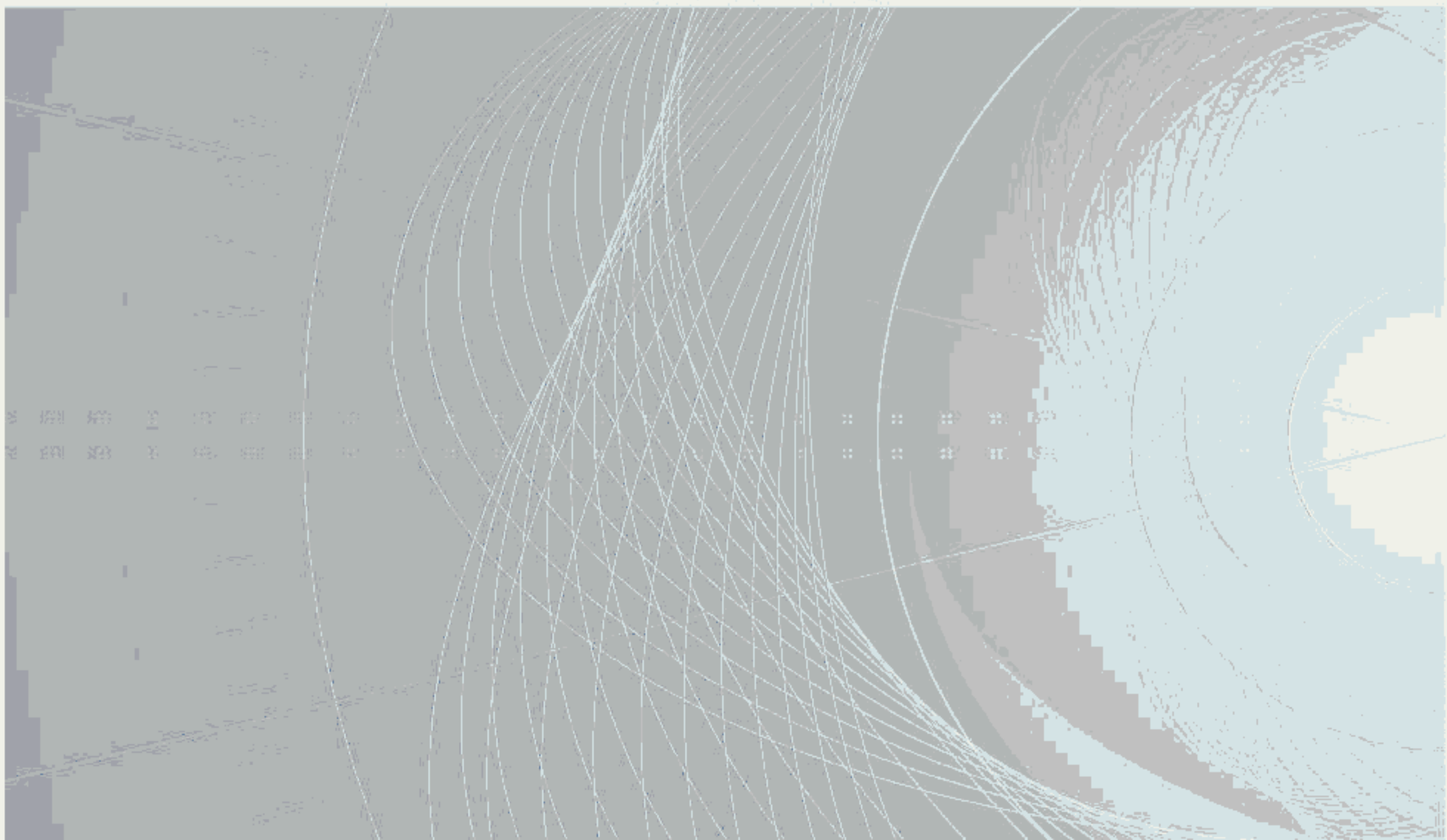
IEC 62282-7-2

Edition 1.0 2021-05

INTERNATIONAL STANDARD

Fuel cell technologies –
Part 7-2: Test methods – Single cell and stack performance tests for solid oxide fuel cells (SOFCs)



IEC 62282-7-2:2021-05(en)

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INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 27.070

ISBN 978-2-8322-9805-3

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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FUEL CELL TECHNOLOGIES –

Part 7-2: Test methods – Single cell and stack performance tests for solid oxide fuel cells (SOFCs)

FOREWORD

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IEC 62282-7-2 has been prepared by IEC technical committee 105: Fuel cell technologies. It is an International Standard.

This first edition cancels and replaces IEC TS 62282-7-2 published in 2014.

This edition includes the following significant technical changes with respect to IEC TS 62282-7-2:2014:

a) users can substitute selected test methods of this document with equivalent test methods of IEC 62282-8-101 for solid oxide cell (SOC) operation for energy storage purposes, operated in reverse or reversible mode;
b) terms and definitions are aligned with the corresponding terms and definitions in IEC 62282-8-101;
c) symbols are aligned with the corresponding symbols in IEC 62282-8-101.

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

FDIS	Report on voting
105/847/FDIS	105/851/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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 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.

INTRODUCTION

This part of IEC 62282 specifies test methods for a single cell and stack (denoted as "cell/stack" hereafter) that is required in power generation systems using solid oxide fuel cells (SOFCs).

SOFCs have a broad range of geometry 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 stack but also peripherals.

FUEL CELL TECHNOLOGIES –

Part 7-2: Test methods – Single cell and stack performance tests for solid oxide fuel cells (SOFCs)

1 Scope

This part of IEC 62282 applies to SOFC cell/stack assembly units, testing systems, instruments and measuring methods, and specifies test methods to test the performance of SOFC cells and stacks.

This document is not applicable to small button cells that are designed for SOFC material testing and provide no practical means of fuel utilization measurement.

This document is used based on the recommendation of the entity that provides the cell performance specification 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 can selectively execute test items suitable for their purposes from those described in this document.

Users can substitute selected test methods of this document with equivalent test methods of IEC 62282-8-101 for solid oxide cell (SOC) operation for energy storage purposes, operated in reverse or reversible mode.

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 (IEV) – Part 485: Fuel cell technologies* (available at http://www.electropedia.org)

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

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

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

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 – 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 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 8573-1, *Compressed air – Part 1: Contaminants and purity classes*

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

ISO 12185, *Crude petroleum and petroleum products – Determination of density – Oscillating U-tube method*

3 Terms, definitions 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
cell/stack assembly unit
unit including a single cell or stack, as well as gas supply parts, current collector parts, and any other peripherals as required for power generation tests

3.1.2
active electrode area
geometric electrode area upon which an electrochemical reaction occurs

Note 1 to entry: Usually this is the smaller of the anode and cathode areas.

3.1.3
current density
current divided by the active electrode area

3.1.4
average repeating unit voltage
cell/stack assembly unit voltage divided by the number of the cells in a series connection in the unit

3.1.5
standard temperature and pressure
STP
temperature of 0 °C and an absolute pressure of 101,325 kPa, respectively

3.1.6
anode gas
gas that is supplied to the inlet of the anode of a single cell/stack assembly unit

Note 1 to entry: Such a gas belongs to one of the following categories:

a) pure hydrogen or mixture that contains hydrogen as a principal component with water vapour or nitrogen;

b) reformed gas of raw fuel of SOFC such as methane or kerosene premixed with water vapour or air as oxidant;

c) simulated gas of reformate that contains hydrogen, water vapour, carbon monoxide, carbon dioxide, methane, nitrogen, etc., as main components;

d) methane, alcohols and other raw fuels directly supplied in pure form or mixed with water vapour and/or air.

3.1.7
cathode gas
gas that is supplied to the inlet of the cathode of a single cell/stack assembly unit

Note 1 to entry: Oxygen and nitrogen are its main components.

3.1.8
current collector
conductive material in a fuel cell that collects electrons from the anode side or conducts electrons to the cathode side

3.1.9
stable state
condition of a cell/stack assembly unit at which the unit is stable enough for any controlling parameter and the output voltage or output current of the unit to remain within its tolerance range of variation

3.1.10
theoretical current
current when the supplied anode gas or cathode gas is completely consumed in electrochemical reactions divided by the number of cells in a series connection

3.1.11
effective fuel utilization
ratio of the actual output current of the cell/stack assembly unit to the theoretical current

Note 1 to entry: The effective utilization is the utilization of reactants in the electrochemical reaction due to the actual current. This may be less than the actual or total utilization if there are gas inlet and cross leaks.

Note 2 to entry: Causes of less-than-optimal currents include losses due to electronic conduction within the cell/stack assembly, gas leaks and anode gas pass-through.

Note 3 to entry: A calculation method of effective fuel utilization is given in Annex B.

3.1.12
effective oxygen utilization
ratio of the actual output current of the cell/stack assembly unit to the theoretical current

Note 1 to entry: The effective utilization is the utilization of reactants in the electrochemical reaction due to the actual current. This may be less than the actual or total utilization if there are gas inlet and cross leaks.

Note 2 to entry: A calculation method of effective oxygen utilization is given in Annex C.

3.1.13
maximum effective fuel utilization
highest effective fuel utilization that the unit can operate at, without causing unacceptable degradation

Note 1 to entry: The acceptable degradation rate is usually obtained from the developer.

3.1.14
minimum cell/stack assembly unit voltage
lowest cell/stack assembly unit voltage specified by the manufacturer

3.1.15
open circuit voltage
OCV
voltage across the terminals of a fuel cell with cathode and anode gases present and in the absence of external current flow

Note 1 to entry: Also known as "no-load voltage".

3.1.16
power density
ratio of the power to the active electrode area of a cell/stack assembly unit

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).

3.1.17
total impedance
frequency-dependent losses due to ohmic, activation, diffusion, concentration effects, stray (parasitic) capacitance and inductances

3.1.18
total resistance
real part of the low-frequency limit of total impedance

3.1.19
stoichiometric ratio
ratio between the number of moles of reactant gas flowing per unit time to that needed by the electrochemical reaction

Note 1 to entry: The terms, "stoichiometric ratio" and "reactant gas utilization," are related. The reciprocal of the fraction of the gas utilized is the stoichiometric ratio.

