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EU harmonised testing protocols for high-temperature steam electrolysis

Performance and durability of stacks and systems

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Contents

Abstract

The objective of this document is to present testing protocols for establishing the performance and durability of high-temperature electrolyser (HTE) stacks and high-temperature steam electrolysis (HTSEL) systems for the generation of bulk amounts of hydrogen by the electrolysis of steam (water vapour) using electricity mostly from variable renewable energy sources (RESs). In addition, stacks and systems may utilise heat from energy conversion and industrial processes.

By applying these testing protocols, it will be generally possible to characterise and evaluate the performance and durability of different stacks and systems aiming at an adequate comparison of different solid oxide cell (SOC) technologies, namely solid oxide steam electrolysis (SOEL) and proton-conducting ceramic steam electrolysis (PCCEL).

The test methods contained herein are based on standards of the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). In addition, we consider testing procedures previously developed by research projects funded by the Fuel Cells and Hydrogen second Joint Undertaking (FCH2JU) as well as those published as part of the European Union (EU) electrolysis harmonisation activities. The duty cycles contained herein serve as examples and may be complemented by more appropriate cycles, for example, to reflect realistic RES power profiles for on-demand HTE operation.

These testing protocols are intended to be used by the research community and industry alike, for example, to evaluate research and development (R&D) progress, set research and innovation (R&I) priorities including cost targets, development milestones and technological benchmarks as well as making informed decisions regarding technology selection in power-to-hydrogen (P2H2) and hydrogen-to-industry (H2I) applications.

Foreword

This report was carried out under the framework contract between the Directorate-General JRC of the European Commission (EC) and the FCH2JU, the predecessor to the Clean Hydrogen Joint Undertaking (Clean H_2 JU) (1). The JRC contractual activities are summarised in the strategic research and innovation agenda 2021-2027 of the Clean Hydrogen Partnership for Europe (SRIA) (2). This report constitutes the deliverable B.3 of the Rolling Plan 2022, contained in the Clean H_2 JU work programme 2022 (3). It is the result of a collaborative effort between European partners from research and technology organisations in industry and academia participating to EU funded R&D projects (4) in P2H2 and H2I applications involving HTE for demonstration and eventually, industrial deployment.

(1) According to Article 3(1)(c) of Council Regulation (EU) No 2021/2085 of 19/11/2021 (EU OJ L 427, 30.11.2021, p. 17), the Clean H_2 JU succeeds the FCH2JU as of 30 November 2021.

(2) see online at https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en on p. 103

(3) see online at https://www.clean-hydrogen.europa.eu/about-us/key-documents/annual-work-programmes_en on p. 209

(4) For a list of projects, see online at https://www.clean-hydrogen.europa.eu/projects-repository_en. More comprehensive information can be searched at the Community Research and Development Information Service (CORDIS) under https://cordis.europa.eu.

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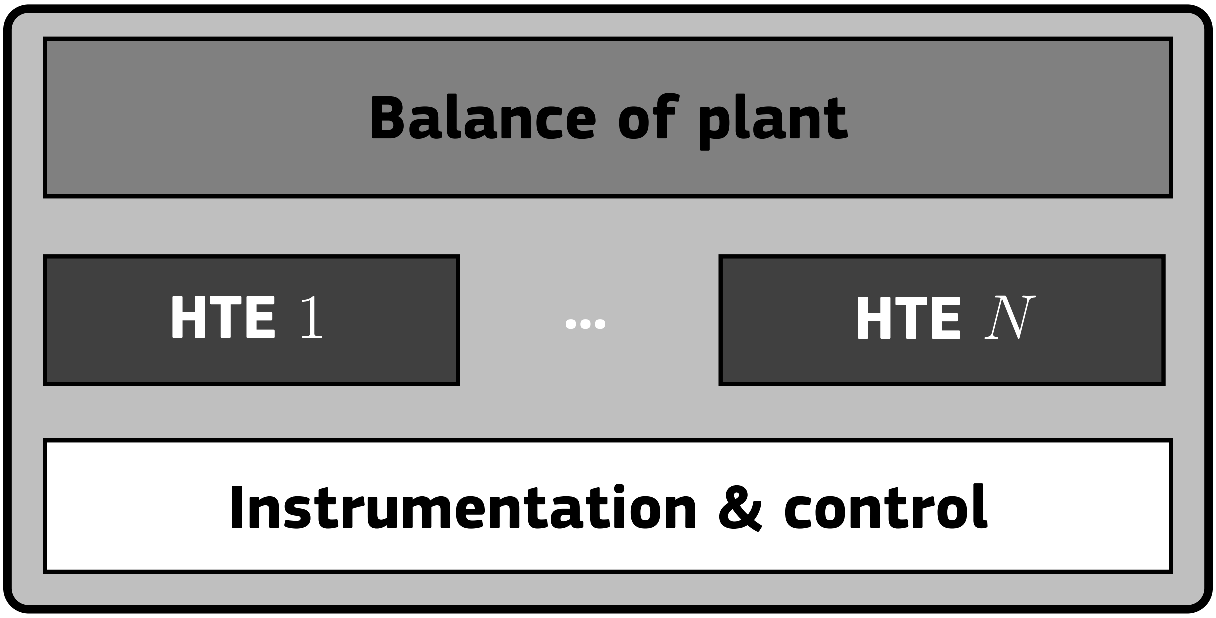
1 Introduction

