Solid Oxide Cell and Stack Testing, Safety and Quality Assurance

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Test Module 00: General SOC Testing Guidelines

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Abbreviations

APU	Auxiliary power unit
ASR	Area specific resistance
BOP	Balance of plant
CHP	Combined heat and power
EIS	Electrochemical impedance spectroscopy
FFT	Fast Fourier Transform
HHV	Higher heating value
LHV	Lower heating value
nlpm	Normal litre per minute
OCV	Open circuit voltage
RMS	Root mean square
RU	Repeating unit
SOC	Solid oxide cell
SOFC	Solid oxide fuel cell
SOEC	Solid oxide electrolysis cell
slpm	Standard litre per minute
TIP	Test input parameter
TOC	Test operating conditions
TOP	Test output parameter

TM00 – General SOC Testing Guidelines

1 Objective and scope

The present document shall give general guidelines regarding the testing of solid oxide cells and stacks. Unlike the other test modules of the SOCTESQA project (with numbers starting from 01), this test module (named TM00) will not be called by any test program which will be defined according to the targeted applications. It shall however address common issues which are applicable for all other test modules. It will therefore be referred to by the other test modules.

2 Normative references

The following documents have been considered for the present document:

IEC TS 62282-7-2:2014, Fuel cell technologies - Part 7-2: Single cell and stack test methods – Single cell and stack performance tests for solid oxide fuel cells (SOFC) [1]

IEC TS 62282-1:2013, Fuel cell technologies - Part 1: Terminology [2]

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

Table 1: Terms and Definitions

active electrode area (A)= effective electrode area	Geometric area of the electrode where the electrochemical reaction takes place. Area perpendicular to the direction of the current flow, usually expressed in m^2 or cm^2. NOTE: Usually this corresponds to the smaller area of the **negative electrode** and **positive electrode**.
area specific resistance (ASR)	Internal resistance of any component of a cell or a stack. It is normalized by the area and has a unit of Ω cm^2.
bipolar plate	Conductive plate separating individual cells in a stack, acting as current collector and gas distributor for the electrodes of the **SOC**. The **bipolar plate** usually incorporates flow field on both sides for the distribution of reactants and removal of products. The bipolar plate provides a physical barrier to avoid mixing of oxidant and fuel. The bipolar plate is also known as **interconnect**.
cell	A **cell** consists of two electrodes – a **positive electrode** and a

	negative electrode - with an electrolyte between them.
compression force (axial load)	Compressive load applied to the single **cell** or to the end plates of an **SOC** stack to assure electrical contact and/or gas tightness. NOTE: The compression force is in practice expressed in N.
conditioning	Related to the preliminary step of treatment that is required to properly operate an **SOC** and is usually realized by following a protocol specified by the manufacturer. NOTE: The conditioning may include reversible and/or irreversible processes depending on the cell technology.
contact layer	Layer applied between interconnect and the cell to minimize the contact resistance.
cross leakage	See **crossover**
crossover	Leakage between the positive electrode side and the negative electrode side of an **SOC**, in either direction, either through the electrolyte or through the sealant. NOTE: **crossover** is also called **cross leakage**.
current collector	Electronically conductive material in a cell that collects/conducts electrons from/to the electrodes.
current density	Current per unit **active electrode area** (usually expressed in A m^{-2} or A cm^{-2})
degradation rate	Rate at which a **cell**/**stack**'s performance deteriorates over time. Performance in this instance refers to the intended operation mode of the SOC (fuel production or electrical power generation). The degradation rate can be used to measure both recoverable and permanent losses in cell/stack performance. Depending on the operating mode, degradation rate can be expressed by the rate of evolution of any quantity of interest, which serves as an indicator of a **cell**/**stack**'s performance, for instance electrical current, fuel production rate, voltage, electrical power or area specific resistance. It is recommended to use always a sign before the number to indicate univocally the variation direction of the quantity. A positive sign means that the quantity is increasing with time and a negative sign means that the quantity is decreasing with time. Usually the degradation rate of a cell/stack is a function of time. Therefore the time frame under which the degradation rate is evaluated should always be indicated.
derived quantities	Values that can be derived or calculated from **test input parameters** and/or **test output parameters** (e.g. current density, reactant utilization, electrical efficiency). In comparison to **test output parameters**, **derived quantities** are not directly measurable.
external leakage	Leakage from gas compartments to the surrounding environment and

	vice versa.
efficiency	Efficiency is often defined as the ratio of useful output to total input.
electric efficiency	Ratio of net electric power produced by a fuel cell power system to the total enthalpy flow supplied to the fuel cell power system (based on LHV) [2].
heat recovery efficiency	Ratio of recovered heat flow of a fuel cell power system and the total enthalpy flow supplied to the fuel cell power system (based on LHV) [2].
heating value (HV)	The heating value of a fuel is the amount of heat released during the combustion of a specified amount of it. The heating value usually is the same as the thermodynamic heat of combustion $\Delta_f H$, or the thermodynamic heat of reaction $\Delta^r H$. The energy value is a characteristic for each substance. It is measured in unit of energy per unit of the substance, such as: kJ/kg or kJ/mol.
higher heating value (HHV)	The higher heating value (also known as gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products. This is the same as the thermodynamic heat of combustion $\Delta_f H$ since the enthalpy change for the reaction assumes a common temperature of the compounds before and after combustion. Please note that HHV and LHV have positive signs whereas ΔH is negative.
interconnect	See **bipolar plate**
leakage current	Electric current in an unwanted conductive path other than a short-circuit
lower heating value (LHV)	The lower heating value of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered. The lower heating value is obtained by subtracting the latent heat of vaporization of the water vapour from the higher heating value.
negative electrode	Electrode at which fuel gas is consumed or produced. It may also be called fuel electrode. In the fuel cell mode, it is actually called anode where the fuel is oxidized. In the steam electrolysis mode, it is called cathode where steam is reduced producing H_2.
positive electrode	Electrode at which O_2 is consumed or produced. It may also be called oxidant electrode. In the fuel cell mode it is actually called cathode where O_2 is reduced producing oxide ions going through the

	electrolyte. In the steam electrolysis mode, it is called anode where two oxide ions are recombined to form one molecule of O_2.
protection gas (safety gas)	Usually refers to a mixture of hydrogen and inert gas (usually Ar or N_2). It is often used to protect the Ni-containing **negative electrode** of the **SOC** from being re-oxidized in case of abnormal operating conditions (e.g. fuel interruption, emergency stop of the test station). It can also be used during the heating-up and cooling down processes of the stack. The hydrogen fraction should be low enough (usually 0.03-0.05) to avoid the formation of explosive atmosphere. It should be high enough to keep a reducing atmosphere at the **negative electrode** of the **SOC** to avoid the re-oxidation of Ni.
rated current	Recommended continuous electric current as specified by the manufacturer, at which the **SOC** power system has been designed to operate
reactant utilization (U_{gas})	Gas utilization at the negative electrode (**fuel utilization in SOFC mode**, **steam conversion rate in SOEC mode**) or gas utilization at the positive electrode (air utilization or oxygen utilization in SOFC mode)
repeating unit (RU)	An elementary unit which periodically repeats itself to form a **stack**. It is composed of one single **cell** and two half-**interconnects** on both sides of the single **cell** and usually also sealant to assure gas-tightness and contact layers to minimize contact resistances between cells and **interconnects**.
reversible voltage /Nernst voltage(V_N)	Thermodynamic or reversible voltage of a redox system. This is a theoretical and not a measured value.
solid oxide cell (SOC)	**Cell** composed of three functional elements (negative electrode, electrolyte and positive electrode) based on ceramic oxide materials. Two electrodes made of ionic and/or electronic conducting ceramics are attached to one purely ionic conducting solid oxide ceramic electrolyte. Furthermore, the cell may contain a support layer which may be a ceramic layer or a non-ceramic layer as is the case for metal-supported cells. **SOC**s can be used as an **SOFC** or an **SOEC**.
solid oxide electrolysis cell (SOEC)	An **SOEC** is an **SOC** operated in the electrolysis mode, i.e., reversed fuel cell mode. It can be used to produce hydrogen from steam or to produce CO from CO_2. Electricity and also eventual heat are used as energy input.

solid oxide fuel cell (SOFC)	An **SOFC** is an **SOC** operated in the fuel cell mode. It is used for cogeneration of electricity and heat using fuels such as natural gas. In some applications only the electricity part is used and the co-generated heat is just dissipated.
stack	A fuel cell stack or an electrolyzer stack is composed of a number of **repeating units**. Normally two endplates (top plate and bottom plate) are used to facilitate applying a compression force to all **repeating units**.
test input parameter (TIP)	Parameters whose values can be set in order to define the test conditions of the test system including the operating conditions of the test object. 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 duration of the selected test module.
test output parameter (TOP)	Parameters that indicate the response of the test system/test object as a result of variation of TIPs. Values of TOPs are unknown before conducting the test and will be measured during the test. TOPs must be measurable.
thermoneutral voltage (V_{tn})	Thermoneutral voltage relates to the enthalpy of a reaction. An electrolysis cell operates adiabatically at V_{tn}, i.e, no heat exchange is needed between the electrolyzer and its environment. In other words, heat produced in the cell due to the internal resistance (Joule heat) compensates exactly the heat needed by the endothermic electrolysis reaction. The electricity input to the electrolyzer matches exactly the enthalpy of the electrolysis reaction.
open circuit voltage (OCV)	The measured voltage of an electrochemical system without external electrical current.
voltage drop at the positive endplate ($V_{ep, pos}$)	Voltage drop due to the contact resistance between the positive endplate and its adjacent RU
voltage drop at the negative endplate ($V_{ep, neg}$)	Voltage drop due to the contact resistance between the negative endplate and its adjacent RU
voltage of a cell (V_{cell})	Voltage measured between the positive and negative electrode of a cell.
voltage of a RU (V_{RU})	Voltage measured between the two bipolar plates of a RU.
voltage of the stack (V_{stack})	The voltage measured between the two current connection terminals (for instance two endplates) of the stack. It should be noted that the stack voltage can be different from the sum of all RU voltages in the stack due to non-negligible voltage drops caused by contact resistances between endplates and their adjacent RUs.

4 General safety aspects

An operating SOC uses oxidizing and combustible gases. Typically, these gases are stored in high-pressure containers. The SOC itself may be operated at pressures greater than atmospheric pressure. The solid oxide cell/stack in particular operates at high temperatures, typically above 600°C, which are higher than the auto ignition temperatures of both hydrogen (565°C) and methane (537°C). Those who carry out solid oxide cell/stack assembly unit testing shall be trained and experienced in the operation of test systems and specifically in safety procedures involving explosive atmospheres, fire protection, electrical equipment and reactive, compressed gases.

