{neg,out}}$	Volumetric flow rate of gas component i at negative electrode outlet (at STP)	m ³ /s, l/min
$q_{V,i,\text{pos,out}}$	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	Ω·m ² , Ω·cm ²
R_{LF}	Low frequency resistance	Ω
R_{HF}	High frequency resistance	Ω
R_{ohm}	Ohmic resistance	Ω
$R_{\text{non-ohm}}$	Non-ohmic resistance	Ω
R_{g}	Universal gas constant (8,3145)	J/(mol·K)

Table 1 (continued)

Symbol	Definition	Unit
T	Temperature	
$T_{\text{cell/stack}}$	Temperature of the cell or stack	°C, K
$T_{\text{stack,av}}$	Average temperature of the stack	°C, K
$T_{\text{stack,intern}}$	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
$T_{\text{neg,in}}$	Temperature of negative electrode gas stream at cell/stack inlet	°C, K
$T_{\text{pos,in}}$	Temperature of positive electrode gas stream at cell/stack inlet	°C, K
$T_{\text{neg,out}}$	Temperature of negative electrode gas stream at cell/stack outlet	°C, K
$T_{\text{pos,out}}$	Temperature of positive electrode gas stream at cell/stack outlet	°C, K
$T_{\text{PH,neg}}$	Temperature of the pre-heater for preheating the negative electrode gas stream	°C, K
$T_{\text{PH,pos}}$	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	
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

Table 1 (continued)

Symbol	Definition	Unit
$x_{i,\text{pos,in}}$	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
Y, Z	Admittance, impedance	
Y	Admittance	S
	Specific admittance	$\text{S}\cdot\text{m}^{-2}$, S cm^{-2}
Y'	Real part of admittance (conductance)	S
	Real part of specific admittance	$\text{S}\cdot\text{m}^{-2}$, S cm^{-2}
Y''	Imaginary part of admittance (susceptance)	S
	Imaginary part of specific admittance	$\text{S}\cdot\text{m}^{-2}$, S cm^{-2}
Z	Impedance	Ω
	Specific impedance	$\Omega\cdot\text{cm}^2$, $\Omega\cdot\text{m}^2$
$ Z $	Modulus of impedance	Ω
	Modulus of specific impedance	$\Omega\cdot\text{cm}^2$, $\Omega\cdot\text{m}^2$
Z'	Real part of impedance (resistance)	Ω
	Real part of specific impedance	$\Omega\cdot\text{cm}^2$, $\Omega\cdot\text{m}^2$
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	rad/s
ω_{min}	Minimum frequency for EIS spectra	rad/s
ω_{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 $\text{Re}(Z)$ and $\text{Im}(Z)$, 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 H₂), 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.

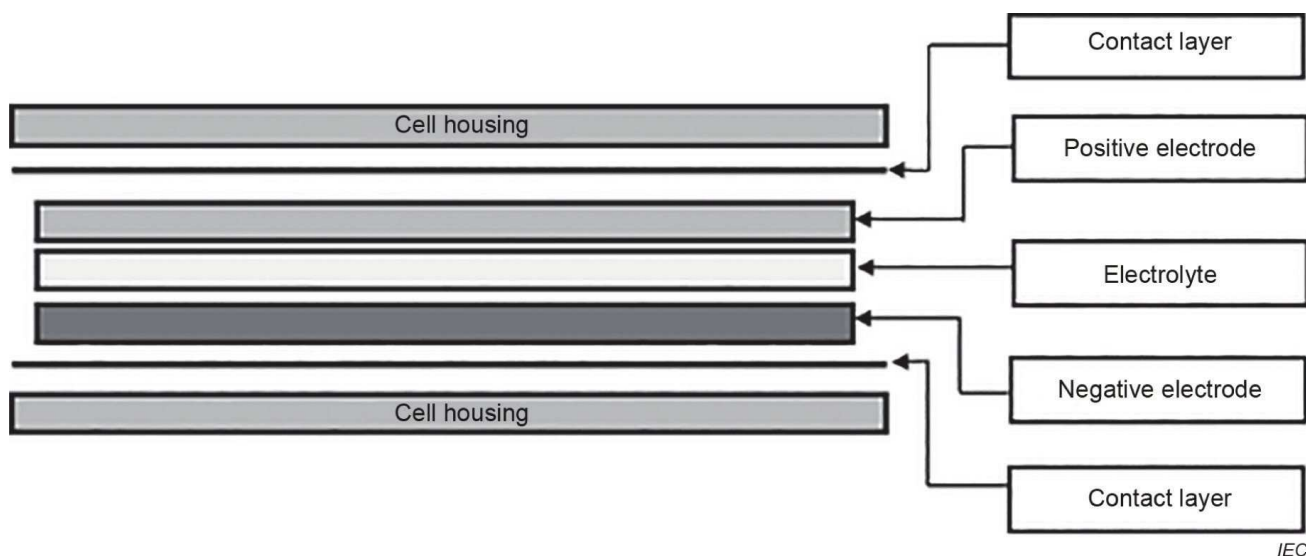


Figure 1 — Exploded schematic representation of a planar-type single cell test object consisting of a SOC in a cell housing

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.