HTE stacks and HTSEL systems (Figure 1.1) increasingly play an important role for the generation of bulk amounts hydrogen (H_2) by HTSEL in P2H2 applications and H2I processes. They use electricity particularly from variable RESs and heat from energy conversion and other industrial processes making them more efficient than their more mature counterparts using commercially readily available low-temperature water electrolysis (LTWE) technologies, *i. e.* alkaline water electrolyser (AWE) and proton exchange polymer membrane water electrolyser (PEMWE) (Chatenet *et al.*, 2022, Shih *et al.*, 2022, Ebbesen *et al.*, 2014). SOC technologies comprise both solid oxide electrolysis cells (SOECs) in solid oxide electrolysers (SOEs) including reversible solid oxide electrolysers (rSOEs) and proton-conducting ceramic electrolysis cells (PCECs) in proton-conducting ceramic electrolysers (PCEs) including reversible proton-conducting ceramic electrolysers (rPCEs).

Figure 1.1: Schematic of a HTSEL system comprising one or more HTEs, common balance of plant (BoP) and instrumentation & control devices including safety sensors and operation software.



Source: JRC, 2023.

Commonly, the manufacturer specifies which BoP components form part of the system. Besides common hardware (piping, valves, actuators, sensors, wiring/cabling, etc), BoP usually consists of

- **power supply** such as an alternating current-to-direct current (AC/DC) converter (rectifier) when grid-connected, or direct current-to-direct current (DC/DC) converter(s) when directly coupled (off-grid) to one or another RES, for example, photovoltaic (PV) arrays and/or wind turbines,
- **steam generator** for feeding steam to the HTE stack(s) or **conditioning unit** for supplied steam and
- **gas purification** including cooler(s), dryer(s), steam-trap and de-oxidiser.

The immediate use of the generated hydrogen may require compression equipment as part of the BoP especially in power-to-gas (P2G) applications and in industrial processes requiring high pressure hydrogen. In energy-storage (ES) applications including hydrogen-to-power (HtP) with hydrogen stored as compressed hydrogen (CH2) in vessels or large (seasonal) underground storage facilities, compression equipment (Sdanghi *et al.*, 2020, Marciuš *et al.*, 2022) including electrochemical hydrogen compressors (EHCs) may or may not be part of the BoP of a particular system. EHC can be proton exchange polymer membrane (PEM) based operating at low temperature (< 100 °C) or proton-conducting ceramic (PCC) (**4.1.9**) based operating at high temperature (500-800 °C).

In power-to-mobility (P2M) applications with hydrogen stored as liquefied hydrogen (LH_2) in vessels, liquefaction equipment may or may not be part of the BoP of a particular system.

Where systems jointly use points of connection (PoCs) for electricity and/or fluid supply as well as for conveying exiting hydrogen as part of a plant, the system boundary as the delineation between system interior and system exterior should be defined by the manufacturer preferably in agreement with the user.

The application of the testing protocols presented herein do not require specification of the type and characteristic of the test item (**4.1.14**), whether a HTE stack or a HTSEL system (section 5).