The test personnel are responsible for obtaining and following all applicable safety regulations 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 must 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 safe facilities and equipment, all of which are outside the scope of this set of test procedures.

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 preventing safety issues through an appropriate emergency shutdown system.

- Gas sensors: It is recommended to have gas sensors in close proximity to the test station (in particular for H_2, CO and CH_4), which are connected to an automated emergency shutdown system that cuts off fuel feed to the test station if hazardous concentrations of said gases are measured.

- Protection gas emergency supply: In the case of emergency shut-downs, it is recommended that a line containing an inert, reducing gas (“protection gas”, typically 3-5% hydrogen in a nitrogen matrix) be employed for the flushing of the negative electrode side of the solid oxide cell/stack assembly. This helps to expel flammable reactants from the system and at the same time protects the negative electrode (often composed of metallic nickel) from re-oxidizing, which may compromise the gas tightness of the SOC assembly.

- Protection gas for heating up and cooling down: Risk of explosion exists when the furnace temperature is below auto ignition temperatures of fuel gases in case of gas leakage. This risk can be avoided through the use of protection gas (typically 3-5% hydrogen in a nitrogen matrix) at the negative electrode side during phases of heating up and cooling down.The protection gas contains sufficiently low concentration of flammable gas to prevent explosion in case of gas leakage. It is yet still reducing to help to avoid re-oxidation of the negative electrode. It is recommended to use pre-mixed gases stored in bottles or big containers for this purpose. Caution should be taken when the protection gas is obtained through fresh mixing of two gas streams (H_2 and inert gas) in the test bench since mass flow controllers could fail, which might result in undesired concentration of H_2.

- Monitoring cell/stack voltage: A low open circuit voltage (OCV) may be an indication of gas leakage from the cell/stack assembly. During test operation (in closed circuit), it is advisable to monitor the cell/stack closed circuit voltage and implement an automated opening of the circuit in case the measured cell/stack voltage falls outside of the predefined operating window.

- Redundant Temperature sensors: It is recommended to place extra temperature sensors in the temperature-controlled furnace to ensure that igniting gas leaking from the cell/stack assembly may be detected from the measurement of high local temperatures.

- A humidity sensor could also be used at the oxidant outlet in order to detect cross leakage in the SOC cell/stack assembly unit.

- Pressure sensors could also help to control overpressures in the SOC cell/stack assembly unit and to prevent a break in tightness.

- When operating the SOC cell/stack in electrolysis mode, care must be taken that the produced hydrogen is adequately dealt with. For small production rates it will be sufficient to dilute the exhaust gas from the negative electrode with air or inert gas before venting. In case large stacks are used, it will be necessary to adopt a (catalytic) afterburner before venting.

This by no means claims to be an exhaustive or even sufficient list for safe operation during testing. It is therefore recommended to refer to applicable safety regulations and norms as well as consult experts in the field.

5 Test object

5.1 Cell

Figure 1 shows a single cell test object, as an assembly of two electrodes and the electrolyte which is integrated in a cell housing. For testing a cell ideally, the cell housing design and materials are optimized in that way of not having an influence on the results of the cell. Therefore, usually the electrical contact resistances of the electrodes in the cell housing are negligible and the supply of the electrodes with fuel and oxidant gases in the cell housing is ideal.

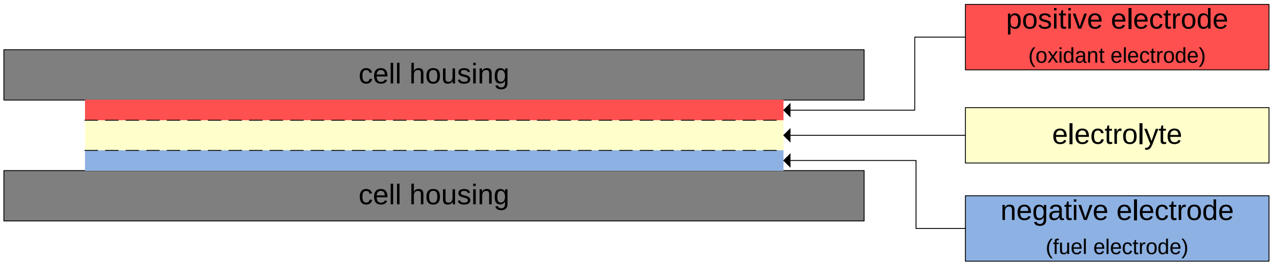

Figure 1: Scheme of a single cell test object consisting of an SOC in a cell housing

5.2 Stack

Figure 2 shows the scheme of an SOC-stack test object, consisting of multiple repeating units (RUs) which are assembled in series. The waved line in the middle shows that the number of repeating units is not specified. 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 might be influenced by electrical contact and gas flow conditions.

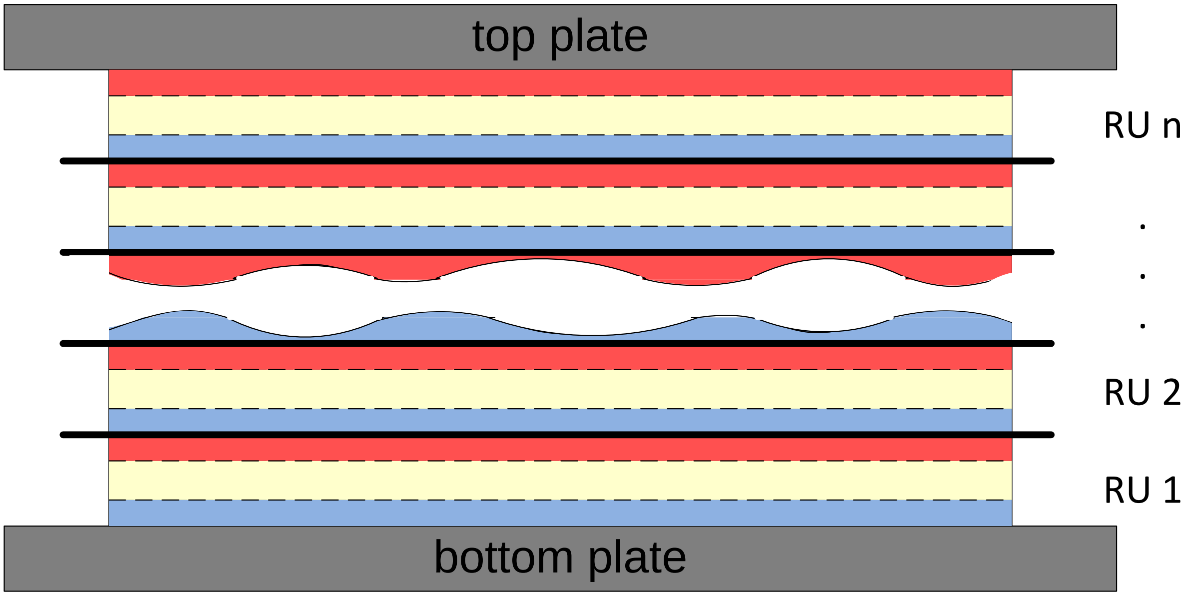

Figure 2: Scheme of an SOC stack test object

6 Test system

6.1 Subsystems in test system

Figure 3 shows a complete test system which consists of the solid oxide cell/stack assembly unit (test object) and the corresponding test and control subsystems. The test object is exposed to test inputs or operational conditions and delivers test outputs or object test results.

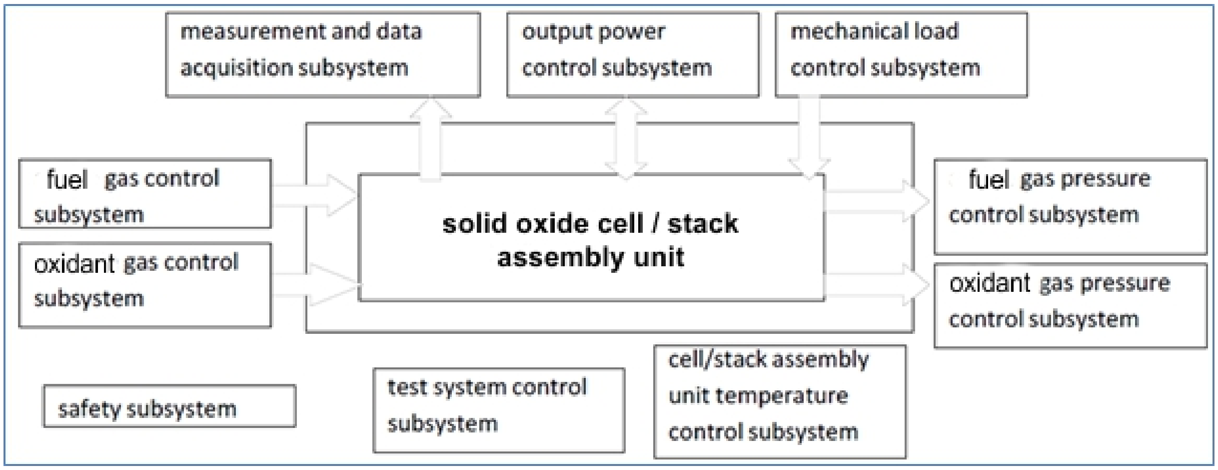

Figure 3: Schematic graph of a complete test system for high temperature solid oxide assembly unit

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

6.2 Interface between test object and test environment

Figure 4 and Figure 5 show the physical interfaces between the SOC cell / SOC stack test object and the test environment. The physical interfaces between the test environment (test station) and the SOC cell/stack test object can be separated in media, electric, heat and mechanic interfaces. Media interfaces are the reactants inlet and outlet; electric interfaces are the load and power supply and voltage wiring; heat interface is the oven and the mechanic interface is to mount the cell/stack on the test station which may supply compression force to the cell/stack. These interfaces will be defined by different physical parameters. Depending on the test program these physical parameters can be either of input nature (TIP) or of output nature (TOP) (see Table 1).