3.2 Symbols

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

Table 1 – Symbols

Symbol	Definition	Unit
a	Error limit specified from specification of instrument	a
I	Current	A
J	Current density	A/cm 2
n	Number of transferred electrons	
N	Number of cells in a series connection	
p_a	Absolute pressure of anode gas	kPa
p_c	Absolute pressure of cathode gas	kPa
P	Output power	W
P_d	Output power density	W/cm 2
q_a	Flow rate of anode gas	l/min (STP)
q_c	Flow rate of cathode gas	l/min (STP)
q_j	Flow rate of fuel component j in anode gas	l/min (STP)
t	Time	s, min, h
T_{op}	Cell/stack assembly unit operating temperature	°C
u_I	Combined standard uncertainty for instruments	a
$u_{I,i}$	Standard uncertainty for instrument i	a

Symbol	Definition	Unit
U_f	Effective fuel utilization	%
U_{O2}	Effective oxygen utilization	%
U_l	Extended instrument uncertainty	a
V	Voltage	V
x_i	Molar fraction of component i or Mole percent of component i	mol/mol or mol % b
c_i	Concentration of component i	mol/m 3
ξ_j	Hydrocarbon conversion rate for hydrocarbon component j	%

a Denotes where the unit varies depending on the specification.

b Mole percent expressed as one hundred times mole fraction.

4 General safety conditions

An operating fuel cell uses oxidizing and combustible gases. Typically, these gases are stored in high-pressure containers. The fuel cell itself may be operated at pressures greater than atmospheric pressure. 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 and reactive, compressed gases.

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 should be followed.

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

5 Cell/stack assembly unit

A cell/stack assembly unit includes a cell or stack, gas supply, current leads, and such other peripherals as required for power generation tests. 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.

As shown in Annex A, the boundary of a cell/stack assembly unit goes through the anode gas supply port, cathode gas supply port, temperature measuring point, current lead points, voltage measuring points and mechanical load application points.

Some cell/stack assembly units may have no exhaust port for the anode gas or cathode gas because of the configuration of the cells. In such cases, the gas flow field pattern and its material shall be determined by the method recommended by the manufacturer. The load application method shall be also based on the recommendation of the manufacturer. The maximum operating temperature from the manufacturer shall not be exceeded.

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, as a minimum:

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

b) flow patterns and directions of anode and cathode gases;

c) locations of temperature measurement, mechanical load application, voltage measurement and current leads;

d) magnitude of the mechanical load;

e) configuration of assembly unit and its assembling method.

6 Testing system

6.1 Subsystems in testing system

6.1.1 General

As shown in Figure 1, a testing system consists of an anode gas control subsystem, cathode gas control subsystem, cell/stack assembly unit temperature control subsystem, output power control subsystem, measurement and data acquisition subsystem and safety subsystem. It may also include a mechanical load control subsystem, anode gas and cathode gas pressure control subsystem and/or a test system control subsystem that controls the whole testing system, if needed.

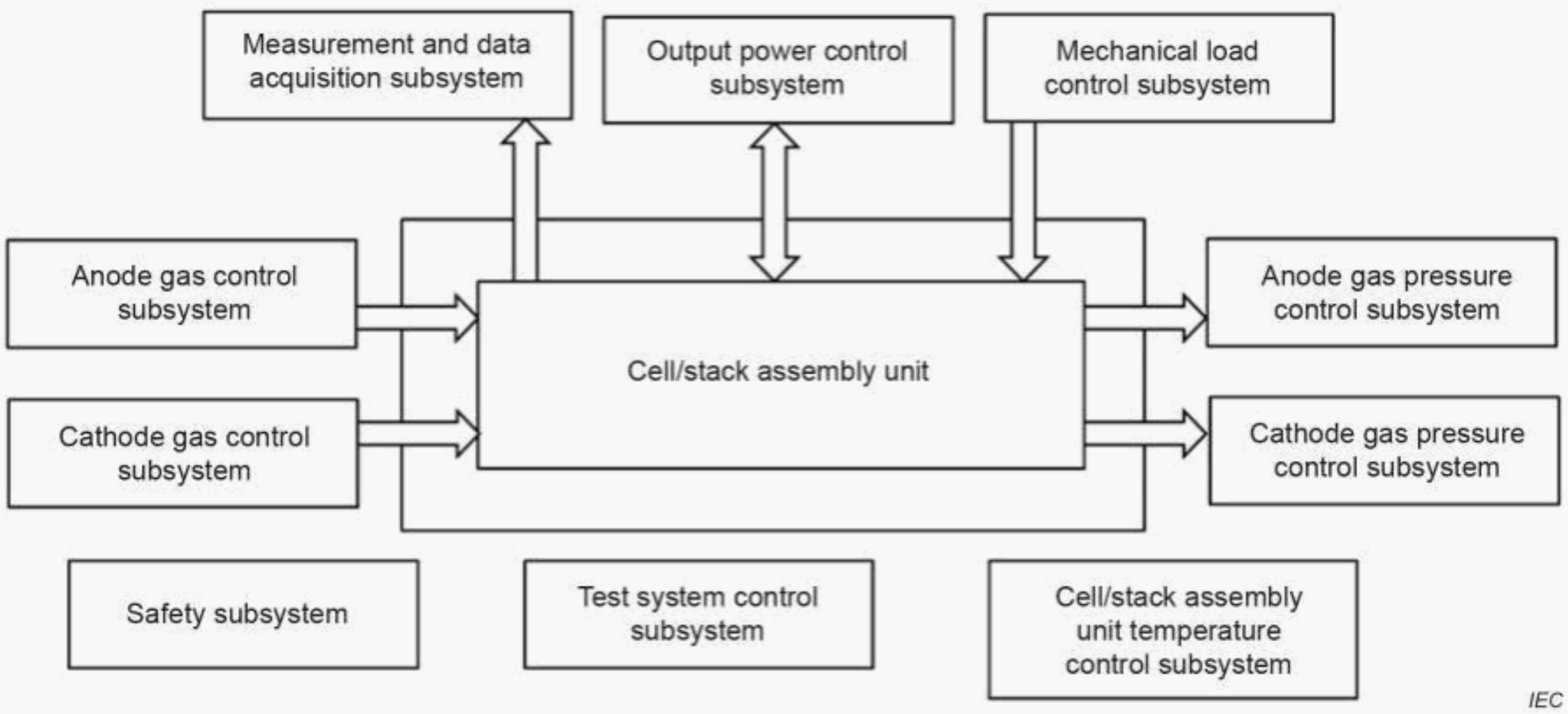


Figure 1 – Testing system

6.1.2 Anode gas control subsystem

The anode gas control subsystem controls the flow rate, composition and temperature of the anode 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.

Care should be taken to avoid other phenomena, such as carbon deposits, and the evaporation and transport of undesired materials in the gas streams, such as chromium.

6.1.3 Cathode gas control subsystem

The cathode gas control subsystem controls the flow rate, composition and temperature of the cathode gas supplied to the cell/stack assembly unit.

6.1.4 Cell/stack assembly unit temperature control subsystem

The cell/stack assembly unit temperature control subsystem controls, at least, the electric furnace or the unit temperature. It maintains the operating temperature. The electric furnace shall be selected to maintain the temperature distribution within the specified tolerance level. Efforts should 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 electrical furnace for simplicity and safety reasons.

6.1.5 Output power control subsystem

The output power control subsystem controls the output current or output voltage of the cell/stack assembly unit.

6.1.6 Measurement and data acquisition subsystem

The measurement and data acquisition subsystem acquires and records the cell/stack assembly unit temperature, current, voltage, anode gas flow rate, cathode gas flow rate, and optionally, environmental conditions (ambient temperature, relative humidity, and atmospheric pressure) in accordance with the specified method. If necessary, it also acquires and records the mechanical load applied to the cell; the temperature, composition and pressure of the cathode gas and the anode gas; the flow rate, composition, temperature and pressure of anode and cathode exhaust gases; and cell/stack assembly unit impedance data, etc., in accordance with the specified method.

6.1.7 Safety subsystem

The safety subsystem functions as a detector and alarm system for 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 anode should be purged with an inert gas, such as nitrogen, which could also contain hydrogen at concentrations below the lower flammability limit.

6.1.8 Mechanical load control subsystem

The optional mechanical load control subsystem regulates the mechanical load that is applied to increase the contact among components in the cell/stack assembly unit. The subsystem should be strong enough to apply the required mechanical load under the test conditions and to maintain the load for long term operation.

6.1.9 Gas pressure control subsystem for anode and cathode

The optional gas pressure control subsystem for anode and cathode gases regulates the pressure of these gases by the use of a back pressure control valve, etc.

6.1.10 Test system control subsystem

The test system control subsystem provides the integrated control for each control subsystem and data acquisition subsystem.

6.2 Maximum variation in control items of testing system

The tolerable variation of each control item in the testing system shall fall within the following ranges:

In the case of current control:	current: ±1 % relative to rated value point;
In the case of voltage control:	voltage: ±1 % relative to set point;
Temperature:	±1,0 % relative to set point;

NOTE 1 Temperature variation at the set point of less than ±5 K will increase reproducibility.

Anode and cathode gas flow rates:	±1 % relative to rated;
Anode gas composition:	±2,0 mol % for H_2, N_2; ±2,0 mol % for CO, CO_2, CH_4; ±5,0 mol % for H_2O (water vapour concentration);
In case of bubbler or sparger humidification:	Dew point temperature: ±1 °C;

NOTE 2 At water vapour concentrations greater than 10 mol %, a bubbler system (sparger) can cause higher uncertainty.

Cathode gas composition:	±1,0 mol % of the target O_2 concentration;
Where pressures of anode and cathode gases are to be controlled, pressures of anode and cathode gases:	±1 % of rated condition, when pressure of rated condition is equal to or larger than 0,3 MPa; and 3 kPa, when pressure of rated condition is smaller than 0,3 MPa.