HTSEL systems operating as rSOEs or rPCEs may comprise stacks of reversible fuel cell (rFC) type in a single device capable of operating in electrolysis mode and fuel cell (FC) mode. Alternatively, the system could comprise two types of separate stacks operating as electrolyser and FC, respectively.

2 Objective and scope of this document

The objective of this document is to present testing protocols (section 6) for establishing the performance (**4.1.7**) and durability (**4.1.3**) of HTE stacks and the reliability (**4.1.11**) of HTSEL systems and of individual HTEs used for generating bulk amounts of hydrogen by high-temperature electrolysis (HTEL) of (pressurised) steam (section 3) at temperature in excess of 500 °C (723 K). The stacks and systems (section 5) use electricity preferably from least dispatchable sources of renewable energy (solar, tidal, wave, wind, etc) as well as available (waste) heat from power generation or various industrial processes.

The systems may be used in various applications where hydrogen is used as an energy carrier (fuel or commodity) among others in ES such as P2G, P2M (road, rail, maritime) and power-to-X (P2X) including power-to-chemical (P2C), power-to-liquid (P2L) and power-to-fuel (P2F), as well as direct use as feedstock or reductant in H2I processes.

By applying the testing protocols to a test plan (section 6.4), the performance and durability of stacks and systems are established under given test conditions (section 6.2) ([5]), for example,

- To evaluate R&D progress made,
- To set R&I priorities for development milestones and technological benchmarks to improve technology and assess impact on cost and
- To make well informed business decisions regarding technology selection of a particular stack or system.

Note, these protocols apply to oxygen ion-conducting solid oxide electrolyser (O-SOE) performing SOEL and similarly to proton-conducting solid oxide electrolyser (P-SOE) also known as PCE performing PCCEL.

The test methods suggested for establishing the performance of stacks and systems are mainly those contained in standards of ISO and IEC ([6]).

In addition, we also consider testing procedures previously developed by FCH2JU funded research projects ([7]) particularly REFLEX (CEA, 2018), GAMER (SINTEF, 2018) and SOCTESQA (DLR, 2014, Lang *et al.*, 2019) as well as those resulting from the EU electrolysis harmonisation activities (Malkow and Pilenga, 2023). This document is not intended to exclude any other related testing procedures or test methods.

The duty cycles presented (section 6.6) serve as examples to establish primarily the durability of HTE stacks as well as the reliability of HTSEL systems. They can be complemented by more appropriate cycles, for example, to reflect realistic RES profiles for on-demand stack operation including the performance of services especially to balance renewable energy loads on the electricity grid (grid balancing services) ([8]). The estimation of durability serves to assess performance degradation and to predict useful life and maintenance needs of HTE stacks and HTSEL systems.

These generic protocols constitute testing guidance including mandatory requirements and agreed reference operating conditions for HTE stacks (SOE and PCE) to establish the performance and durability of stacks and the reliability of HTSEL systems in a given P2H2 application. They also allow sufficient flexibility when the test plan (section 6.4) of a scheduled test campaign is drawn up. Thus, the test plan is to provide further details on

- test execution including
  - test input parameter (TIP) settings with permissible variations,
  - test criteria and
  - duty cycle(s)

  based on the stated purpose(s) and objective(s) of the tests and
- where necessary, provide more specific details on
  - testing procedures,
  - measurement methods,
  - data acquisition (DAQ) and
  - post-processing of test results including an agreed set of test output parameters (TOPs).

Users of this document may selectively execute tests that are suitable for the objective(s) and purpose(s) of their test campaign from those described herein.

([5]) Note, the key performance indicator (KPI) targets of the SRIA state for SOEL technologies atmospheric pressure of hydrogen at a purity of 5 (99,999 vol-% of hydrogen in the yielded product gas), see online the notes at `https://www.clean-hydrogen.europa.eu/knowledge-management/sria-key-performance-indicators-kpis_en`.

([6]) These standards can be purchased directly from ISO and IEC or their constituting national committees.

([7]) These documents (Graves *et al.*, 2018, Vøllestad *et al.*, 2018, Malkow *et al.*, 2014) are available for download, see References.