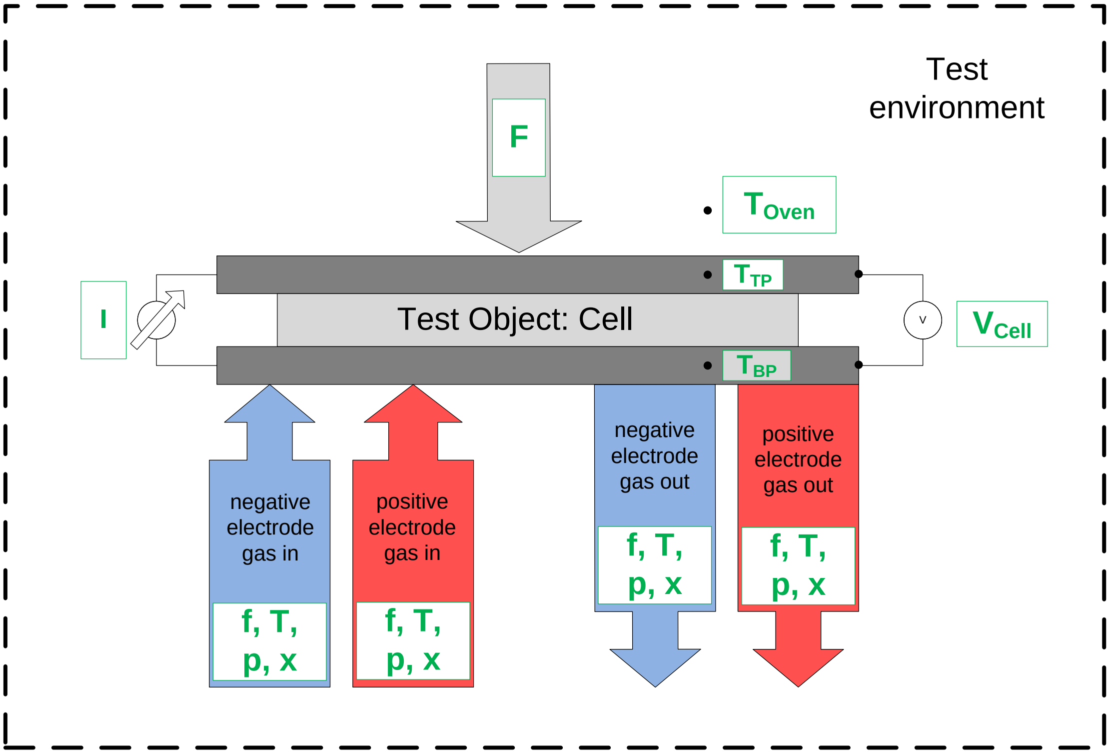

Figure 4: Interfaces between SOC cell and test environment

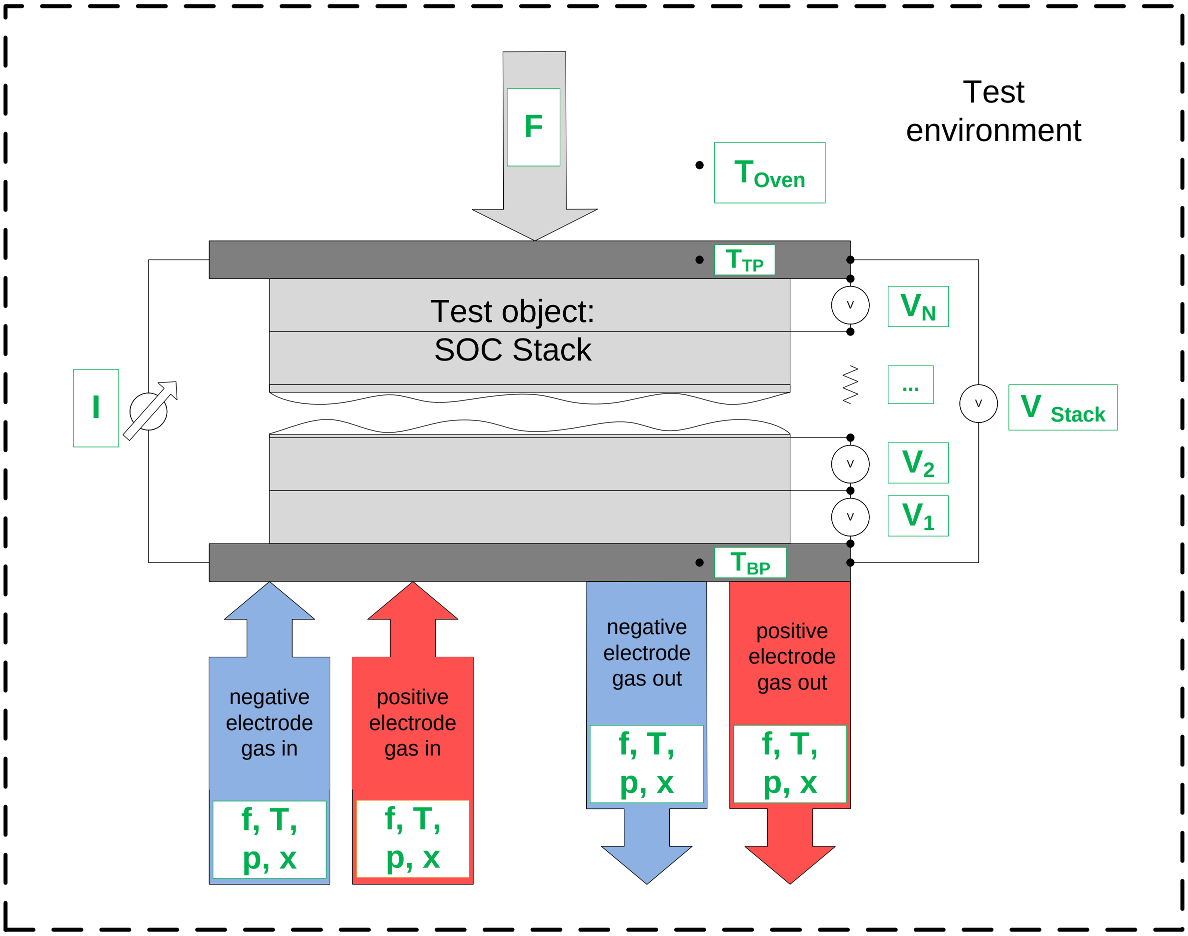

Figure 5: Interfaces between SOC stack and test environment

For the reactants at cell/stack inlet and/or outlet these parameters are:

- Temperature,T
- Flow (mass or volume),f
- Pressure,p
- Gas composition,x

The electric interface parameters are:

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

The heat interface parameters are:

- Oven temperature, T_{oven}
- Stack top plate temperature, T_{TP}
- Stack bottom plate temperature, T_{BP}
- Cell or stack internal temperature T_{cell} or $T_{stack,intern}$

Considering the fact that a temperature gradient in the stack is unavoidable and depends on various factors such as gas flow rates, current, thermal exchange rate with the furnace, it is difficult to determine the stack temperature. In practice, depending on the stack design, temperature sensors mounted at different locations in or around the stack (e.g., in endplates, in gas inlet/outlet channels, or just in close proximity to the stack) can be used to estimate the stack temperature. It is however important to identify the one that represents the best the real stack temperature. In order to make results comparable among different test facilities, it is necessary to agree prior to the test on which temperature is used to represent the stack temperature. For the results presentation, it is recommended to show also other temperatures measured in order to obtain information on the temperature distribution in the stack.

The mechanic interface parameter is:

- Cell or stack compression force, F_{compr}

Ideally, the positions for the setting/monitoring of the input/output parameters are as close as possible to the boundary of the test object and the test environment. Chapter 7 shows the recommended nomenclature to describe the parameters that are recommended to be measured and/or calculated.

6.3 Electrical output / input power control subsystem

The test objects are usually measured in galvanostatic mode, which means that a defined electrical current is applied to the test object and the corresponding voltage is measured. For *j*-*V* curves the electrical current normally is increased and decreased stepwise. This is usually done by connecting both current and voltage probes of the test object to an electronic load. Different setups are necessary for testing of either cells or stacks in fuel cell (SOFC) or electrolysis (SOEC) mode. For stack measurements the current is always applied to or taken from the whole stack whereas the voltage probes can either be connected to the complete stack or the repeat units of interest. The latter case has the advantage to examine the electrochemical behaviour of individual repeat units of the stack.

Setup for testing in SOFC mode:
In SOFC mode for testing of single cells or short stacks an additional voltage supply may be needed, e.g. to overcome voltage drops in the hot current wires (Fig. 6). The negative electrode in SOFC (anode) is connected with the negative pole of the electronic load. The power supply is connected with the electronic load in series in order to increase the voltage in the current circuit. For testing of SOC stacks, which have higher voltages than cells, usually the power supply is not needed (Fig. 7). In this case the stack is connected directly to the electronic load. If the voltage drop in the current circuit is too high, also an additional power supply is necessary for stack testing.