7 Instruments and measurement methods

7.1 General

Measuring instruments shall meet the requirement of 7.2. As a minimum, the flow rate and composition of the anode and cathode gases as well as the temperature, voltage, and current of the cell/stack assembly unit shall be measured. Additional measurements shall be taken based on the test parameters and/or test conditions. Some of the following items specified in 7.3 or 7.4 may not be measurable in the case of a cell/stack assembly unit having no anode or cathode gas exhaust port.

7.2 Instrument uncertainty

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 meet the following requirements:

NOTE Coverage factor is defined in ISO/IEC Guide 98-3.

Current:	±1 % relative to rated;
Voltage:	±0,5 % relative to OCV;
Temperature:	±1,0 % of reading;
Flow rates of anode and cathode gases:	±2 % of rated;
Pressures of anode and cathode gases:	±1 % of reading;average
Anode gas composition:	±2 mol % for H_2, H_2O, and N_2; ±1 mol % for CO, CO_2, and CH_4;
Cathode gas composition:	±0,3 mol % for O_2 (balance N_2).

7.3 Anode gas

7.3.1 Anode gas flow rate

The anode gas flow rate shall be measured using mass flow meters, volumetric flow meters or turbine-type flow meters. The flow meter shall be selected by taking into consideration the species in the supplied gas, the range of flow rates, and the allowable uncertainty of the flow meter. When measurements are made on a volumetric basis, they shall be converted to mass flow rate by measuring the gas temperature and pressure or gas density in the vicinity of the flow meters. Measurement uncertainty for dry gases should be evaluated in accordance with ISO 5168 or ISO 7066-2.

7.3.2 Anode gas composition

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

When anode gas is supplied in one of the following conditions a) to d) below, and if the gas supply line has no reactors, such as a reformer, and is confirmed to insignificantly change the gas composition, 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) a single-composition gas such as hydrogen is supplied;

b) a mixed gas of known composition is supplied;

c) anode gas is supplied by mixing component gases in a controlled manner using multiple flow meters;

d) gases under b) and c) above are supplied in combination.

The anode gas shall be sampled near the anode gas supply port of the cell/stack assembly unit and analysed using an infrared spectroscopy, mass spectrometer, gas chromatograph or similar device. 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 necessary, it shall be heated to avoid the condensation of the water vapour.

If water vapour is likely to affect measurement, remove water from the gas sample or dilute the gas sample with argon or a similar inert gas.

The result of such analysis for gas component i, expressed as c_i (mol/m 3) shall be normalized to obtain a normalized concentration, xi (mol /mol), using the following equation:

$$xi = \frac{c_i}{\sum_{ici}} \quad (1)$$

where $\sum_{ici}$ represents the sum of concentrations of all component gases in the analysis.

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.

7.3.3 Anode gas temperature

The gas temperature shall be measured near the anode gas supply port of the cell/stack assembly unit by using a thermocouple or sheathed thermocouple and an extension leadwire of a type and class in accordance with IEC 60584-1, IEC 60584-3 or IEC 61515. When there is a reactor such as a reformer, the gas temperature at the exit of the reactor should also be measured.

NOTE There can be significant differences between the temperature of the tube wall and the temperature of the bulk gas.

If it is difficult to measure the gas temperature during the cell performance test, the anode gas temperature shall be measured during the preparation of the performance test under the same conditions as those of the performance test.

7.3.4 Anode gas pressure

The anode gas pressure shall be measured upstream of the anode gas supply port of the cell/stack assembly unit by using a calibrated 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, piping temperature and other factors. Condensation of water vapour during measurement shall be prevented. One way 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.

7.3.5 Anode exhaust gas flow rate

The anode exhaust gas flow rate shall be measured using mass flow meters, volumetric flow meters or turbine-type flow meters after implementing a means to prevent water condensation from affecting the stability of anode gas flow or after removing water from the gas flow. When measurements are made on a volumetric basis, they shall be converted to mass flow rate by measuring the gas temperature and pressure or gas density in the vicinity of the flow meters. Alternatively, the anode exhaust gas flow rate can be calculated from the component concentrations of the anode exhaust gas, tracer concentration and tracer flow rate by precisely adding a minute amount of a gas that is not contained in the anode exhaust gas as the tracer. The gas analyser shall be calibrated using a standard gas of known mass ratio. Measurement uncertainty shall be evaluated in accordance with ISO 6974 (all parts), ISO 6141, ISO 6142-1, or ISO 6143.

The exhaust gas shall be handled with caution for reasons of safety and the environment, since it may still contain hydrogen, carbon monoxide and hydrocarbons.

7.3.6 Anode exhaust gas component

The anode exhaust gas shall be sampled near the anode gas exhaust port of the cell/stack assembly unit. The sample shall be analysed using an infrared spectrophotometer, mass spectrometer, gas chromatograph or similar device. If water vapour is likely to affect the measurement, remove water from the gas sample or dilute the sample with argon gas or similar. When measuring, attention shall be paid to the materials, temperature, inner diameter and length of piping in order to ensure that any changes the gas composition may have within the piping are insignificant. In particular, the piping shall be heated where necessary to prevent water vapour from condensing in the piping. The gas analyser shall be calibrated using a standard gas of known mass ratio.

7.3.7 Anode exhaust gas temperature

The gas temperature shall be measured near the anode gas exhaust port of the cell/stack assembly unit by selecting a thermocouple or sheathed thermocouple, and an extension lead wire of the type and class that are appropriate and in accordance with IEC 61515, IEC 60584-1 or IEC 60584-3. If it is difficult to measure the gas temperature during the cell performance test, the anode exhaust gas temperature shall be measured during the preparation of the performance test under the same conditions as those of the performance test.

NOTE There can be significant differences between the temperature of the tube wall and the temperature of the bulk gas.

7.3.8 Anode exhaust gas pressure

The anode exhaust gas pressure shall be measured downstream of the anode gas exhaust port of the cell/stack assembly unit by using a pressure sensor, manometer, Bourdon tube or similar device. The measuring instrument should be located in such a manner that the uncertainty is minimized in consideration of any pressure loss within the piping, piping (gas) temperature and other factors. Condensation of water vapour during measurement shall be prevented. One way 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.

7.4 Cathode gas

7.4.1 Cathode gas flow rate

The cathode gas flow rate shall be measured by using mass flow meters, volumetric flow meters or turbine-type flow meters. When measurements are made on a volumetric basis, they shall be converted to mass flow rate by measuring the gas temperature and pressure or gas density in the vicinity of the flow meters. The flow meter shall be selected in consideration of 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.

7.4.2 Cathode gas component

For cathode gas composition, the oxygen concentration shall be measured using a gas chromatograph or an oxygen concentration meter. The cathode gas should consist of clean (oil-free), compressed air or bottled gas. If a bottled gas mixture is used, the values described on its composition certificate published by the gas supplier may be used. 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.

When it is necessary to measure humidity, a dew point meter, water content meter or gas chromatograph shall be used while controlling the gas temperature to prevent condensation of water vapour.

7.4.3 Cathode gas temperature

The gas temperature shall be measured near the cathode gas supply port of the cell/stack assembly unit by selecting a thermocouple or sheathed thermocouple, and an extension leadwire of the type and class that are appropriate in accordance with IEC 60584-1, IEC 60584-3 or IEC 61515.

NOTE There can be significant differences between the temperature of the tube wall and the temperature of the bulk gas.

If it is difficult to measure the gas temperature during the cell performance test, the cathode gas temperature shall be measured during the preparation of the performance test under the same conditions as those of the performance test.

7.4.4 Cathode gas pressure

The cathode gas pressure shall be measured upstream of the cathode gas supply port of the cell/stack assembly unit by using a pressure sensor, manometer, Bourdon tube, or similar device. The measuring instrument should be located in such a manner that the uncertainty is minimized in consideration of any pressure loss within the piping, piping temperature, and other factors.

7.4.5 Cathode exhaust gas flow rate

The cathode exhaust gas flow rate shall be measured using a mass flow meter, volumetric flow meters or turbine-type flow meters after cooling the gas. When measurements are made on a volumetric basis, they shall be converted to mass flow rate by measuring the gas temperature and pressure or gas density in the vicinity of the flow meters. The flow meter shall be selected in consideration of 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.

7.4.6 Cathode exhaust gas component

For cathode exhaust gas composition, the oxygen concentration shall be measured using a gas chromatograph or an oxygen concentration meter after cooling the gas. When it is necessary to measure an extremely low water concentration, a dew point meter, water content meter or gas chromatograph shall be used while controlling the gas temperature to prevent condensation of water vapour.

7.4.7 Cathode exhaust gas temperature

The cathode exhaust gas temperature shall be measured near the cathode gas exhaust port of the cell/stack assembly unit by selecting a thermocouple or sheathed thermocouple and an extension leadwire of the type and class that are appropriate in accordance with IEC 60584-1, IEC 60584-3 or IEC 61515. If it is difficult to measure the gas temperature during the cell performance test, the cathode exhaust gas temperature shall be measured during the preparation of the performance test under the same conditions as those of the performance test.

NOTE There can be significant differences between the temperature of the tube wall and the temperature of the bulk gas.

7.4.8 Cathode exhaust gas pressure

The cathode exhaust gas pressure shall be measured downstream of the cathode gas exhaust port of the cell/stack assembly unit by using a pressure sensor, manometer, Bourdon tube or similar device. The measuring instrument should be located in such a manner that the uncertainty is minimized in consideration of any pressure loss within the piping, piping temperature and other factors.

7.5 Output voltage

A voltage meter shall be connected to the voltage measuring points, as described in Clause 5. The voltage thus measured shall be deemed to be the voltage of the cell/stack. The connecting cable shall be durable enough for the test conditions.

7.6 Output current

A galvanostat or electric load connected to the current lead 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 or recording instrument. The connecting cable shall be selected for appropriate materials and geometry in consideration of the test conditions and possible voltage drop within the cable.

7.7 Cell/stack assembly unit temperature

A thermocouple, or sheathed thermocouple, and an extension leadwire of the type and class that are appropriate shall be selected in accordance with IEC 60584-1, IEC 60584-3 or IEC 61515. They shall be placed at the temperature measuring point as described in Clause 5 and connected with a recorder or similar device 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.

7.8 Mechanical load

A mechanical load applied as recommended by the manufacturer shall be measured.