([8]) Working group (WG) 32 of ISO Technical Committee (TC) 197 currently prepares the approved working item (AWI) entitled "ISO 22734-2 Hydrogen generators using water electrolysis - Industrial, commercial, and residential applications - Part 2: Testing guidance for performing electricity grid service".

3 Overview of high-temperature steam electrolysis technologies

For the generation of one mole of gaseous (denoted by subscript $_{(g)}$) hydrogen ($H_{2\,(g)}$) along with half a mole of gaseous oxygen ($O_{2\,(g)}$) by HTSEL of one mole of water vapour ($H_2O_{(g)}$), the two known HTE technologies are

SOE where oxygen is formed by oxidising oxygen ions at the anode (positive electrode, oxygen electrode or positrode) in the oxygen evolution reaction (OER):

$$\text{Anode (positrode):}\quad O^{2-}{}_{(el)} \xrightarrow{\text{OER}} \frac{1}{2} O_{2\,(g)} + 2e^-{}_{(ed)} \tag{3.0.1a}$$

under a positive difference in potential (voltage) in excess of the open circuit voltage (OCV). This difference is the result of the supplied direct current (DC). Gaseous hydrogen is formed by reducing water vapour (steam) at the cathode (negative electrode, hydrogen electrode or negatrode) in the hydrogen evolution reaction (HER):

$$\text{Cathode (negatrode):}\quad H_2O_{(g)} + 2e^-{}_{(ed)} \xrightarrow{\text{HER}} H_{2\,(g)} + O^{2-}{}_{(el)}. \tag{3.0.1b}$$

The electrons (e^-) are conducted via the electrodes (denoted by subscript $_{(ed)}$) connected to an external circuit (DC power supply) entailing an ohmic resistance. The oxygen ions (O^{2-}) diffuse under the potential difference along grain boundaries (two-dimensional crystalline planar defects between lattices of different crystalline orientation) and via doubly positively charged oxygen ion lattice vacancies ($V_O^{\cdot\cdot}$) through the grains (lattices with same crystal orientation) of the polycrystalline perovskite-type oxide ceramic electrolyte membrane (denoted by subscript $_{(el)}$) of the SOC. This entails an additive ionic resistance.
In Kröger–Vink notation (Kröger and Vink, 1956, Kröger and Vink, 1958), the reactions (3.0.1) read

$$\text{Anode (positrode):}\quad O^x_{O\,(el)} \xrightarrow{\text{OER}} \frac{1}{2} O_{2\,(g)} + 2\,e'_{(ed)} + V^{\cdot\cdot}_{O\,(el)} \quad \text{and} \tag{3.0.2a}$$

$$\text{Cathode (negatrode):}\quad H_2O_{(g)} + 2\,e'_{(ed)} + V^{\cdot\cdot}_{O\,(el)} \xrightarrow{\text{HER}} H_{2\,(g)} + O^x_{O\,(el)}; \tag{3.0.2b}$$

O^x_O and e' denote neutral oxygen ion lattice site and electron in the lattice, respectively.
Note, in a rSOE operated in FC mode also known as solid oxide fuel cell (SOFC) mode, the electrode reactions (3.0.1) proceed by drawing current in reverse order from right to left. Then, the reverse of reaction (3.0.1a) is the oxygen reduction reaction (ORR) at the FC cathode to generate oxygen ions and the reverse of reaction (3.0.1b) is the hydrogen oxidation reaction (HOR) at the FC anode to generate water vapour and electrons. The SOFC cathode is the SOEC anode and the SOFC anode is the SOEC cathode. In SOFC mode, also heat is produced while in SOEC mode, a rSOE like an ordinary SOE consumes heat when operated below the temperature-dependent thermal-neutral voltage (U_{tn}) and produces heat when operated above this voltage. The heat is removed from the stack(s) primarily by sweep gas (**4.1.13**) usually air.