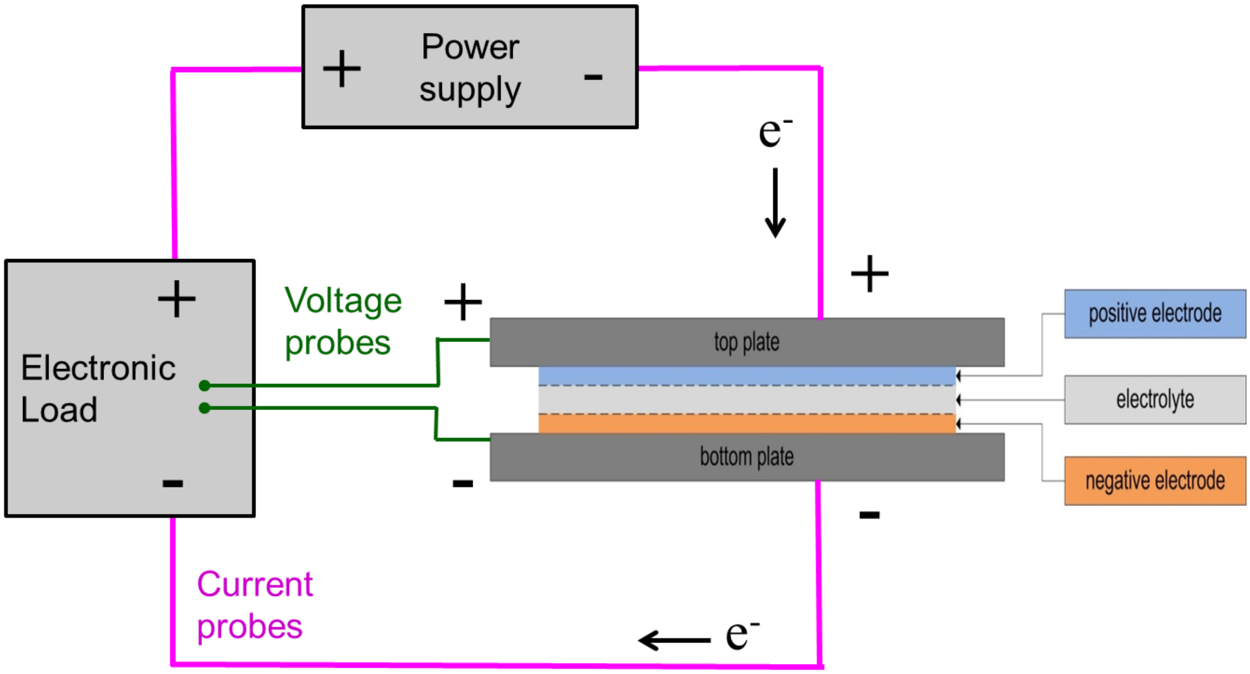

Figure 6: Setup of electrical power control system of SOC cells in SOFC mode

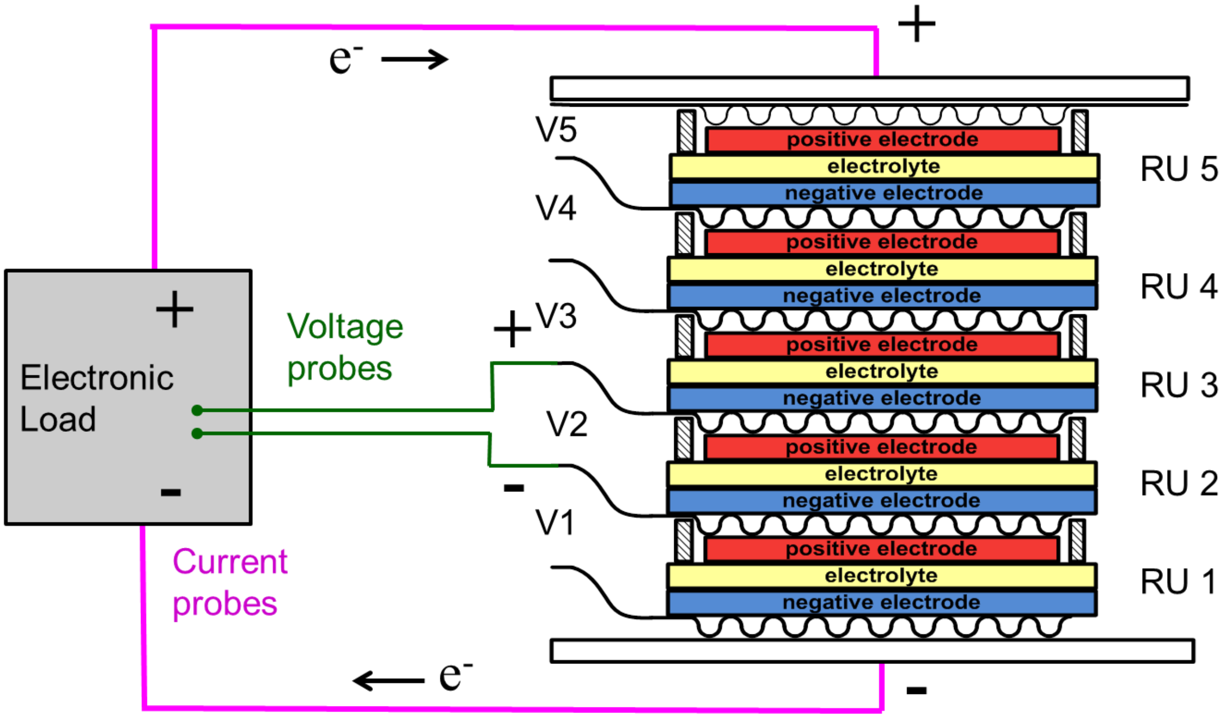

Figure 7: Setup of electrical power control system of SOC stacks in SOFC mode

Setup for testing in SOEC mode:
In SOEC mode a power supply in the current circuit is necessary in order to impose the electrolysis voltage on the SOEC cell/stack object (Fig. 8 and Fig. 9). In this case the polarity of the cell/stack has

to be reversed in the test setup compared to the SOFC mode in order to reverse the current direction. Therefore, the voltage of the power supply has to be higher than the voltage of the cell or stack.

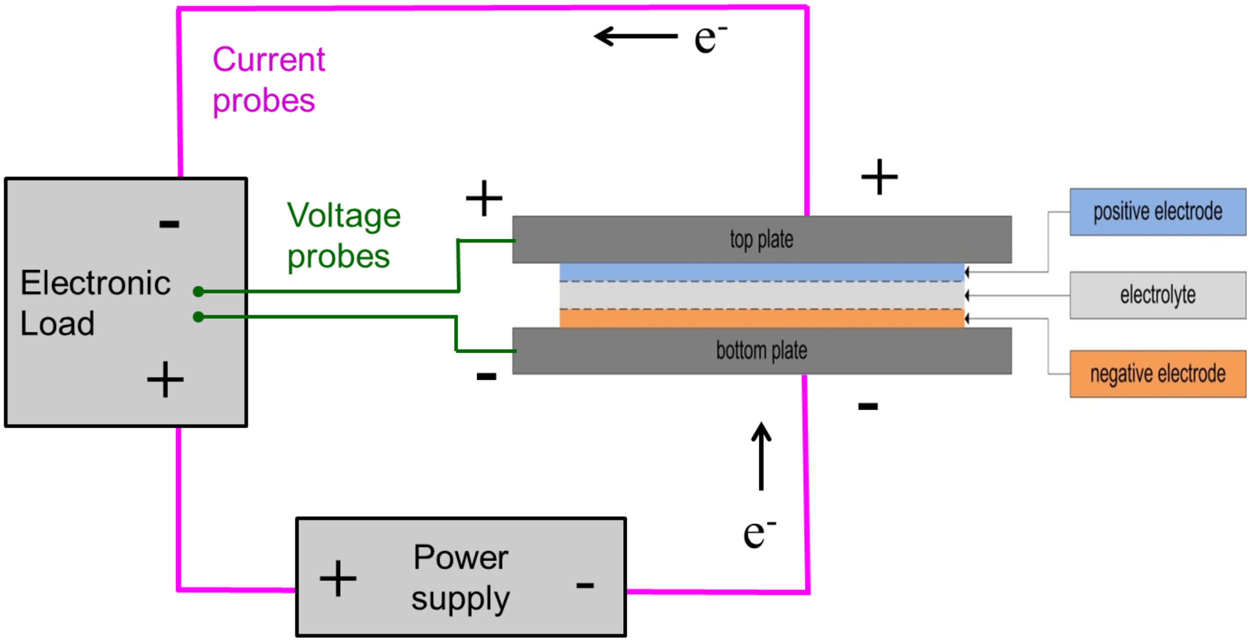

Figure 8: Setup of electrical power control system of SOC cells in SOEC mode

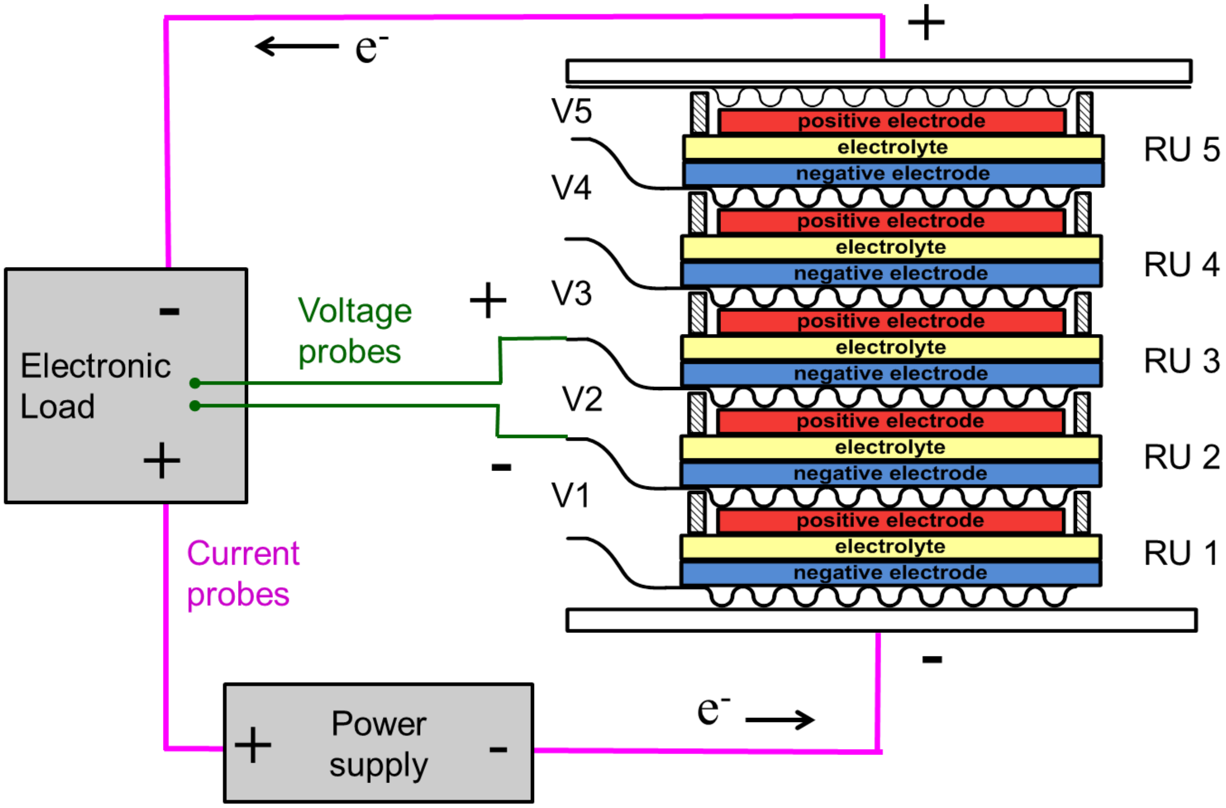

Figure 9: Setup of electrical power control system of SOC stacks in SOEC mode

6.4 *Measurement methods of TIPs and TOPs and control accuracy*

As mentioned in chapter 3, TIPs are controllable/regulated and measurable physical quantities whose values can be set in order to define the test conditions of the test system including the operating conditions of the test object. On the other side, TOPs are measurable physical quantities whose values are affected by the values of the TIPs. The process of determining the *precision*, *accuracy* and *uncertainty* of TIPs and TOPs measurement is an extensive process beyond the scope of this TM00.More details can be found in [3]: JCGM 100 (2008): Evaluation of measurement data - Guide to the expression of uncertainty in measurement (GUM).

Precision is the closeness of agreement between independent measurements of a quantity under the same conditions. It is a measure of how well a measurement can be made without reference to a theoretical or true value and depends only on the distribution of random errors.

Accuracy is the closeness of agreement between a measured value and the true value. Error is the difference between a measurement and the true value of the quantity being measured.

Uncertainty is the component of a reported value that characterizes the range of values within which the true value is asserted to lie. An uncertainty estimate should address error from all possible effects (both systematic and random) and, therefore, usually is the most appropriate means of expressing the accuracy of results.

Based on the aforementioned definitions it is clear that the most appropriate means of expressing the values of TOPs is the *Uncertainty* of the measured values, while for the TIPs, the *Control Accuracy* (which is usually instrument specific) should be reported.