7.9 Total impedance

The total impedance of the cell/stack assembly unit shall be measured by either the AC impedance method 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.

7.10 Ambient conditions

In defining the ambient conditions, ambient temperature, pressure and relative humidity shall be measured. The sampling interval shall be the value specified in ISO 8756 or less.

8 Test preparation

8.1 General

The type of cell/stack assembly unit to be tested, the number of samples, test parameters, and test conditions shall be determined.

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. The method and cycle of calibration and replacement shall be designed to ensure that there is no increase in measurement uncertainty.

The components of the anode and cathode gases and their main impurities shall be verified. As described in Clause 7, a preliminary test shall be performed for gas composition and temperature in order to ensure that the gas compositions are established within the anticipated uncertainty and that the supply gas temperature does not affect the unit temperature. Further, the test procedure, test conditions, and judging criteria for stable state, among others, shall be determined based on the preliminary test results and other factors.

8.2 Standard test conditions and test range

The standard test conditions and the typical test range that are recommended by the manufacturer shall be reviewed for the following parameters in order to determine the test conditions and range:

a) cell/stack assembly unit temperature;
b) allowable cell/stack assembly unit temperature distribution (if multiple measuring points);
c) anode gas flow rate;
d) anode gas composition;
e) anode gas pressure;
f) cathode gas flow rate;
g) cathode gas composition;
h) cathode gas pressure;
i) effective fuel utilization;
j) effective oxygen utilization;
k) current or current density;
l) minimum cell/stack assembly unit voltage;
m) minimum cell/stack assembly unit current (under a constant effective fuel utilization, see Annex E for more information);
n) maximum cell/stack assembly unit current (under a constant effective fuel utilization). Damage due to excessive degradation is possible beyond this value;
o) mechanical load.

8.3 Components and impurities of anode gas and cathode gas

If gases are used to prepare the anode gas, purity level or components and major impurities of each gas shall be verified by the composition tables published by the respective gas suppliers or through analysis. When the anode gas is produced from liquid fuel, its density, its carbon, hydrogen, and oxygen content, and content of impurities, such as sulphur, shall be verified by the composition table published by the gas supplier or through analysis in accordance with ISO 12185.

The purity or components and major impurities of the cathode gas shall be verified by the composition table published by the gas supplier or through analysis. If a compressor is used, the compressed air shall be free of oil and particles in accordance with ISO 8573-1.

The result of each verification or analysis shall be described in the test report.

8.4 Basis of the test procedure

The start-up conditions, such as heating rate and ambient conditions during the heating ramp, the condition of the anode (i.e. the extent of reduction of the nickel oxide to nickel), and the shut-down conditions, such as cooling rate and ambient conditions during the cooling ramp, shall be based on those recommended by the manufacturer or the results of preliminary tests.

8.5 Confirmation of aging conditions of unit

The aging conditions of the cell/stack assembly unit shall be determined based on the aging conditions recommended by the manufacturer, as well as the preliminary tests to be conducted, to ensure that the output drift at the time of measurement is insignificant.

8.6 Confirmation of criteria of stable state

The tolerance level of variation shall be determined for the output current or output voltage of the cell/stack assembly unit, and the judgement criteria of stable state shall be determined through preliminary testing and others.

The judgement criteria of stable state shall be described in the test report.

8.7 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 of the measured 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.

9 Test procedure

9.1 Set-up

The test set-up procedure shall be as follows:

a) Check each control or measurement subsystem 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 should be verified by comparing its performance with the parameters specified in 7.2.

b) 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 cathode and anode current lead points to determine if there is a short-circuit. Measure the resistance between cell voltage measuring points to determine if they are electrically insulated. Measure the cell-to-cell resistances. These values should not indicate a short-circuit, but, rather, should be similar to those specified by the manufacturer.

c) Set up the cell/stack assembly unit in a temperature control subsystem and install the wiring for voltage measurement and current leads, the mechanical load, and thermocouples as well as the piping for the gas supply and exhaust. Connect the wires to their corresponding subsystems. Ensure proper insulation between thermocouples and the cell/stack. There should also be electrical insulation between the mechanical load and the cell/stack.

d) Check gas pipe connections for leakage (see 9.1.a).

e) If needed, verify the wiring for insulation to earth. It is recommended to check the insulation before the output control subsystem or measurement subsystem is connected. In addition, proper wiring shall be verified at joint connections.

f) When the above are all completed, the measurement subsystem is checked for its proper operation.

9.2 Initial conditioning

The cell/stack assembly unit shall be started up at the temperature increasing rate and ambient conditions as specified in 8.4 and operated until it reaches the stable state after going through anode reduction and conditioning.

9.3 Shut-down

The shut-down procedure shall be initiated at the specified temperature decreasing rate and ambient conditions as specified in 8.4. Unless otherwise provided, the temperature shall be decreased under such conditions as the user has determined, based on preliminary tests or as directed by the manufacturer. During this time, the air flow to the air electrode is maintained and hydrogen diluted with nitrogen (or other inert gas) is flowing to the fuel electrode. The concentration of hydrogen in this gas mixture shall be below the lower explosive limit.

10 Performance test

10.1 Rated power test

10.1.1 Objective

The objective of this test is to measure and verify the output of the cell/stack assembly unit under rated conditions.

10.1.2 Test method

All control parameters shall be set at rated conditions, and after the cell/stack assembly unit has reached the stable state, the voltage, current and other control parameters shall be measured repeatedly at a sampling interval until the number of samples and measurements are obtained as specified in 8.7. The average value of the measurements shall be the measured value. Optionally, include the standard deviation of the measurements.

10.1.3 Presentation of results

The measurement results shall be used to calculate the rated power output and recorded in the test report with voltage, current and other measurements of the test conditions.

10.2 Current-voltage characteristics test

10.2.1 Objective

The objective of this test is to determine the dependency of current-voltage characteristics on temperature, pressure, gas composition, gas flow rate or effective gas utilization.

10.2.2 Test method

10.2.2.1 Test under constant flow rate

The control parameter on which the dependency is to be measured shall be set at its initial value while the anode gas and cathode gas flow rates as well as other control parameters shall be set at those of the test conditions. The unit shall be operated until the stable state is reached under open-circuit conditions, and current-voltage characteristics are measured by changing the current or voltage stepwise, or sweeping it at a constant speed. After the measurement, the control parameter is set to the next value and the measurement shall be repeated within the measuring range specified in 8.2.

a) When current is step-changed, the cell/stack assembly unit shall be operated until it reaches the stable state in each step (temperature and voltage), and at each step measurements are taken over the duration of time at the sampling intervals as specified in 8.7. The average value of the measurements after the stable state is reached shall be the measured value for that step.

b) When a current sweep is used, the sweep speed shall be determined such that the maximum width of the voltage hysteresis does not exceed the voltage variation in the stable state.

c) When voltage control is used, step a) or b) shall be taken with step voltage or voltage sweep, respectively.

NOTE The meaning of the maximum width of the voltage hysteresis is explained in Annex D.

10.2.2.2 Test under constant effective fuel and/or oxygen utilization, or constant stoichiometric ratio

The control parameter on which the dependency is to be measured shall be set at its initial value while effective fuel utilization and/or effective oxygen utilization, and other control parameters shall be set at those of the test operating conditions given in 8.2. The unit shall be operated at the minimum current specified by the manufacturer until it reaches the stable state, and current-voltage characteristics shall be measured by changing the current or voltage stepwise. The unit shall be operated in each step until it reaches the stable state with measurements being taken over the duration of time at the sampling rate as specified in 8.7. The average value of the measurements after the stable state is reached shall be the measured value for that step. After the measurement, the control parameter is set to the next value and the measurement shall be repeated within the measuring range specified in 8.2.

An example of the record of I-V characteristics test under constant effective fuel utilization is given in Annex E.

10.2.3 Presentation of results

The results shall be expressed in a two-dimensional plot with its horizontal axis representing current density or effective fuel utilization, or a combination of current density and fuel utilization, and its vertical axis representing cell/stack assembly unit voltage. This plot shall be included in the test report with the other test conditions. Alternatively to the stack voltage, the measured cell voltages or the average repeating unit voltage may be plotted against current density. Optionally, include the standard deviation of the measurements.

10.3 Effective fuel utilization dependency test

10.3.1 Objective

The objective of this test is to study the dependency of the performance of the cell/stack assembly unit on effective fuel utilization and to confirm the maximum effective fuel utilization under various operating conditions.

10.3.2 Test method

10.3.2.1 General

The maximum fuel utilization as well as the conditions used to obtain this value shall be obtained from the manufacturer or determined through consultation between the manufacturer and the evaluator.

The test shall be conducted either by decreasing the anode gas flow rate at constant current or by increasing the current at constant anode gas flow rate.

10.3.2.2 Test at constant current

The following steps shall be carried out:

a) Set the cell/stack assembly unit at the test conditions as specified in 8.2, operate it and verify that it has reached the stable state.

b) Decrease the anode gas flow rate stepwise until the cell/stack assembly unit reaches the maximum effective fuel utilization as specified by the manufacturer. For each step, verify that the voltage has reached the stable state and record it.

c) When the fuel utilization reaches the maximum effective value, return the anode gas flow rate stepwise to the original value and record the voltage. Comparing this voltage to that before this step provides information about whether or not the maximum effective fuel utilization specified by the manufacturer as achievable, if only for a short period of time, can be reached by the cell/stack assembly unit. This is different to that seen in 10.4.

10.3.2.3 Test at constant anode gas flow rate

The following steps shall be carried out:

a) Set the cell/stack assembly unit at the specified test conditions, operate it and verify that it has reached the stable state.

b) Increase the current stepwise until the cell/stack assembly unit reaches the maximum effective fuel utilization. For each step, verify that the voltage has reached the stable state and record it.

c) When the fuel utilization reaches the maximum effective value, return the current to the original value stepwise and record the voltage. Comparing this voltage to that before this step provides information about the maximum effective fuel utilization which can be achieved by the cell/stack assembly unit, if only for a short period of time. This is different to that seen in 10.4.

The criteria for suspending the test should be determined in advance either by preliminary testing or by consulting with the manufacturer in order to prevent any performance degradation or damage to the cell/stack assembly unit.