PCE where oxygen is formed by oxidising water vapour (steam) at the anode in the OER:

$$\text{Anode (positrode):}\quad H_2O_{(g)} \xrightarrow{\text{OER}} 2\,H^+{}_{(el)} + 2e^-{}_{(ed)} + \frac{1}{2} O_{2\,(g)} \tag{3.0.3a}$$

under an applied potential (voltage) in excess of the OCV. Gaseous hydrogen is formed by reducing protons (H^+) at the cathode in the HER:

$$\text{Cathode (negatrode):}\quad 2\,H^+{}_{(el)} + 2e^-{}_{(ed)} \xrightarrow{\text{HER}} H_{2\,(g)}. \tag{3.0.3b}$$

Whereas electrons are conducted via the electrodes connected to an external circuit, protons are conducted mainly by Grotthuss-type diffusion (proton hoping) via protonic defects such as hydroxide ions at singly positively charged oxygen ion lattice sites ($OH^{\cdot}_O$) through the PCC electrolyte membrane of the SOC made of disordered or sub-stoichiometric oxides. In Kröger–Vink notation, the reactions (3.0.3) read

$$\text{Anode (positrode):}\quad H_2O_{(g)} + O^x_{O\,(el)} \xrightarrow{\text{OER}} 2\,OH^{\cdot}_{O\,(el)} + 2\,e'_{(ed)} + \frac{1}{2} O_{2\,(g)} \quad \text{and} \tag{3.0.4a}$$

$$\text{Cathode (negatrode):}\quad 2\,OH^{\cdot}_{O\,(el)} + 2\,e'_{(ed)} \xrightarrow{\text{HER}} H_{2\,(g)} + O^x_{O\,(el)}. \tag{3.0.4b}$$

Note, in a rPCE operated in FC mode also known as proton-conducting ceramic fuel cell (PCFC) mode, the electrode reactions (3.0.3) proceed by drawing current in reverse order from right to left. Then, the reverse of reaction (3.0.3a) is the ORR at the FC cathode to generate water vapour and the reverse of reaction (3.0.3b) is the HOR at the FC anode to generate protons and electrons. The PCFC cathode is the PCEC anode and the PCFC anode is the PCEC cathode. In PCFC mode, also heat is produced while in PCEC mode, a rPCE like an ordinary PCE consumes heat when operated below the thermal-neutral voltage and produces heat when operated above this voltage. The heat is removed from the stack(s) primarily by steam as sweep gas.

Remark, the OCV of a HTE stack, whether of type SOE or type PCE, is only measurable reliably in the presence of the respective reactants concomitant on the two electrodes in sufficient quantities.

Whereas rSOE have to-date obtained technology readiness level (TRL) 5 at most (Bianchi and Bosio, 2021), SOEs with SOEC as constituting units are most mature with TRL 6 (Bianchi and Bosio, 2021) benefiting from decades of SOFC research. Least mature with TRL lower than 5 are PCEs which are currently at the early development phase including research for suitable stack design and manufacturing processes as well as research for most suitable combinations of electrode and electrolyte materials for PCECs as constituting units. Most common in SOECs are yttria-stabilised zirconia (YSZ) as electrolyte, strontium-doped lanthanum manganite (LSM) with YSZ and strontium-doped lanthanum cobalt iron oxide (LSCF) with and without ceria-doped gadolinium oxide (CGO) as anode and Ni-cermet as cathode.

SOC geometries can be tubular or planar. Planar SOCs may be circular, square or rectangular. The mechanical support of planar SOCs may be provided by one of the electrodes, by the electrolyte or by a metal interconnect. For planar SOCs, the interconnect acts simultaneously as current collector.

The geometry of planar HTE stacks being assemblies of several cells sandwiched between gas flow channel containing interconnects which are electrically connected in series, is usually either planar or cylindrical. Note, monolithic is a less common stack geometry. Stacks comprising various tubular cells bundled together in parallel arrangement are also possible. Likewise, they are electrically connected using metallic interconnects.

4 Terminology

Terms and definitions used in this document are given below as well as in two JRC reports (Tsotridis and Pilenga, 2018,Malkow *et al.*, 2021). In addition, ISO and IEC maintain terminological databases at the following websites:

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

The verbal forms used have the following meaning:

- “shall” indicates a requirement,
- “should” indicates a recommendation,
- “may” indicates a permission and
- “can” indicates a possibility or a capability.

Reference to Système International d’Unités (SI) coherent (derived) units includes, as appropriate, metric prefixes of the concerned unit. Decimal fractions are denoted by comma. Alongside SI units, non-SI units may be used as customary. For example, degree Celsius (°C) is used as unit of temperature (T) alongside Kelvin (K) and kilo Watt hours (kWh) is used as unit of energy (E) instead of kilo Joule (kJ).