Description of each testing parameter and measurement method follows:

Gas flow rate

Gas flow rates should be measured using mass flow meters. The mass flow meter size shall be selected taking into account the species of the measured gas and the flow range used during the test execution as well. Usually the digital mass flow meters used on the test benches are provided with an accuracy level of 1% of the Full Scale (maximum flow) and with a minimum measurable flow (generally 10% of the maximum flow). When using volumetric gas flow rate instead of mass flow rate, which is normally applied in the community of fuel cell testing, the conditions to which the gas flow rate refers should be carefully checked (see the note in chapter 7).

Reactant gas temperature

Reactant gas temperature shall be measured at inlet and outlet of the cell/stack. The measurement shall be done by using thermocouples placed in the gas stream line and as near as possible to the object under test.

Reactant gas pressure

Pressures of reactant gases shall be measured upstream (at the cell/stack gas inlet lines) at both positive and negative electrodes gas lines. The pressure shall be measured by using calibrated pressure sensors. Caution shall be taken to minimize pressure losses in the piping from the cell/stack and the pressure sensors. In the test report the selected option shall be stated, whether the cell/stack inlet pressure or the cell/stack outlet pressure is controlled to be kept constant. However, cell/stack inlet pressure control is strongly recommended.

Voltage

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

Current

Electrical current shall be measured directly by the electrical load in SOFC mode or power supply in SOEC mode. Current can also be measured by using a shunt on the power cables.

The following table contains all control accuracies for each TIP while for each TOP the instrument uncertainty is stated.

The measuring parameters listed in Table 2 should be recorded and stored with a sampling rate fast enough to ensure that all relevant changes in the parameters are recorded for later data analyses. The required sampling rate depends on the test objective. In most cases a sampling rate of 1 Hz is considered sufficient.

Table 2: Control accuracies for each TIP and instrument uncertainty of TOPs

Symbol	Instrument Uncertainty	Control Accuracy
I	± 1% *	± 0.001A
V	± 0.5%*	± 0.001V**
T	± 1 ºC	± 2 ºC
$f_{neg/pos,\ in/out}$	± 2% ***	± 2% FS (Full scale)
x_i	± 2.0 mol % for H_2, H_2O,N_2; ± 1.0 mol % for CO, CO_2, CH_4	± 2.0 mol % for H_2, H_2O, N_2; ± 2.0 mol % for CO, CO_2, CH_4
x_{O2}	± 0.3 mol % O_2	± 1.0 mol % O_2
$p_{neg/pos,\ in/out}$	± 3%***	± 2%

** Note 1: Percentages relative to setpoint.*
*** Note 2: Potentiostatic testing*
**** Note 3: Percentage of maximum expected value.*

6.5 Stability criteria

To evaluate the influence of operating conditions on the cell/stack performance, a certain degree of stability of both TIPs and TOPs is required. One simple option to evaluate stability is to record a parameter with a desired sampling rate for a desired sampling duration. The parameter is considered stable if the maximum variation (difference between the maximum value and the minimum value recorded) does not exceed a pre-defined threshold value. However, it is difficult to give a generic definition of the sampling rate, sampling duration and variation threshold. This is due to the fact that each individual TIP may have a different impact on the cell/stack performance. If the cell/stack performance is not so sensitive to a TIP, it is then acceptable to set a larger variation threshold for that TIP. A parameter sensitivity investigation needs thus to be performed to define precisely the stability criteria. In addition, the measurement uncertainty of TOPs should also be taken into account for the definition of stability criteria. Furthermore, in many cases a compromise needs to be found between good stability and reasonable test duration. A very strict stability criterion may not be fulfilled due to the time constraint.

Nevertheless, the following stability criteria in Table 3 can be taken as a reference and can be adapted according to the test object, test system and test objective.

Table 3: Stability criteria for TIPs and TOPs as a reference.

Parameter	Sampling rate	Sampling duration	Variation threshold
V_{cell}, $V_{RU,i}$	1 Hz	3 min	5 mV (SOFC mode) 10 mV (SOEC mode)
I	1 Hz	3 min	0.5 A
T	1 Hz	3 min	1 K
$f_{neg/pos,\ in/out}$	1 Hz	3 min	3% FS
$p_{neg/pos,\ in/out}$	1 Hz	3 min	3% FS

6.6 Mounting of the test object into the test system

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

When testing a **single ceramic solid oxide cell**, the cell is mounted within a cell test fixture, which provides gas connections and possible sensory connections similar to a stack assembly. When mounting a cell within a cell test fixture, some general considerations have to be made to assure that the influence of the test setup on the results is minimized:

- Electrical contact to both the negative and positive electrodes has to be assured; this is done by ensuring actual mechanical contact of the cell to the contact components, and by having sufficient contact points to avoid current restrictions.
- A well-defined or masked geometric area of an electrode has to be defined as the geometric cell area.
- The cell has to be sufficiently leak-tight to avoid significant mixing of the test gases with other gases, before passing the negative or positive electrodes.
- Any potential pollutants (sulphur, phosphorous, etc.) from components used in the cell test fixture have to be avoided.

- Mechanical stresses from the cell test fixture components have to be avoided, to prevent any potential cracking of the cell during testing.
- Furthermore, flow fields at the electrodes have to distribute the gas evenly, and without a potential turbulent flow, to avoid gas starvation and mass transport limitations at the electrodes.

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

When the **cell/stack assembly** has to be mounted in the test setup, it has to be securely positioned, to avoid accidental movement during testing. Electrical connections have to be properly done and gas connections securely tightened, while sharp bends of the gas tubes should be avoided. Isolation resistances between the repeating units in the stack should be checked to avoid a short circuit. Gas tightness of the gas supply subsystem of the test station, of the stack itself and of the interface between stack and test station should also be checked. Furthermore, the gases fed into the cell test fixture/stack assembly have to be preheated to the ambient oven temperature, to avoid a significant temperature difference at the gas inlet. The mechanical load applied on the cell/stack should be uniform. In some cases, the compression mechanism required for stack transport may need to be removed after mounting the stack into the test station.

6.7 Precaution regarding the quality of the testing environment

Following the recommended practices described in this test module on mounting of the stack in the test bench/setup is advised, and any deviations from described practices should be noted in the test report. Further, the responsible organization shall make sure the quality of the testing environment is as good as possible, with emphasis on accuracy of measurements and controls, e.g. that mass flow controllers are correctly controlled and that the testing environment elsewise is functioning as intended.

7 List of quantities

Table 4: List of quantities

Description of quantity	**Symbol**	**Unit often used**	**SI Unit**	**Unit conversion**
Active electrode area	A	cm²	m²	1 m² = 10^4 cm²
Area specific resistance	ASR	Ω cm^2	Ω m^2	1 Ω m^2 = 10^4 Ω cm^2
Phase angle	φ	°	rad	$1° = \frac{\pi}{180} rad$
Compression force applied onto the cell/stack	F_{compr}	N	N	-
Capacitance of positive electrode	C_{pos}	F	F	-
Capacitance of negative electrode	C_{neg}	F	F	-
Flow rate of component *i* in the negative	$f_{i,neg,in}$	nlpm, slpm	$m^3 s^{-1}$	1 lpm = $10^{-4}/6$ $m^3 s^{-1}$

electrode gas stream at cell/stack inlet		l_n min^{-1}, l_s min^{-1}		
Flow rate of component *i* in the negative electrode gas stream at cell/stack outlet	$f_{i,neg,out}$	nlpm, slpm l_n min^{-1}, l_s min^{-1}	m^3 s^{-1}	1 lpm = 10^{-4}/6 m^3 s^{-1}
Flow rate of component *i* in the positive electrode gas stream at cell/stack inlet	$f_{i,pos,in}$	nlpm, slpm l_n min^{-1}, l_s min^{-1}	m^3 s^{-1}	1 lpm = 10^{-4}/6 m^3 s^{-1}
Flow rate of component *i* in the positive electrode gas stream at cell/stack outlet	$f_{i,pos,out}$	nlpm, slpm l_n min^{-1}, l_s min^{-1}	m^3 s^{-1}	1 lpm = 10^{-4}/6 m^3 s^{-1}
Flow rate of the negative electrode gas stream at cell/stack inlet	$f_{neg,in}$	nlpm, slpm l_n min^{-1}, l_s min^{-1}	m^3 s^{-1}	1 lpm = 10^{-4}/6 m^3 s^{-1}
Flow rate of the negative electrode gas stream at cell/stack outlet	$f_{neg,out}$	nlpm, slpm l_n min^{-1}, l_s min^{-1}	m^3 s^{-1}	1 lpm = 10^{-4}/6 m^3 s^{-1}
Flow rate of the positive electrode gas stream at cell/stack inlet	$f_{pos,in}$	nlpm, slpm l_n min^{-1}, l_s min^{-1}	m^3 s^{-1}	1 lpm = 10^{-4}/6 m^3 s^{-1}
Flow rate of the positive electrode gas stream at cell/stack outlet	$f_{pos,out}$	nlpm, slpm l_n min^{-1}, l_s min^{-1}	m^3 s^{-1}	1 lpm = 10^{-4}/6 m^3 s^{-1}
Gibbs free enthalpy of reaction	$\Delta^r G$	kJ/mol	J/mol	1 kJ/mol = 10^3 J/mol
Enthalpy of reaction	$\Delta^r H$	kJ/mol	J/mol	1 kJ/mol = 10^3 J/mol
Higher heating value of fuel component *i*	HHV_i	J mol^{-1}	J mol^{-1}	-
Electrical current through the cell/stack	I	A	A	-
Inductance	L	H	H	-
Amplitude of alternating current	$\bar{I}$	A	A	-
Imaginary unit	i	-	-	-
Electrical current density through the cell/stack	j	A cm^{-2}	A m^{-2}	1 A cm^{-2} = 10^4 A m^{-2}
Lower heating value of fuel component *i*	LHV_i	J mol^{-1}	J mol^{-1}	-

Number of measuring periods for each measuring point for EIS spectra	k	-	-	-
Number of cycles	m	-	-	-
Number of repeating units in the stack	N	-	-	-
Number of measuring points per decade for EIS spectra	n	-	-	-
Electrical efficiency based on LHV of fuels	$\eta_{el,LHV}$	-	-	-
Electrical efficiency based on HHV of fuels	$\eta_{el,HHV}$	-	-	-
Electrical power density (area specific)	$P_{d,el}$	W cm^{-2}	J s^{-1} m^{-2}	1 W cm^{-2} = 10^{4} W m^{-2}
Electrical power of the cell/stack	P_{el}	W	J s^{-1} (W)	-
Partial pressure of component *i* of the negative electrode gas stream at cell/stack inlet	$p_{i,neg,in}$	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Partial pressure of component *i* of the negative electrode gas stream at cell/stack outlet	$p_{i,neg,out}$	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Partial pressure of component *i* of the positive electrode gas stream at cell/stack inlet	$p_{i,pos,in}$	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Partial pressure of component *i* of the positive electrode gas stream at cell/stack outlet	$p_{i,pos,out}$	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Pressure of the negative electrode gas stream at cell/stack inlet	$p_{neg,in}$	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Pressure of the negative electrode gas stream at cell/stack outlet	$p_{neg,out}$	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Pressure of the positive electrode gas stream at cell/stack inlet	$p_{pos,in}$	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Pressure of the positive electrode gas stream at cell/stack outlet	$p_{pos,out}$	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Pressure drop of the negative electrode gas stream over the cell/stack	Δp_{neg}	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Pressure drop of the positive electrode gas stream over the cell/stack	Δp_{pos}	mbar, kPa	N m^{-2} (Pa)	1 kPa = 10^{3} Pa 1 mbar = 100 Pa
Electrical charge	Q	C	C	-