10.3.3 Presentation of results

The results shall be expressed in a two-dimensional plot with its horizontal axis representing effective fuel utilization, or a combination of anode gas flow rate and effective fuel utilization in the case of 10.3.2.2, and effective fuel utilization, or a combination of current density and effective fuel utilization in the case of 10.3.2.3, and its vertical axis representing the cell/stack assembly unit voltage. This plot shall be included in the test report with the other test conditions.

The stack assembly unit voltage can be replaced by the average repeating unit voltage. Alternatively, the measured cell voltages may be plotted against current density.

10.4 Long term durability test

10.4.1 Objective

The objective of this test is to evaluate the performance degradation of the cell/stack assembly unit when it is exposed to certain test conditions over a long period of time and to examine the effect of temperature, current, gas composition, gas impurities and other factors on the durability of the cell/stack assembly unit.

10.4.2 Test method

10.4.2.1 General

This test shall be conducted by maintaining the test conditions constant for the duration of the test, either measuring change in the cell/stack assembly unit voltage at constant current, or measuring change in the unit voltage together with total resistance. The total resistance shall be measured at a certain interval (100 h to 500 h) by the I-V curve in 10.2 or the impedance spectrum in 10.7.

10.4.2.2 Voltage change in long term durability test

Set up all the controlling parameters at the specified test conditions and measure the voltage of the cell/stack assembly unit at regular intervals. The measured values shall be used to obtain the rate of voltage change for the entire test period or the specific time duration.

10.4.2.3 Total resistance change in long term durability test

This test may be performed during 10.4.2.2.

The following method shall be used for the measurement of total resistance:

a) Measure whole I-V characteristics between 0 to maximum current as specified in 8.2, or measure partial I-V characteristics in the vicinity of the holding current, both in a similar manner to that stated in 10.2.

b) Derive the approximate tangent to the I-V curve at holding current by connecting two points on the I-V curve in the vicinity across the holding current and find the slope of the tangent. Report the slope as total resistance.

   Selection of the points in the vicinity of the holding current requires care. The points should be closer to the holding current when the curvature of the I-V curve is large. The uncertainty in the voltage and current measurements should be kept as small as possible.

c) After measuring the I-V curve, restore the values to those of the original test conditions and measure voltage until the next measuring cycle.

d) Repeat this measurement at a certain interval throughout the test duration.

The results shall be used to calculate the voltage variation rate and total resistance variation rate for the entire test period or specific time duration within the test period.

It is also possible to measure the total impedance described in 10.7 at the time of total resistance measurement.

10.4.3 Presentation of results

In the case of 10.4.2.2, the results shall be expressed in a two-dimensional plot with the horizontal axis representing time and the vertical axis representing voltage and shall be included in the test report with the voltage change rate and test conditions. In the case of 10.4.2.3, the vertical axis shall represent voltage and total resistance, and the plot shall be included in the test report along with voltage change rate, total resistance variation rate and test conditions.

The stack assembly unit voltage may be replaced with the average repeating unit voltage. Alternatively, the measured cell voltages may be plotted against time.

NOTE These results can also be represented as area-specific resistance (or impedance). Here, the area-specific resistance (impedance) equals the measured resistance (impedance) multiplied by the active electrode area.

10.5 Thermal cycling durability test

10.5.1 Objective

The objective of this test is to evaluate the durability of the cell/stack assembly unit with thermal cycling. The thermal cycles shall be within the manufacturer's specifications.

10.5.2 Test method

10.5.2.1 General

For this test, the following test conditions shall be obtained from the manufacturer or determined through consultation between the manufacturer and the evaluator in advance.

The operating temperature shall be the temperature of the standard test conditions.

a) number of thermal cycles;
b) cooling rate;
c) heating rate;
d) minimum temperature;
e) operating conditions at operating temperature;
f) period to maintain operating temperature;
g) period to maintain minimum temperature;
h) total test period;
i) gas flow rate and composition at heating and cooling conditions, and minimum temperature, respectively.

10.5.2.2 Test procedure

In accordance with the above test conditions, either the method of measuring cell/stack assembly unit voltage variation at the operating temperature or measuring total resistance together with cell/stack assembly unit voltage shall be chosen. When measuring total resistance, follow the method of 10.4.2.3. The voltage shall be measured over the specified duration of time. After a certain operating temperature period, the temperature of the cell/stack assembly unit shall be decreased to the minimum temperature with the cell/stack assembly unit at open circuit under the specified conditions, and the minimum temperature shall be maintained for the specified time. The temperature of the cell/stack assembly unit shall then be raised under the specified conditions to the operating temperature and the measurement shall resume as before.

These measurements shall be repeated until the specified number is reached. The results obtained shall be used to calculate the voltage variation rate and total resistance variation rate over the entire test period or specific time duration within the test period.

10.5.3 Presentation of results

The results shall be expressed in a two-dimensional plot with the horizontal axis representing either (a) time or (b) number of cycles. The test conditions shall also be described in the test report.

If (a), unit voltage, total resistance (optional), and temperature shall be plotted on the vertical axis.

If (b), unit voltage and total resistance (optional) shall be plotted on the vertical axis.

10.6 Internal reforming performance test

10.6.1 Objective

The objective of this test is to evaluate the internal reforming performance of the cell/stack assembly unit under the open-circuit conditions or rated conditions against hydrocarbons (HC) such as methane contained in the anode gas.

10.6.2 Test method

10.6.2.1 General

This test shall be performed in accordance with the manufacturer's recommendation or after consultation between the manufacturer and the evaluator regarding the cell/stack's ability to reform HCs internally; some cell/stack assembly units may not be able to do so.

NOTE Many complex reactions can occur with HC-containing anode gases, depending on composition and thermodynamic equilibria. These reactions can affect the temperature gradients in the cell and stack.

This test is applicable when anode gas and anode exhaust gas can be sampled without any mixing with cathode gas or cathode exhaust gas.

10.6.2.2 Test procedure

Anode gas containing HCs shall be supplied to the cell/stack assembly unit. After the unit reaches the stable state in the open circuit or rated conditions, the anode gas and anode exhaust gas shall be analysed for their compositions; these are used to calculate the HC conversion rate that indicates the internal reforming characteristic.

The HC conversion rate for a specific HC $_j$, ξ_j (%) is calculated as follows:

$$\xi_j = 100 \left(q_{\mathrm{HC},\ j,\ \mathrm{in}} - q_{\mathrm{HC},\ j,\ \mathrm{out}} \right) / \ q_{\mathrm{HC},\ j,\ \mathrm{in}} \qquad (2)$$

where $q_{\mathrm{HC},\ j,\mathrm{in}}$ and $q_{\mathrm{HC},\ j,\mathrm{out}}$ represent the flow rates of the specific HC $_j$ at the anode inlet and outlet, respectively, which are calculated from the anode gas flow rate and its HC concentration, and the anode exhaust gas flow rate and its HC concentration, respectively.

10.6.3 Presentation of results

The compositions and flow rates of anode gas and anode exhaust gas as well as the HC conversion rate shall be described in the test report with the test conditions.

10.7 Resistance components identification test

10.7.1 Objective

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.

10.7.2 Test method

10.7.2.1 General

The separation of resistance components of the cell/stack assembly unit shall be evaluated by either the AC impedance method or the current interruption method.

10.7.2.2 AC electrochemical impedance method

The following test conditions shall be determined in advance by conducting preliminary tests.

a) Measuring range for frequencies:

The highest frequency should roughly identify point A, and the lowest frequency should roughly identify point C when plotted in the complex impedance diagram (see Figure 2).

b) Number of measuring points:

Four to twenty points per one order of frequencies (to be distributed evenly as logarithms, if possible) shall be 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.

The test shall be conducted using the following procedure:

a) establish the test conditions;

b) verify that the stable state has been reached;

c) superimpose AC sinusoidal waves on DC current or voltage and start measurements. Sweep the AC sinusoidal waves within the specified frequency range and measure the impedance at each frequency.

The amplitude of the AC signal for the measurement shall be enough to activate the cell but not overly polarize it. The amplitude per cell may be obtained by dividing the total voltage amplitude with the number of cells in series. As an option, the validity of the impedance spectrum shall be verified by using appropriate validation relations such as the Kramers-Kronig (KK) relationships or Z-hit.

10.7.2.3 Current interruption method

When employing this method, the current interruption characteristics and sampling rate to allow the evaluation of a target property of the cell/stack assembly unit shall be identified by preliminary testing. Measurements shall be taken after ensuring that the unit is in the stable state under the test conditions.