4.1 Terms and definitions

4.1.1 accelerated life testing (ALT)
destructive testing of an item by subjecting it to aggravated conditions (*e. g.* pressure, temperature, voltage, vibration, etc) in excess of nominal conditions of real-life use, in an attempt to reveal faults and modes of failure in a short amount of time and to assess the item’s useful life mainly for commercial purposes

4.1.2 accelerated stress testing (AST)
non-destructive testing of an item by applying high levels of stress when operated (*e. g.* pressure, temperature, voltage, etc) for a short amount of time in an attempt to trigger the same performance degradation mechanism(s) as would presumably occur for a longer exposure of the item when tested under normal conditions of use; it is mainly for identifying potentially detrimental operating conditions and modes of operation as well as unsuitable designs and ineffective materials

4.1.3 durability
ability of a test item to maintain its performance characteristics as required until the end of useful life, under given conditions of use and maintenance

4.1.4 durability test
test intended to verify whether, or to evaluate to which degree, a test item is able to maintain its performance characteristics over a period of use

4.1.5 flexibility
ability of a test item to operate variably, that is, to ramp-up and/or ramp-down its output rapidly in response to a change in input

4.1.6 hydrogen output conditions
specified conditions of of hydrogen ($p_{\mathrm{H_2}}$) and temperature of hydrogen ($T_{\mathrm{H_2}}$)

4.1.7 performance characteristics
characteristics defining the ability of a test item to operate as required, under given conditions of use and maintenance

4.1.8 performance test
test intended to verify whether, or to evaluate to which degree, a test item is able to accomplish its performance characteristics

4.1.9 proton-conducting ceramic (PCC)
(sub-stoichiometric) membrane enabling bulk conduction of protons (H^+)

4.1.10 reactivity
time taken (t_{resp}) by a test item in response to a change in input

4.1.11 reliability

ability of a test item to adequately perform as required, without failure, for a specified time (t), under given conditions of use and maintenance

4.1.12 standard ambient temperature and pressure (SATP) conditions

conditions of standard ambient , p^0 = 100 kPa and standard ambient temperature, T^0 = 298,15 K

4.1.13 sweep gas

inlet stream of (reactant) gas used to remove heat alongside oxygen from a high-temperature electrolyser stack

4.1.14 test item

high-temperature electrolyser stack or high-temperature steam electrolysis system

4.2 Abbreviations and acronyms used

A list of abbreviations and acronyms used in this report is appended, see page 33.

4.3 Symbols used

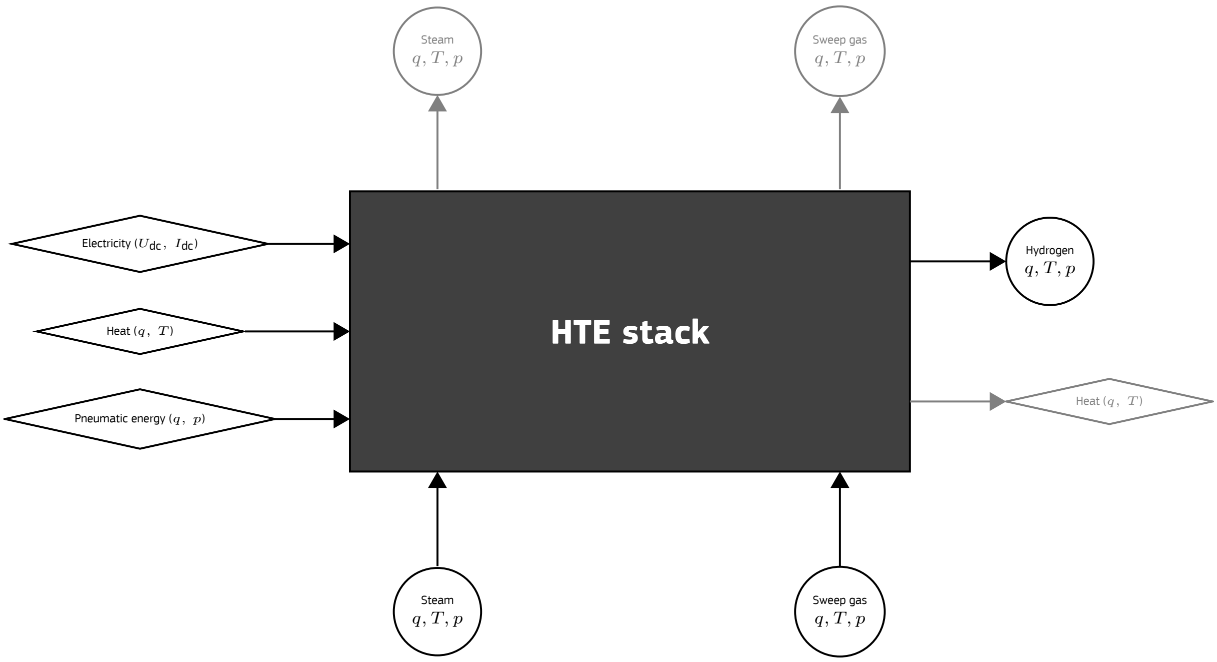
A list of symbols used in this report is appended, see page 36.