Resistance	R	Ω	Ω	-
Low frequency resistance	R_{LF}	Ω	Ω	-
Total (or overall) resistance	R_{tot}	Ω	Ω	-
High frequency resistance	R_{HF}	Ω	Ω	-
Ohmic resistance	R_{ohm}	Ω	Ω	-
Polarisation resistance of positive electrode	$R_{pol,pos}$	Ω	Ω	-
Polarisation resistance of negative electrode	$R_{pol,neg}$	Ω	Ω	-
Gas concentration resistance of positive electrode	$R_{GC,pos}$	Ω	Ω	-
Gas concentration resistance of negative electrode	$R_{GC,neg}$	Ω	Ω	-
Time	t	s, min, h	s	1 min = 60 s 1 h = 3600 s
Average temperature of the stack	T_{av}	°C	K	x °C = (x + 273.15) K
Temperature of the bottom plate of the stack	T_{BP}	°C	K	x °C = (x + 273.15) K
Temperature of the cell	T_{cell}	°C	K	x °C = (x + 273.15) K
Maximum temperature difference during start-up	ΔT_{max}	°C	K	x °C = (x + 273.15) K
Temperature of the negative electrode gas stream at cell/stack inlet	$T_{neg,in}$	°C	K	x °C = (x + 273.15) K
Temperature of the negative electrode gas stream at cell/stack outlet	$T_{neg,out}$	°C	K	x °C = (x + 273.15) K
Temperature of the pre-heater for preheating the negative electrode gas stream	$T_{PH,neg}$	°C	K	x °C = (x + 273.15) K
Temperature of the pre-heater for preheating the positive electrode gas stream	$T_{PH,pos}$	°C	K	x °C = (x + 273.15) K
Temperature of the positive electrode gas stream at cell/stack inlet	$T_{pos,in}$	°C	K	x °C = (x + 273.15) K
Temperature of the positive electrode gas stream at cell/stack outlet	$T_{pos,out}$	°C	K	x °C = (x + 273.15) K
Stack temperature	T_{stack}	°C	K	x °C = (x + 273.15) K

Temperature of the top plate of the stack	T_{TP}	°C	K	x °C = (x + 273.15) K
Temperature of the oven	T_{oven}	°C	K	x °C = (x + 273.15) K
Frequency	υ	Hz	Hz	-
Minimum frequency for EIS spectra	υ_{min}	Hz	Hz	-
Maximum frequency for EIS spectra	υ_{max}	Hz	Hz	-
Gas utilization at the negative electrode (fuel utilization in SOFC mode, steam conversion in SOEC mode)	$U_{gas,neg}$	%	-	-
Gas utilization at the positive electrode (air utilization or oxygen utilization)	$U_{gas,pos}$	%	-	-
Volume	v	cm^3	m^3	1 cm^3 = 10^{-6} m^3
Amplitude of alternating voltage	$\bar{V}$	V	V	-
Voltage of the cell	V_{cell}	V	V	-
Voltage drop at the positive endplate	$V_{ep,pos}$	V	V	
Voltage drop at the negative endplate	$V_{ep,neg}$	V	V	
Reversible (thermodynamic) voltage / Nernst voltage	V_N	V	V	-
Average RU voltage of all RUs in the stack	$V_{RU,av}$	V	V	-
Voltage of repeating unit (RU) *i* in the stack	$V_{RU,i}$	V	V	-
Maximum RU voltage	$V_{RU,max}$	V	V	-
Minimum RU voltage	$V_{RU,min}$	V	V	-
Voltage of the stack	V_{stack}	V	V	-
Thermoneutral voltage	V_{tn}	V	V	-
Angular frequency	ω	rad s^{-1}	rad s^{-1}	1 Hz = 2π rad s^{-1}
Mole fraction of component *i* in the negative electrode gas stream at cell/stack inlet	$x_{i,neg,in}$	-	-	-
Mole fraction of component *i* in the negative electrode gas stream at cell/stack outlet	$x_{i,neg,out}$	-	-	-
Mole fraction of component *i* in the positive electrode gas stream at cell/stack inlet	$x_{i,pos,in}$	-	-	-
Mole fraction of component *i* in the positive electrode gas stream at cell/stack outlet	$x_{i,pos,out}$	-	-	-
Number of exchanged electrons	z	-	-	-

Impedance	Z	Ω	Ω	-
Modulus of impedance	|Z|	Ω	Ω	-
Real part of impedance	Z'	Ω	Ω	-
Imaginary part of impedance	Z''	Ω	Ω	-

Notes:

1. About the unit of gas flow rate. Based on the unit definition of the most commonly used mass flow controllers and meters, the following terms apply: nlpm (normal litre per minute) refers to the volumetric flow rate of gases under normal conditions (0 °C or 273.15 K and 1.01325 bar). **slpm** (**standard litre per minute**) refers to the volumetric flow rate of gases under standard conditions (20 °C or 293.15 K and 1.01325 bar). Mixing up these two reference conditions will cause an error of 7% (293.15/273.15=1.07). Therefore, it is strongly recommended to check the specifications of the mass flow controllers and meters used in test stations before setting the flow rates of gases. In addition, the gas flow rate can be normalized by the active area of the cell or stack. In this case the unit of volumetric gas flow rate will be l_n min^{-1} cm^{-2} or l_s min^{-1} cm^{-2}.

2. To express the rate of change of a certain parameter, 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 min^{-1}, $\dot{f}$ can be used to express the speed of variation of the gas flow rate with a unit of nlpm min^{-1}. 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 ($\Delta j/\Delta t$).

3. About the amplitude of alternating current/voltage with a sine waveform for 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*.

4. The real part and imaginary part of impedance can also be represented by *Re(Z)* and *Im(Z)*, respectively.

8 Definition of test objective, test program and test module

The SOCTESQA project defines test programs that have different objectives and scopes. The test programs are comprised of a series of test modules (Figure 10), in which the actual test parameters, specific conditions and test setup are described in detail. The test program describes the objective and scope of the test as well as the test operating conditions (TOC), where the general application specific parameters are given, such as reactant composition, operating temperature etc.

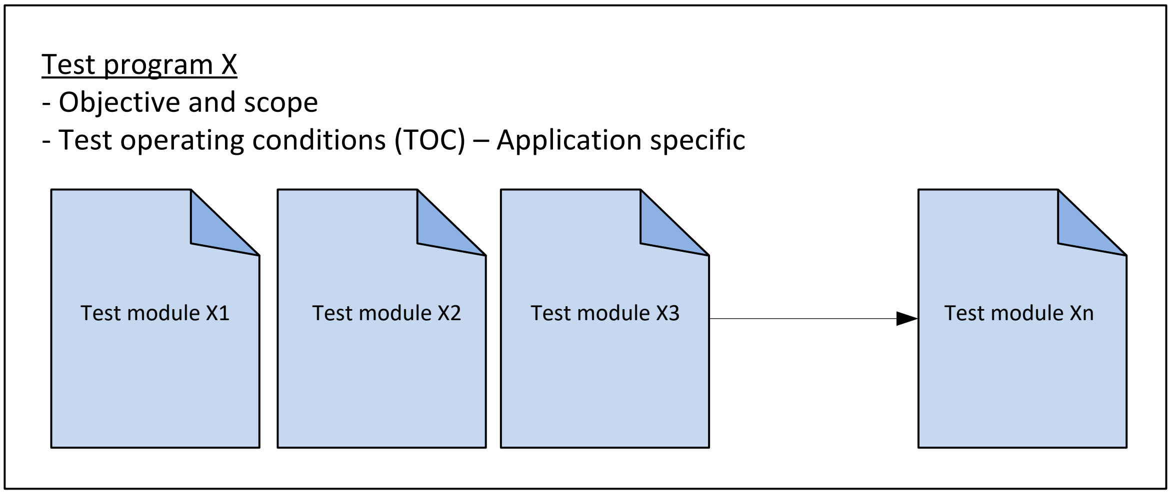

Figure 10: Scheme of a test program consisting of a series of test modules

More than one test program can be run in sequence, whereby time and thermal stress from start-up and shut-down in test programs can be minimized.

SOCTESQA will suggest several test programs, but there is no limitation for others to create their own test programs as needed. Nevertheless, we suggest the following regarding the design of test programs, as it allows for better comparison and benchmarking of results, if this is desired.

- Most test programs will comprise a start-up and a shutdown module to safely start up the stack and document the initial and final performance of the SOC cell/stack.
- Each of these test programs may contain several test modules for characterization, e.g. current-voltage characteristics, electrochemical impedance spectroscopy (EIS) and performance and durability testing, with e.g. dynamic operating profiles or long term stationary operation.

The SOCTESQA test programs will address three different operation modes, solid oxide fuel cell (SOFC), solid oxide electrolysis cell (SOEC) and combined SOFC/SOEC operations. Each of these cases includes both performance and durability. This will cover many potential application requirements, e.g. micro-combined heat and power generation (micro-CHP), auxiliary power unit (APU), SOEC for H_2 production (Power-to-gas) or combined SOFC/SOEC energy conversion systems (Power-to-gas-to-power).

8.1 Test objective and scope

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

- Evaluation of the performance
- Stability over time at constant conditions
- …

With the objective of the test in mind, the test can be planned by first choosing the relevant scope, that covers the relevant test operating condition (depending on type of application), operating mode, cell, short-stack or stack testing. Figure 11 shows an example. SOCTESQA defines a set of recommended values for test operating conditions for different applications.

Test program: Temperature

Objective and scope: To investigate the influence of the cell/stack temperature on performance, in terms of cell/stack voltage (SOFC), or hydrogen production (SOEC).

It can be used to determine the sensitivity of an SOC cell/stack to the nominal operating temperature as well as to the variation in the cell/stack temperature at varying current.

Figure11: Example of test objective and scope

8.2 Test program

Test programs comprise a set of test modules, each module with its own specific objective, as well as the test program objective. The test program specifies the order of test modules, the number and in some instances also parameters such as total test time, e.g. in the case of durability testing where you would need intermittent characterisation throughout the test. Figure 12 shows an example of this.