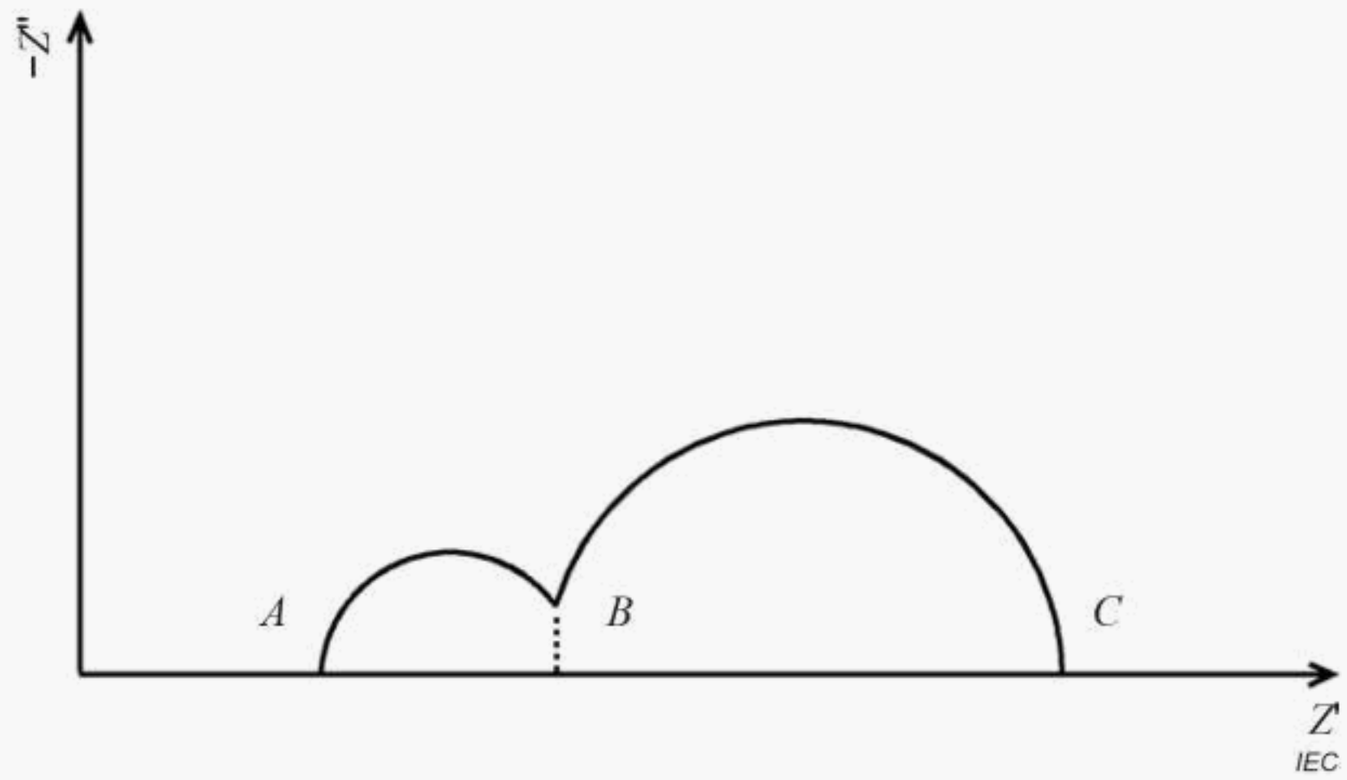
10.7.3 Presentation of results

a) AC impedance method

The test results shall be expressed as a complex impedance or Cole-Cole plot (indicate characteristic frequencies) or Bode plot (a plot of impedance components against the logarithm of measured frequency). The impedance per unit area calculated by active area defined in 3.1.2 shall be plotted.

b) Current interruption method

The current (density) and voltage response waveforms observed before and after current interruption shall be plotted against the time axis. The sampling rate shall be appropriate to identify the ohmic resistance component. The ohmic resistance component so obtained shall be reported with the test conditions.



Key

A	high frequency end impedance
C	low frequency end impedance
$A–B$	high frequency arc impedance
$B–C$	low frequency arc impedance
Z'	real part of impedance
$-Z''$	imaginary part of impedance

Figure 2 – Typical diagram of complex impedance plot for SOFC

NOTE These results can also be represented as area-specific resistance (or impedance). Here, the area-specific resistance (impedance) equals the measured resistance (impedance) multiplied by the active electrode area.

11 Test report

11.1 General

Test reports shall accurately, clearly and objectively present sufficient information to demonstrate that all the objectives of the tests have been attained. A suggested template for the test report is given in Annex F.

11.2 Report items

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

a) title of the report;
b) authors of the report;
c) date of the report;
d) test report reference or identification number;
e) location and (start) date and time of the test;
f) test bench used;
g) test unit data (see 11.3 for details);

h) test conditions (see 11.4 for details);

i) test data (see 11.5 for details).

11.3 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 load application positions.

11.4 Test conditions description

The test conditions 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) aging conditions;

e) criteria of stable state;

f) data acquisition method;

g) gas purity and impurities;

h) test bench layout.

11.5 Test data description

Test data shall include the following information:

a) title of the test(s);

b) test operating conditions;

c) test result;

d) ambient conditions;

e) uncertainty evaluation (see 11.6 for details).

11.6 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 should be reported.

Annex A
(informative)

Example of cell assembly unit

An example configuration and test boundary of a cell assembly unit described in this document is shown in Figure A.1.

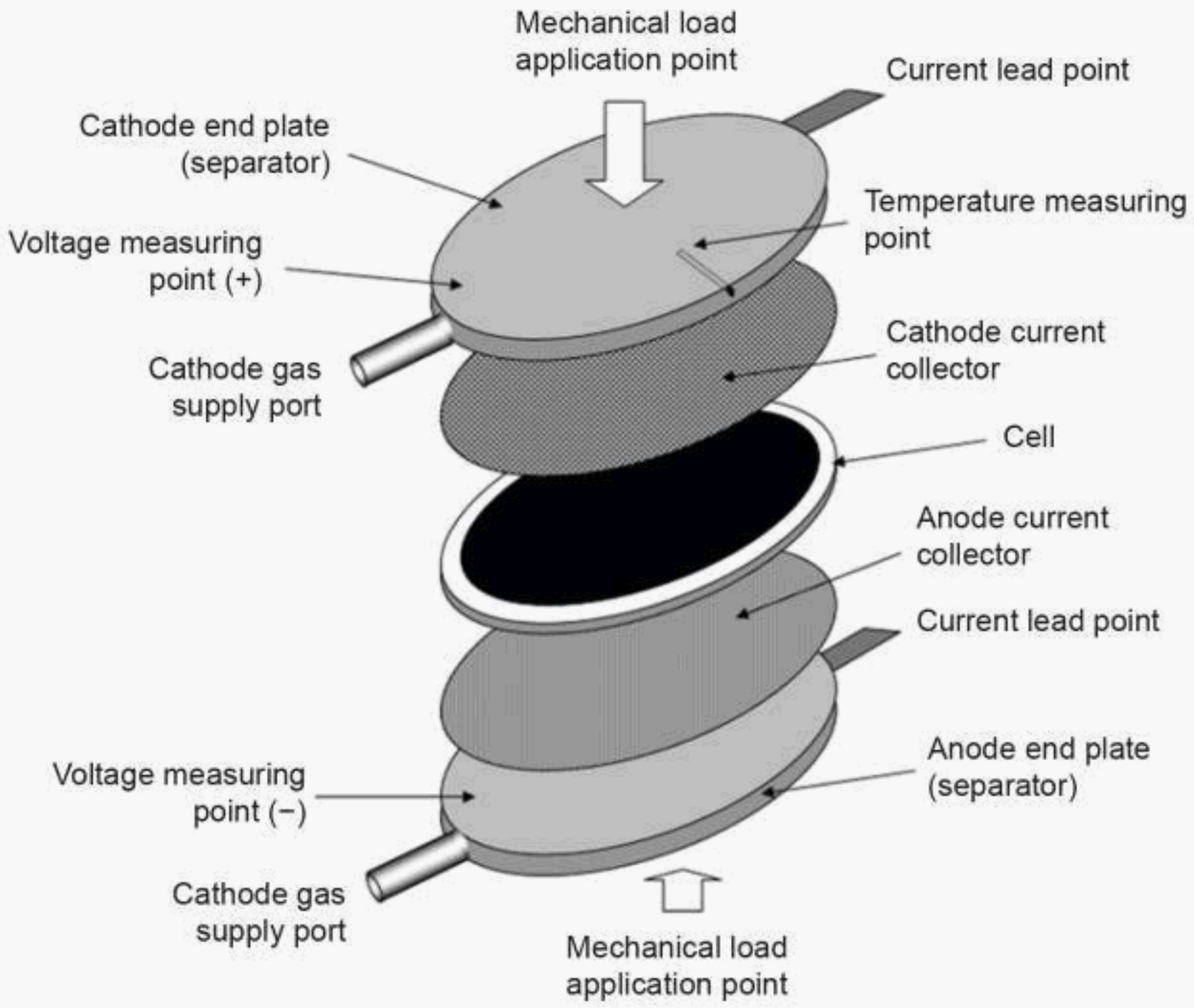


Figure A.1 – Example of cell assembly unit

In this schematic example, the cathode current collector and anode current collector also work as cathode gas flow channel and anode gas flow channel, respectively. The exhaust gas comes out from the respective circumference of each current collector.

NOTE It is possible to measure the voltage at the current collector to exclude the voltage drop due to contact resistances (plate-current collector).

Annex B
(informative)

Calculation of effective fuel utilization

B.1 General

Annex B describes a method for the calculation of effective fuel utilization as defined in 3.1.11.

B.2 Calculation method

In a performance test, an anode gas is supplied at a rate of q_a (l/min (STP)). The flow-rate of each fuel component in the anode gas is expressed as q_j (l/min (STP)) (j = H_2, CO, CH_4, …, $C_pH_qO_r$) where $C_pH_qO_r$ is the chemical formula of a general fuel. In the case that the anode gas composition is analysed, q_j shall be calculated from the molar fraction of each fuel component (x_j (mol /mol)) and q_a using Equation (B.1):

$$q_j = x_j \times q_a \tag{B.1}$$

In the example that follows, it is assumed that N cells are connected in series and that the fuel is uniformly distributed between the cells. A theoretical current defined in 3.1.10, I_{theory} (A), assuming that the supplied fuel gas is completely consumed in electrochemical reactions, shall be calculated from Equation (B.2):

$$I_{theory} = \frac{P_{st}}{R \times T_{st} \times 60 \times 1\,000} \times F \times \frac{\sum_j n_j \times q_j}{N} \tag{B.2}$$

$$= \frac{101\,325}{8{,}314\,51 \times 273{,}15 \times 60 \times 1\,000} \times 96\,485 \times \frac{\sum_j n_j \times q_j}{N} = 71{,}74 \times \frac{\sum_j n_j \times q_j}{N}$$

where

P_{st} is the standard pressure (101 325 Nm^{-2});

T_{st} is the standard temperature (273,15 K);

R is the gas constant (8,314 4 $Jmol^{-1}K^{-1}$);

F is Faraday's constant (96 485 C/mol);

n_j is the number of electrons transferred when one molecule of fuel component j is electrochemically reacted;

N is the number of cells in series.