5 Description of test items

5.1 HTE stack

Figure 5.1 shows schematically the input and output streams of energy forms and substances of a HTE stack where the symbols I_{dc}, U_{dc}, q, p and T stand respectively for direct current, DC voltage, flow rate, pressure and temperature.

Figure 5.1: Schematic of the input and output streams (directional arrows) of energy (diamond shape) and substances (circular shape) of a high-temperature electrolyser stack (rectangular shape). The thick line around the grey shaded box represents the stack boundary.



Source: JRC, 2023.

At its PoCs, the input energy streams to a HTE stack are

- **Electricity** in the form of electric energy:

$$E_{\mathrm{el}}\ (\mathrm{kWh}) = P_{\mathrm{el}}\ (\mathrm{kW}) \cdot t\ (\mathrm{h}) \ \text{ where} \tag{5.1.1}$$

  P_{el} is electric power and t is the duration during which the electric power is applied. Specifically, the electric power of a stack is DC power:

$$P_{\mathrm{el,\,dc}}\ (\mathrm{kW}) = U_{\mathrm{dc}}\ (\mathrm{kV}) \cdot I_{\mathrm{dc}}\ (\mathrm{A}). \tag{5.1.2}$$

- **Heat**, if any, in the form of thermal energy:

$$E_{\mathrm{th}}\ (\mathrm{kWh}) = P_{\mathrm{th}}\ (\mathrm{kW}) \cdot t\ (\mathrm{h}) \ \text{ where} \tag{5.1.3}$$

  P_{th} is thermal power given by equation (5.1.4) and t is the duration of heat supply.

$$P_{\mathrm{th}}\ (\mathrm{kW}) = \sum_{\mathrm{i}} q_{\mathrm{m}}^{\mathrm{i}}\ (\mathrm{kg/s}) \cdot c_{\mathrm{p}}^{\mathrm{i}}\ (\mathrm{kJ/(kg\ K)}) \cdot (T^{\mathrm{i}}\ (\mathrm{K}) - T^{0}\ (\mathrm{K})); \tag{5.1.4}$$

  $q_{\mathrm{m}}^{\mathrm{i}}$, $c_{\mathrm{p}}^{\mathrm{i}}$, T^{i} and T^{0} are of fluid i, of fluid i, temperature of fluid i and standard ambient temperature, respectively. The fluids i (input substance streams) are

  - air as sweep gas to SOEs and
  - steam as feed to SOEs and as feed and sweep gas to PCEs.

- **Pneumatic energy**:

$$E_{\mathrm{compr}}\ (\mathrm{kWh}) = P_{\mathrm{compr}}\ (\mathrm{kW}) \cdot t\ (\mathrm{h}) \ \text{ where} \tag{5.1.5}$$

P_{compr} is power of compression given by equation (5.1.6) and t is the duration of stack operation under pressure.

$$P_{\text{compr}}\ (\text{kW}) \ = \ \sum_{\text{j}} \left(\frac{\gamma^{\text{j}}}{\gamma^{\text{j}} - 1} \right) \frac{\bar{Z}^{\text{j}} \cdot R_{\text{g}}\ (\text{kJ/(mol K)}) \cdot T^0\ (\text{K}) \cdot q_{\text{n}}^{\text{j}}\ (\text{mol/h})}{3600\ (\text{s/h})} \left(\frac{p^{\text{j}}\ (\text{kPa})}{p^0\ (\text{kPa})} \right)^{\frac{\gamma^{\text{j}}-1}{\gamma^{\text{j}}}} ; \qquad (5.1.6)$$