Test programs can ideally be planned in sequence to investigate several objectives, and thus the shutdown and start-up in between can be omitted.

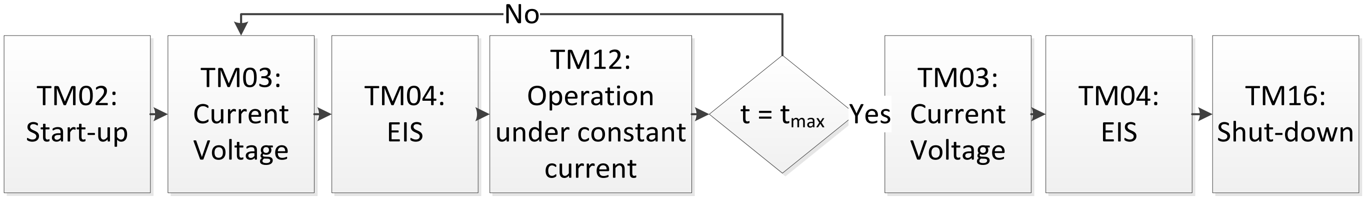

Figure 12: Example of a test program structure, comprising several test modules for characterization and performance evaluation

8.3 Test module

A test module is a confined test procedure in which a minimum of test input parameters is changed to achieve a desired effect. The test module is carried out under the general test operating conditions set in the test program, unless stated in the module.

The test module describes input and output parameters to be controlled and/or measured.

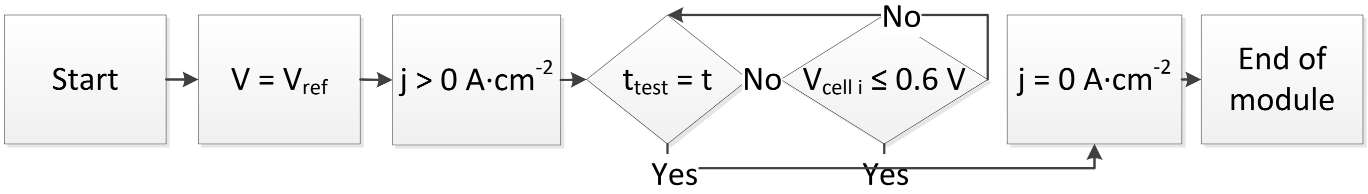

Figure 13: Example of a test module, for durability testing under constant current in SOFC operation

9 Reporting of testing results

The report of the test results should contain all necessary information for the evaluation of the test object. The following templates and tables contain recommendations for a generic test report on SOC test objects, including single cells or stacks under SOFC, SOEC or combined SOFC/SOEC operation.

9.1 Objective and scope of the test

Here the authors should present the objective and the scope of the test.

9.2 Introduction and test planning

Here the author should refer to:

- The Test Modules used to formulate the testing procedure.
- The procedure applied, and if relevant, explain the choice of this procedure.
- The test plan between tester and customer which may also include acceptance criteria and any other documentation used in the report or in the test (terminology document, symbols harmonization etc.).

9.3 General information concerning the test

Table 5: General information on the test report

Test report reference/identification	
Test report title	
Authors	
Date of report	

Table 6: General information concerning the test

Test module / test program number	
Test version	
Company requesting test	
Test Request No	
Person performing the test	

Test date	
Company performing test	
Test location	
Test stack	
Test station ID	

Table 7: Test object description

Test object manufacturer	
Operational mode (SOFC, SOEC or combined)	
Test object model	
Number of cells N	
Product or object tested	
Product number	

Test object identity number	
Test object dimensions (H x L x W) (cm^3)	
Test object weight (kg)	
Test object nominal power (W)	
Test object peak power (W)	
Test object minimum power (W)	
Test object voltage range (V)	
Lowest/highest voltage allowed (V)	
Lowest/highest allowed individual single cell voltage (mV)	
Maximum allowed pressure difference between anode and cathode (kPa)	
Maximum allowed temperature difference between gas inlet and outlet temperature (°C)	

Solid oxide cell (SOC): material/coating of the bipolar plates / technology	
Solid oxide cell (SOC): flow field design	
Solid oxide cell (SOC): active area (cm^2)	
Gasket type	
Gasket thickness	
Minimum air flow rate (nlpm)	
Compression force (N)	

Negative electrode material	
Positive electrode material	
Electrolyte material	
Negative electrode thickness	
Positive electrode thickness	
Electrolyte thickness	

Test object leakage $ml_n cm^{-1} min^{-1}$	

The author has to precise the origin of the data (manufacturer or in-house). Proprietary information labelled as such whenever a reference of such data is described in the IEC 62282-2 Part 2: Fuel Cell Module, standard.

9.4 Status of the test object

The author presents here the testing history of the test object with a short description of all diagnostic experiments, specific or baseline experiments and their respective identifiers in sequential order. All test modules and test programs already realized should be mentioned.

9.5 Description of the test setup

A detailed description of the used test equipment and setup, including sensors type and location and specific devices (for example, heating/cooling and humidification sub-systems), has to be presented to aid understanding the test results. A graphical representation may be added here.

Table 8: List of sensors for test setup

Sensor name	Sensor type	Sensor location
…	…	…

9.6 Description of the operating conditions, TIPs and TOPs

Here the following shall be presented:

- The settings of the operating conditions (TIPs).
- The cause of ending the test (where applicable).
- Measurement method(s) of the test module(s) and any deviation from it.

Table 9: Test Input Parameters (TIPs)

TIP	Descrip-tion	Minimum value (unit of TIP)	Maximum value (unit of TIP)	Standard deviation (unit of TIP)	Relative standard deviation (unit of TIP)	Standard error (unit of TIP)	Sampling rate (Hz)
TIP_1							
...							
TIP_n							

Table 10: Test Output Parameters (TOPs)

TOP	Descrip-tion	Minimum value (unit of TOP)	Maximum value (unit of TOP)	Standard deviation (unit of TOP)	Relative standard deviation (unit of TOP)	Standard error (unit of TOP)	Sampling rate (Hz)
TOP_1							
...							
TOP_n							

Graphs may be added here to present the main test inputs and outputs, represented as described in the individual Test Modules used.

Plots of TIPs, TOPs and derived quantities may be grouped in four categories:

- Performance diagrams or maps,
- Stability diagrams
- Property diagrams
- Homogeneity diagrams

The plots that may be included in each of these categories may vary according to the operational mode (SOFC, SOEC or combined) of the test object.

Graphs of the main test inputs and test outputs of the stack versus dwell time or test duration during start-up and conditioning may be included here (and where appropriate for individual cells), to aid the understanding of the stability of such parameters for these test steps.

Performance diagrams / maps

A performance map may include TOPs or derived quantities plotted against TIPs or derived quantities that are directly related to the performance of the test object. Possible plots that may be included in this category are:

- Voltage or power density versus current density, fuel utilization, gas composition, inlet pressure or temperature
- Efficiency versus temperature, inlet pressure, fuel utilization or gas composition
- Hydrogen/oxygen production versus temperature, steam content or pressure
- ….

Stability diagrams

- Degradation or its rate, load cycling, impedance plots versus temperature, test duration, inlet pressure, fuel utilization or gas composition
- …….

Property diagrams

Property diagrams may include plots of derived quantities, reflecting the properties of the test object. Possible plots that may fall into this category are:

- Power density versus Area Specific Resistance, polarization resistance, ohmic resistance, or efficiency
- ….

Homogeneity diagrams

Homogeneity diagrams may include plots of TOPs against local test specimen property:

- Power density versus stack layer
- Current density versus x-position of cell area
- Temperature versus height of stack assembly unit
- gas flow rate against width of cell
- ….
- ….

9.7 Data (Post) Processing

Here, the post processing of the test results (TIPs and TOPs) shall be described.

When reporting, the significant figures of a test variable should be consistent with its measurement uncertainty. For a calculated test variable, the lesser number of significant figures of all of the involved test variables should determine the significant figure. The standard deviation (stdev), relative standard deviation (RSD) and standard error (stderr) should be expressed with at least one additional figure. The RSD should be reported with two significant figures.

10 Appendix (constants and formulary)

<table>
<tr><th>Description</th><th>Constants and Formulary</th></tr>
<tr><td>Faraday constant</td><td>F = 96485.3 C mol^{-1} = 96485.3 A s mol^{-1}</td></tr>
<tr><td>Oxygen fraction in air</td><td>x_{O2} = 0.2095</td></tr>
<tr><td>Lower heating value (LHV) of H_2[7]</td><td>LHV_{H2} = 119.93 kJ g^{-}1 = 241.77 kJ mol^{-1}</td></tr>
<tr><td>Higher heating value (HHV) of H_2[7]</td><td>HHV_{H2} = 141.86 kJ g^{-1} = 285.98 kJ mol^{-1}</td></tr>
<tr><td>Voltage equivalent to LHV of H_2</td><td>$LHV_{H2} / (2F) = 1.253\ V$</td></tr>
<tr><td>Voltage equivalent to HHV of H_2</td><td>$HHV_{H2} / (2F) = 1.482\ V$</td></tr>
<tr><td>Molar gas constant</td><td>R = 8.31446 J K^{-1} mol^{-1}</td></tr>
<tr><td>Normal temperature</td><td>T_n = 273.15 K</td></tr>
<tr><td>Normal pressure</td><td>P_n= 101325 N m^{-2} = 101325 Pa</td></tr>
<tr><td>Molar volume of an ideal gas at normal temperature and pressure</td><td>$V_m = RT_n/P_n$ = 8.31446 x 273.15 / 101325 m_n^3 mol^{-1} = 22.414 l_n mol^{-1}</td></tr>
<tr><td>Number of electrons transferred when one molecule of reactant component i is electrochemically reacted (z_i)</td><td>
<table>
<tr><td>i</td><td>z_i</td><td>*Electrochemical reaction*</td></tr>
<tr><td>H_2</td><td>2</td><td>$H_2 + O^{2-} \rightarrow H_2O + 2e^-$</td></tr>
<tr><td>CO</td><td>2</td><td>$CO + O^{2-} \rightarrow CO_2 + 2e^-$</td></tr>
<tr><td>CH_4</td><td>8</td><td>$CH_4 + 4O^{2-} \rightarrow CO_2 + 2H_2O + 8e^-$</td></tr>
<tr><td>$C_pH_qO_r$</td><td>4p+q-2r</td><td>$C_pH_qO_r + (2p+q/2-r)O^{2-} \rightarrow pCO_2 + q/2H_2O + (4p+q-2r)e^-$</td></tr>
<tr><td>O_2</td><td>4</td><td>$O_2 + 4e^- \rightarrow 2O^{2-}$</td></tr>
<tr><td>H_2O</td><td>2</td><td>$H_2O + 2e^- \rightarrow H_2 + O^{2-}$</td></tr>
</table>
</td></tr>
<tr><td>Gas utilization (U_{gas})</td><td>Number of repeating units in the stack: N
Flow rate of reactant component i (i = 1 … n) in the negative/positive electrode of the stack: $f_{i,in}$(nlpm)
Theoretical current (I_{theory}) assuming 100% gas utilization (all reactant gas is consumed through electrochemical reactions):</td></tr>
</table>