The electron transferred, n_j for representative fuels, is determined by Equations (B.3) to (B.6) and is summarized in Table B.1. For the general $C_pH_qO_r$ component, n_j is equal to $4(p + q/4 - r/2)$:

$$H_2 + O^{2-} \rightarrow H_2O + 2e^- \tag{B.3}$$

$$CO + O^{2-} \rightarrow CO_2 + 2e^- \tag{B.4}$$

$$CH_4 + 4O^{2-} \rightarrow CO_2 + 2H_2O + 8e^- \quad \text{(B.5)}$$

$$C_pH_qO_r + 2(p + q/4 - r/2)O^{2-} \rightarrow pCO_2 + (q/2)H_2O + 4(p + q/4 - r/2)e^- \quad \text{(B.6)}$$

The measured current output of each cell or that from the total cell/stack assembly is expressed as $I_{measured}$. Therefore, effective fuel utilization, or U_f (%) can be calculated from Equation (B.7):

$$U_f = \frac{I_{measured}}{I_{theory}} \times 100\ \% \quad \text{(B.7)}$$

Table B.1 – n_j for representative fuels

Fuel	n_j
H_2	2
CO	2
CH_4	8
$C_pH_qO_r$	$4(p + q/4 - r/2)$

B.3 Calculation examples

B.3.1 Calculation from anode gas composition and flow-rate

Normalized anode gas mole fraction, x_i, is assumed to be as indicated in Table B.2 as a result of anode gas composition analysis. It is presumed that anode gas flow rate, q_a, is 0,500 l/min (STP). The flow rates, q_j, of H_2, CO and CH_4, which are fuel components in the anode gas, are calculated using Equation (B.1) as 0,281, 0,047, 0,003 l/min (STP), respectively. Then, $\sum_j n_j q_j$ is calculated by summing up each $n_j \times q_j$, leading to $\sum_j n_j q_j$ = 0,562 + 0,094 + 0,024 = 0,680 l/min (STP). Hence, if N = 10 cells, I_{theory} = 71,74 × 0,680/10 = 4,88 A is obtained using Equation (B.2). If it is assumed that the actual output current of the stack is 3,90 A, $I_{measured}$ is equal to 3,90 A. Therefore, effective fuel utilization can be calculated using Equation (B.7) as $U_f = \frac{3,90 \times 100}{4,88} = 80\ \%$.

Table B.2 – Anode gas composition, flow rate of each fuel component q_j, and $n_j q_j$

Component	x_i / mol %	q_j / l/min (STP)	$n_j q_j$ / l/min (STP)
H_2	56,1	56,1/100 × 0,500 = 0,281	2 × 0,281 = 0,562
H_2O	27,1		
CO	9,3	9,3/100 × 0,500 = 0,047	2 × 0,047 = 0,094
CO_2	7,1		
CH_4	0,5	0,5/100 × 0,500 = 0,003	8 × 0,003 = 0,024

B.3.2 Calculation from supplied H_2 and H_2O flow rate

It is assumed that H_2 and H_2O are supplied to the anode by controlling each flow rates. It is also assumed that in a performance test of a 40-cell-stack in which the number of series connection is 10 with 4 parallel connections, H_2 flow-rate, q_j, and output current are to be equal to 3,00 l/min (STP) and 32,3 A, respectively. Using Equation (B.2), I_{theory} is calculated as 71,74 × (2 × 3,00) / 10 = 43,0 A. Therefore, with $I_{measured}$ = 32,3 A, effective fuel utilization can be calculated as $U_f = \frac{32,3}{43,0} \times 100 = 75,1\%$ from Equation (B.7).

NOTE The number of parallel connections does not make any difference to the calculation.

Annex C
(informative)

Calculation of effective oxygen utilization

C.1 General

Annex C describes a method for the calculation of effective oxygen utilization as defined in 3.1.12.

C.2 Calculation method

In a performance test, a cathode gas is supplied at a rate of q_c (l/min (STP)). Oxygen flow-rate (q_{O2} (l/min (STP)) shall be calculated from oxygen molar fraction in the cathode gas, or x_{O2} (mol/mol), using Equation (C.1):

$$q_{O2} = x_{O2} \times q_c \tag{C.1}$$

The theoretical current defined in 3.1.10, I_{theory} (A), assuming that the cathode gas is uniformly distributed among N cells connected in series in the stack and that the cathode gas is completely consumed in electrochemical reactions, shall be calculated from Equation (C.2):

$$I_{theory} = \frac{P_{st}}{R \times T_{st} \times 60 \times 1\ 000} \times F \times \frac{n_{O2} \times q_{O2}}{N} \tag{C.2}$$

$$= \frac{8{,}314\ 51 \times 273{,}15}{101\ 325 \times 60 \times 1\ 000} \times 96\ 485 \times \frac{n_{O2} \times q_{O2}}{N} = 287{,}0 \times \frac{n_{O2} \times q_{O2}}{N}$$

where

P_{st} is the standard pressure (101 325 Nm^{-2});

T_{st} is the standard temperature (273,15 K);

R is the gas constant (8,314 4 Jmol^{-1}K^{-1});

F is Faraday's constant (96 485 C/mol);

n_{O2} is the number of electrons transferred when one molecule of oxygen is electrochemically reduced, leading to $n_{O2} = 4$ as shown in Equation (C.3), and

N is the number of cells connected in series:

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{C.3}$$

The measured current output of each cell or that from the total cell/stack assembly is expressed as $I_{measured}$. Therefore, effective oxygen utilization, or U_{O2} (%) shall be calculated from Equation (C.4):

$$U_{O2} = \frac{I_{measured}}{I_{theory}} \times 100\ \% \tag{C.4}$$

C.3 Calculation example

In a performance test, it is assumed that the cathode gas flow-rate, f_C, is 1,50 l/min (STP), there are $N = 10$ cells connected in series in the stack with the gas composition as indicated in Table C.1. f_{O2} = 0,314 l/min (STP) and I_{theory} = 9,01 A can be obtained using Equations (C.1) and (C.2), respectively. When the actual output current at the stack performance test is 2,70 A, $I_{measured}$ is equal to 2,70 A. Therefore, effective oxygen utilization can be calculated as U_{O2} = 2,70/9,01 × 100 = 30 % using Equation (C.4).

Table C.1 − Cathode gas composition, q_{O2}, and I_{theory}

Component	x_i / mol %	q_{O2} / l/min (STP)	I_{theory} / A
O_2	20,95	20,95/100 × 1,50 = 0,314	287,0 × 0,314/10 = 9,01
N_2	79,05		

Annex D
(informative)

Maximum width of the voltage hysteresis in *I-V* characteristics test

When *I-V* characteristics are taken with the current sweep method described in 10.2.2.1 b), measured voltages may be different with a different sweep rate due to hysteresis as shown in the example in Figure D.1. The appropriate sweep rate shall be determined in such a way that the maximum width of the voltage hysteresis is smaller than the allowable maximum variation of voltage that is defined in Clause 7.

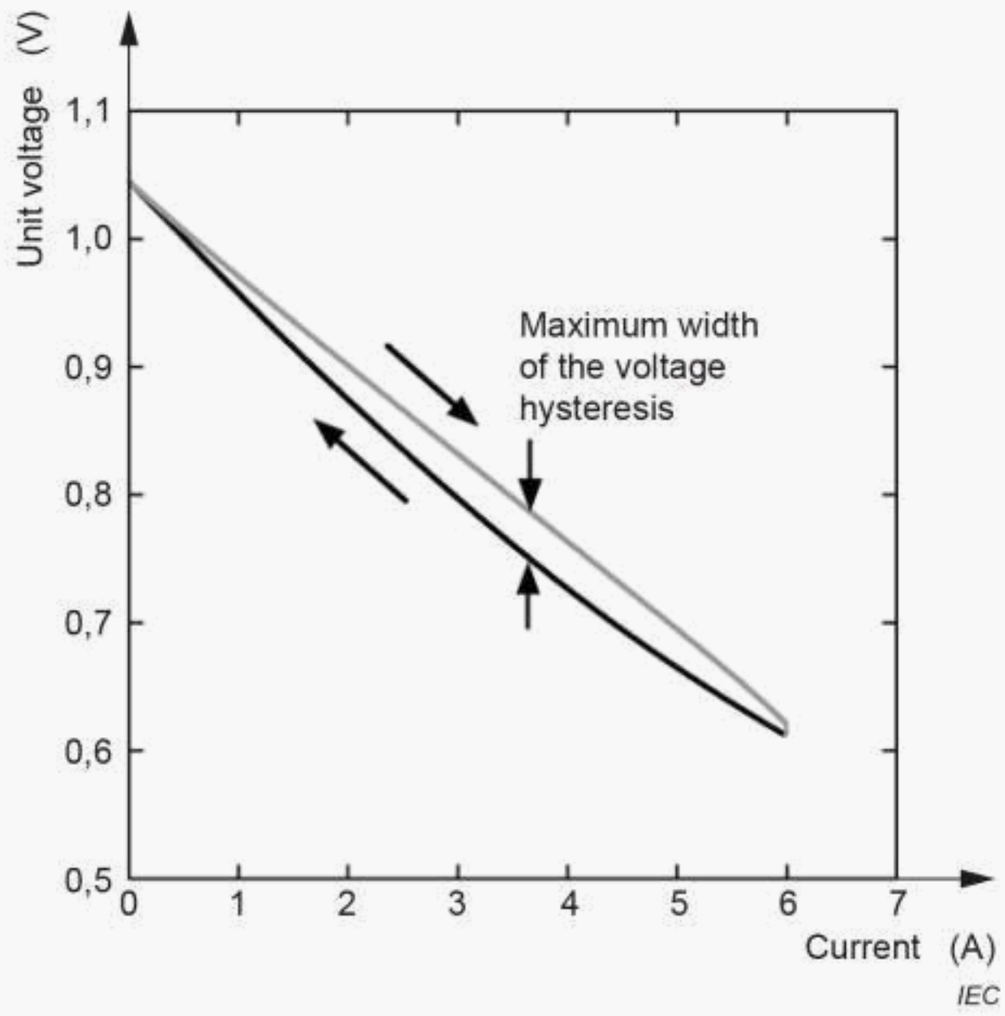


Figure D.1 – Voltage hysteresis at a given sweep rate in *I-V* characteristics test

Annex E
(informative)

Current-voltage characteristics test under constant effective fuel utilization

In order to keep the effective fuel and/or oxygen utilization constant in the measurement range, fuel and/or oxygen flow rates are changed as the current changes. Dependency of unit voltage on current accordingly differs from those observed under a constant gas flow rate. An example of such changes among the unit voltage, current and hydrogen flow rate is shown in Figure E.1.