	$I_{theory} = \frac{F}{V_m \times 60} \cdot \frac{\sum_{i=1}^{n} z_i \times f_{i,in}}{N} = \frac{96485.3}{22.414 \times 60} \times \frac{\sum_{i=1}^{n} z_i \times f_{i,in}}{N} = 71.74 \times \frac{\sum_{i=1}^{n} z_i \times f_{i,in}}{N}$ gas utilization at current *I*: $U_{gas} = \frac{I}{I_{theory}} \times 100\% = \frac{I \times N}{71.74 \times \sum_{i=1}^{n} z_i \times f_{i,in}} \times 100\%$
Nernst voltage / reversible (thermodynamic) voltage / theoretical open circuit voltage (*V*V_N)	$V_N = \frac{RT}{4F} ln \frac{p_{O2,pos}}{p_{O2,neg}}$ (considering SOC as an oxygen concentration cell) $V_N = \lvert \frac{\Delta^r G(T,p)}{zF} \rvert$ (for any reaction) $\Delta^r G(T,p)$: Gibbs free enthalpy of reaction as a function of temperature and pressure. For the reaction: H_2 + 0.5 O_2 = H_2O $\Delta^r G(T,p) = \Delta^r G^0(T) - RT ln \frac{p_{O2,pos}^{\frac{1}{2}} p_{H2,neg}}{p_{H2O,neg}}$ $V_N = -\frac{\Delta^r G(T,p)}{2F} = -\frac{\Delta^r G^0(T)}{2F} + \frac{RT}{2F} ln \frac{p_{O2,pos}^{\frac{1}{2}} p_{H2,neg}}{p_{H2O,neg}} = V_N^0(T) + \frac{RT}{2F} ln \frac{p_{O2,pos}^{\frac{1}{2}} p_{H2,neg}}{p_{H2O,neg}}$ $\Delta^r G^0(T)$: Gibbs free enthalpy of reaction at standard pressure $V_N^0(T)$: reversible voltage at standard pressure
Thermoneutral voltage (V_{tn})	$V_{tn} = \frac{\Delta^r H(T)}{zF}$ $\Delta^r H(T)$: Enthalpy of reaction as a function of temperature. (Note: the enthalpy is independent of the pressure under the assumption of ideal gases). *z*: number of exchanged electrons in the electrochemical reaction. For water electrolysis reaction: H_2O → H_2 + 0.5 O_2 V_{tn} = 1.482 V at 20 °C, 1.283 V at 700 °C, 1.285 V at 750 °C and 1.286 V at 800 °C
Average RU voltage ($V_{RU,av}$)	$V_{RU,av} = \frac{\sum_{i=1}^{N} V_{RU,i}}{N}$
Electrical power of the cell / stack (P_{el})	$P_{el} = V_{cell/stack} \times I$
(Area specific)	$P_{d,el} = \frac{P_{el}}{A \times N}$

electrical power density	
Electrical efficiency of the stack (SOFC mode)	The electrical efficiency of an SOFC stack can be defined as the ratio of electric power output to the total enthalpy flow input (based on either LHV of HHV of feed fuel gases). $\eta_{el,LHV} = 22.414 \times 60 \times \frac{P_{el}}{\sum_{i=1}^{n} LHV_i \times f_{i,neg,in}}$ $\eta_{el,HHV} = 22.414 \times 60 \times \frac{P_{el}}{\sum_{i=1}^{n} HHV_i \times f_{i,neg,in}}$ LHV_i: LHV of fuel component *i* (J mol^{-1}) HHV_i: HHV of fuel component *i* (J mol^{-1}) $f_{i,neg,in}$: flow rate of fuel component *i* (*i* = 1 … *n*)(nlpm) When using H_2 as fuel: $\eta_{el,LHV} = \frac{U_{gas,neg} \times V_{stack}}{1.253 \times N}$ $\eta_{el,HHV} = \frac{U_{gas,neg} \times V_{stack}}{1.482 \times N}$
Electrical efficiency of the stack (SOEC mode: H_2O electrolysis)	The electrical efficiency of an SOEC stack can be defined as the ratio of enthalpy flow of fuel gases produced by the electrolyzer (based on either LHV of HHV of produced fuel gases) to the electrical power consumed by the stack for the electrochemical reaction. Here electrical power consumed by the water evaporator, gas preheaters and the furnace in the test station is not considered. It should be noted that for the calculation of system efficiency, these consumptions have to be taken into account. For H_2O electrolysis and assume 100% current efficiency: $\eta_{el,LHV,H2-production} = \frac{1.253 \times N}{V_{stack}}$ $\eta_{el,HHV,H2-production} = \frac{1.482 \times N}{V_{stack}}$
Degradation	The absolute degradation ΔX of a quantity X within the time from t_0 to t_1 is calculated as the difference between the final value $X(t_1)$ and the initial value $X(t_0)$: $\Delta X = X(t_1) - X(t_0)$ The relative degradation ΔX_{rel} is calculated by dividing ΔX by the initial value $X(t_0)$: $\Delta X_{rel} = \frac{X(t_1) - X(t_0)}{X(t_0)} \times 100\%$

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The degradation rate (rate of change) of quantity X during the time interval (t_1-t_0) is then calculated by:

$\frac{\Delta X}{\Delta t} = \frac{\Delta X}{t_1 - t_0}$ (with the unit [unit of X/time unit])

$\frac{\Delta X_{rel}}{\Delta t} = \frac{\Delta X_{rel}}{t_1 - t_0}$ (with the unit [%/time unit])

Degradation rates are typically expressed by the absolute or relative change per 1000 hours. It is thus advisable to normalize the results to 1000 h time interval. This can be simply done by converting the unit of time interval to kh.

Example:
An SOFC stack with 5 RUs shows a stack voltage of 4.500 V at t_0 = 500 h. At t_1=1300 h, the stack voltage dropped to 4.482 V. The absolute and relative degradation rates of the stack voltage during time interval 500-1300 h are:

$$\frac{\Delta V_{stack}}{\Delta t} = \frac{V_{stack}\,(t_1) - V_{stack}\,(t_0)}{t_1 - t_0} = \frac{V_{stack}\,(1300\ h) - V_{stack}\,(500\ h)}{(1300 - 500)h} = \frac{(4.482 - 4.500)\ V}{(1300 - 500)\ h} = \frac{-0.018\ V}{800\ h} = \frac{-0.018\ V}{0.8\ kh} = -0.0225\ V\ kh^{-1}$$

$$\frac{\Delta V_{stack,rel}}{\Delta t} = \frac{V_{stack}\,(t_1) - V_{stack}\,(t_0)}{V_{stack}\,(t_0) \times\ (t_1 - t_0)} \times 100\% = \frac{V_{stack}\,(1300\ h) - V_{stack}\,(500\ h)}{V_{stack}\,(500\ h) \times (1300 - 500)h} \times 100\% = \frac{4.482 - 4.500}{4.500\ \times (1300 - 500)\ h} \times 100\% = \frac{-0.4\%}{800\ h} = \frac{-0.4\%}{0.8\ kh} = \ -0.5\%\ kh^{-1}$$

Additionally, when long-term cycling is performed (thermal or load cycles for instance), it is common and relevant to express the degradation rate in relation to the number of cycles *m* as follows for absolute and relative degradation:

$$\Delta X_m = \frac{X(t_1) - X(t_0)}{m}$$

$$\Delta X_{m,rel} = \frac{X(t_1) - X(t_0)}{X(t_0) \cdot m} \cdot 100\%$$

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<td>Area specific resistance (ASR)</td>
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The area specific resistance can be determined from the *j*-*V* characteristic. Therefore, a small voltage interval where the current voltage curve is nearly linear is needed. The difference in voltage ($\Delta V(j)$) divided by the difference of the corresponding current density (Δj) is used to calculate the ASR.

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	$ASR(j) = \lvert\frac{\Delta V(j)}{\Delta j}\rvert$ Note that the ASR is dependent on the current/current density. In the non-linear region of the *j*-*V* curve, it is recommended to choose small voltage and current intervals.
Temperatures	Some stack designs do not allow direct measurement of the internal temperature of the stack. In this case an average temperature of the stack T_{av} should be calculated as a substitute for the internal temperature. The calculation can include the temperature of gases as well as the temperature of the end plates. Depending on which temperatures can be measured an average temperature can be calculated exemplarily as follows: $T_{av} = \frac{T_{TP}+T_{BP}+T_{neg,in}+T_{neg,out}+T_{pos,in}+T_{pos,out}}{6}$ A stack can be damaged during the start-up/shut-down if the temperature gradient between the gas inlets and the stack itself is too high. A value for the maximum temperature difference during start-up/shut-down can be calculated with the following formula if the internal temperature cannot be measured directly: $\Delta T_{max} = \left\lvert\frac{(T_{neg,in}+T_{pos,in})}{2} - \frac{(T_{TP}+T_{BP})}{2}\right\rvert$
Electrochemical Impedance Spectroscopy	Alternating current signal (galvanostatic mode) in the time domain: $I(\omega,t) = \bar{I}\sin(\omega t)$ Angular perturbation frequency: $\omega = 2\pi\upsilon$ Alternating voltage response in the time domain: $V(\omega,t) = \bar{V}\sin(\omega t + \varphi)$ Impedance *Z(ω)* of an electrochemical component in the time domain: $Z(\omega) = \frac{V(\omega,t)}{I(\omega,t)} = \frac{\bar{V}\sin(\omega t+\varphi)}{\bar{I}\sin(\omega t)} = \lvert Z\rvert \cdot \frac{\sin(\omega t+\varphi)}{\sin(\omega t)}$ Impedance in the frequency domain (Fourier transform, FT space): $Z(\omega) = \frac{FFT\{V(\omega,t)\}}{FFT\{I(\omega,t)\}} = \lvert Z\rvert\, exp(i\varphi) = \lvert Z\rvert\cos(\varphi) + \lvert Z\rvert i\sin(\varphi) = Z + i \cdot Z''$, Magnitude or modulus of the impedance: $\lvert Z(\omega)\rvert = \sqrt{Z'(\omega)^2 + Z''(\omega)^2}$ $tan\varphi(\omega) = \frac{Z''(\omega)}{Z'(\omega)}$

	Imaginary unit property: $i^2=-1$

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