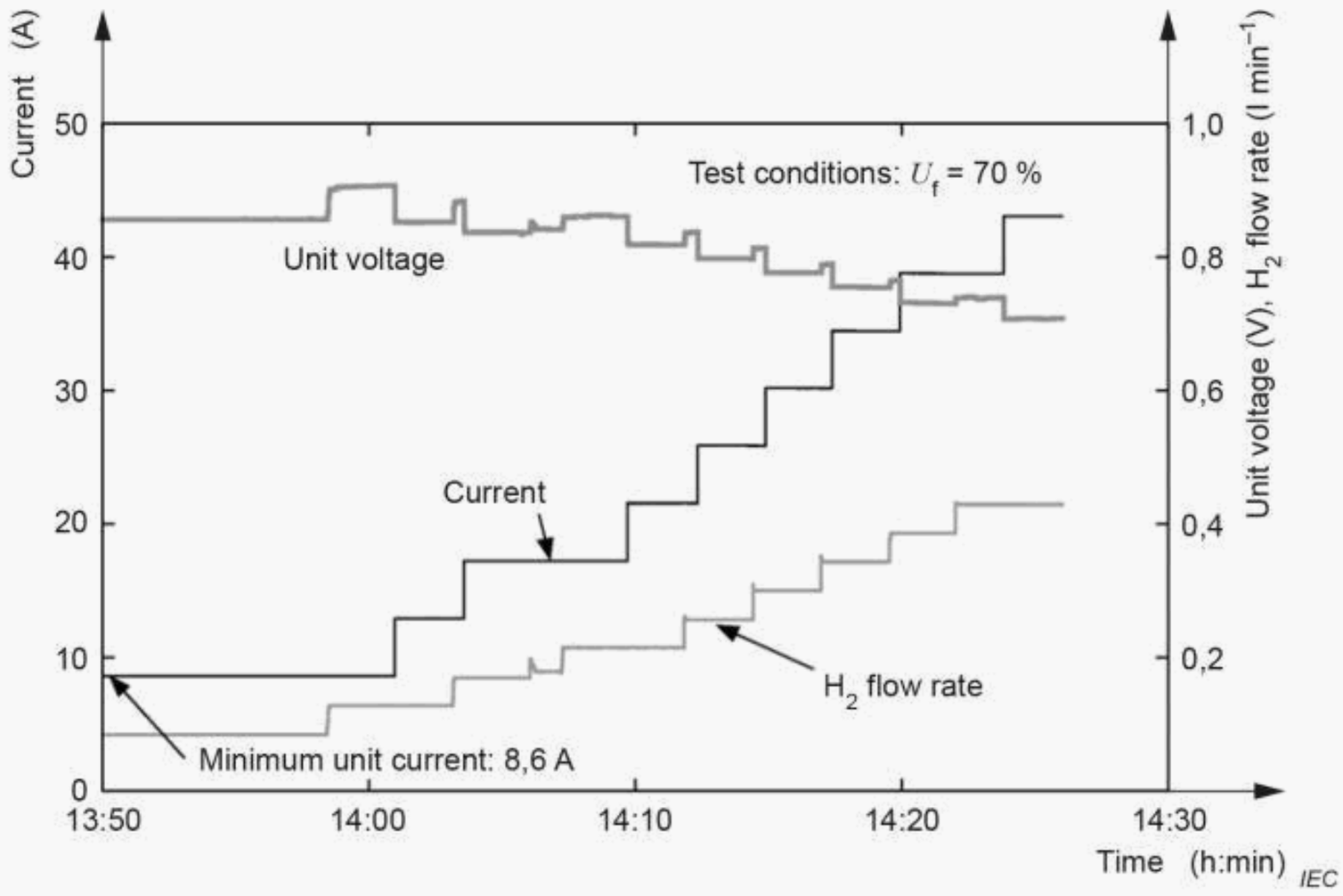


Figure E.1 – Example of the record in current-voltage characteristics test under constant effective fuel utilization

When I-V characteristics are taken under a constant effective fuel utilization, the unit shall initially be kept at the minimum cell/stack assembly unit current as defined in 8.2 m).

Under low current values, voltage becomes unstable due to low gas flow rate. Therefore, the minimum cell/stack assembly unit current should be determined so as to avoid such unstable voltage.

Annex F
(informative)

Test report (template)

F.1 Overview

Examples of a report for general information, test unit data description and test conditions as well as a test report for each test specified in the body text are given below. Instructions to the author are given in *italics* and should not be included in the test report. The method for determining "instrument uncertainty" shown in Clauses F.5, F.6, F.7, F.8 and F.9 is given in Annex G.

F.2 General information

Test report title	
Authors of report	
Date of report	
Test report reference or identification number	
Location of test	
Start date and time of test	
Test bench	

F.3 Test unit data description

Product name and brand name of the unit	
Active electrode area	
Number of cells (total, series, parallel)	
Unit identification number	
Geometry of the unit	
Materials and thickness of electrolyte and electrodes	*If known*

If the following are not available from the manufacturer, they shall be reported.

Configuration of assembly unit and assembling method	
Materials and geometry of the peripheral components	
Flow patterns and directions of anode and cathode gases	
Temperature measurement positions	
Mechanical load (unit) and its application positions	
Voltage measurement positions	
Current lead positions	
Minimum cell voltage (unit)	

F.4 Test conditions

Name of person(s) conducting the test	
Instruments and calibration record	
Test procedure	
Aging conditions	
Criteria of stable state	
Data acquisition method	
Gas purity and impurities	
Mechanical load	

F.5 Rated power test

Operating conditions

Input	Value (unit)	Instrument uncertainty (unit)	Variation of measurement (Standard deviation) (unit)
q_a			
q_c			
p_a			
p_c			
T_{op}			

Test results

Output	Value (unit)	Instrument uncertainty (unit)	Variation of measurement (Standard deviation) (unit)
OCV			
V			
I			
P			

The data average method shall be described.

F.6 Current-voltage characteristics test

Operating conditions

Input	Value (unit)
q_a (or its range in the case of 10.2.2.2)	
q_c (or its range in the case of 10.2.2.2)	
p_a	
p_c	
T_{op}	
U_f (in the case of 10.2.2.2)	
U_{02} (in the case of 10.2.2.2)	

Test results

Output	Value (unit)	Instrument uncertainty (unit)	Variation of measurement (Standard deviation) (unit)
OCV			

The I-V curve shall be presented (see 10.2.3).

F.7 Effective fuel utilization dependency test

Initial operating conditions

Input	Value (unit)
q_a	
q_c	
p_a	
p_c	
T_{op}	
I	

Preliminary information

Expected maximum fuel utilization	/ %

Test results

Output	Value (unit)	Instrument uncertainty (unit)	Variation of measurement (Standard deviation) (unit)
OCV			

In the case of 10.3.2.2

Step number	f_a (unit)	V (unit)	U_f / %
0			
1			
2			
3			
m			

The $U_f(f_a)$-V curve that can replace the above table (see 10.3.3) shall be presented .

In the case of 10.3.2.3

Step number	I (unit)	V (unit)	U_f / %
0			
1			
2			
3			
m			

The $U_f(I)$ -V curve that can replace the above table (see 10.3.3) shall be presented.

F.8 Long-term durability test

Operating conditions

Input	Value (unit)
q_a	
U_f	
q_c	
U_{O2}	
p_a	
p_c	
T_{op}	
I	

Test results

Output	Value (unit)	Instrument uncertainty (unit)	Variation of measurement (Standard deviation) (unit)
OCV (start)			
OCV (end)			
t (end)			

The other test results should be presented by means of a two-dimensional plot (see 10.4.3).

F.9 Thermal cycling durability test

Test conditions

Cooling rate	
Heating rate	
Minimum temperature	
Period to maintain operating temperature	
Period to maintain minimum temperature	
Gas composition during heating	
Gas flow rate during heating	
Gas composition during cooling	
Gas flow rate during cooling	
Gas composition at minimum temperature	
Gas flow rate at minimum temperature	

Operating conditions

Input	Value (unit)
q_a	
q_c	
p_a	
p_c	
T_{op}	
I	

Test results

Output	Value (unit)	Instrument uncertainty (unit)	Variation of measurement (standard deviation) (unit)
OCV (start)			
OCV (end)			

The other results should be presented as specified in 10.5.3.

F.10 Internal reforming performance test

Operating conditions

Input	Value (unit)
q_a	
q_c	
U_f	
p_a	
p_c	
T_{op}	
I	

Test results

Output	Value (unit)
OCV	
Composition of anode exhaust gas	
Flow rate of anode exhaust gas	
HC conversion rate	/ %

F.11 Resistance components identification test

Operating conditions

Input	Value (unit)
q_a	
q_c	
p_a	
p_c	
T_{op}	
I or V	
Frequency range	
Operating mode (galvanostatic or potentiostatic)	
Amplitude	

Test results

Output	Value (unit)
Total resistance	
Ohmic resistance	

Depending upon the method, corresponding figures shall be attached (see 10.7.3).

Annex G
(informative)

Method for determining instrument uncertainty

Instrument uncertainty, U_I, can be obtained by the calibrations using traceable standard instruments. See ISO/IEC Guide 98-3 for further information.

It may also be obtained from the error limit ($\pm a$) of instrument as shown in Formula (G.1) assuming uniform distribution of the probability within the error limit range:

$$U_I = 2u_I = 2\frac{a}{\sqrt{3}} \tag{G.1}$$

where u_I is the standard instrument uncertainty.

Some of the measurements are made using several instruments (e.g. for current measurement, the combination of current sensor and digital voltage recorder may be used). The standard uncertainty for such a case can be obtained as shown in Formula (G.2) assuming no correlation between the instruments:

$$u_I^2 = \sum u_{I,i}^2 \tag{G.2}$$

where $u_{I,i}$ represents standard instrument uncertainty for the ith instrument. Therefore,

$$U_I = 2u_I = 2\left(\sum u_{I,i}\right)^{\frac{1}{2}} \tag{G.3}$$

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