$\bar{Z}^{\text{j}}$, R_{g}, T^0, q_{n}^{j}, p^{j} and p^0 are of fluid j, universal gas constant, standard ambient temperature, of fluid j, of fluid j and standard ambient , respectively. The of fluid j is

$$\gamma^{\text{j}} \ = \ \frac{c_{\text{p}}^{\text{j}}\ (\text{kJ/(kg K)})}{c_{\text{V}}^{\text{j}}\ (\text{kJ/(kg K)})};$$

c_{p}^{j} and c_{V}^{j} are of fluid j and of fluid j, respectively. The fluids j (input substance streams) are

- pressurised steam to SOEs and PCEs and
- compressed air to SOEs.

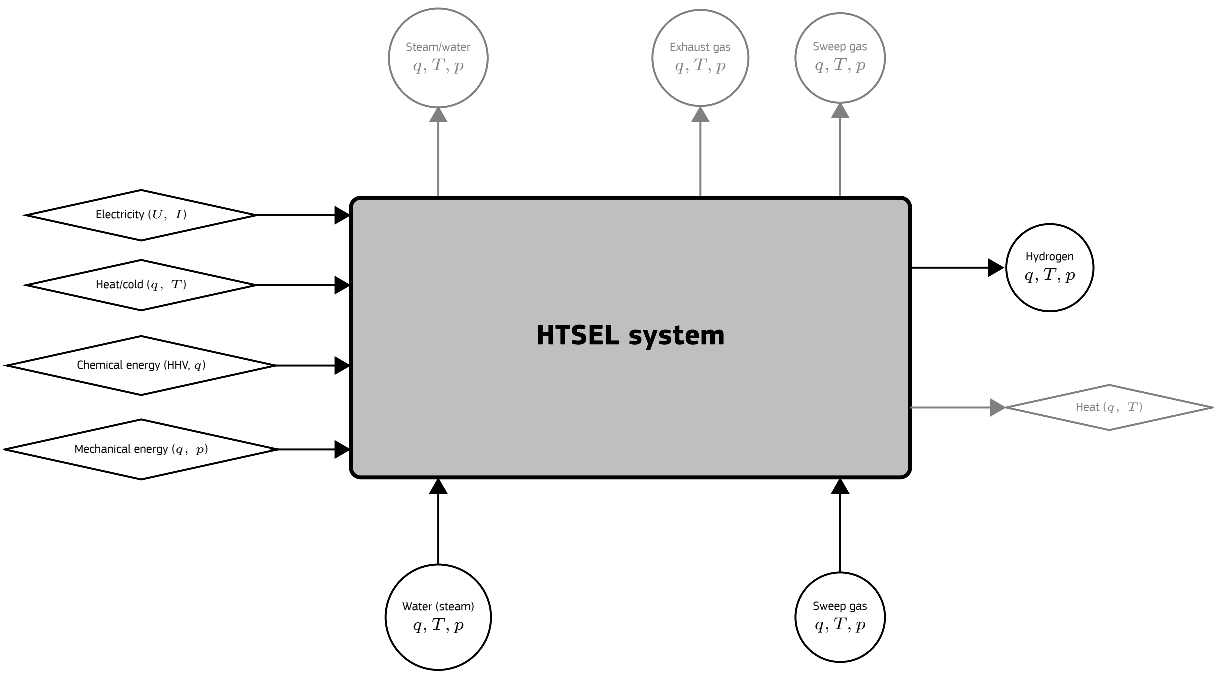
The output streams of the stack are for

- **SOE**
  - **oxygen** in **sweep gas** (air) at the anode,
  - **hydrogen** in **steam** at the cathode and
  - Heat conveyed by these fluids.
- **PCE**
  - **oxygen** in **sweep gas** (steam) at the anode,
  - **hydrogen** at the cathode and
  - Heat conveyed by these fluids.

5.2 HTSEL system

Figure 5.2 shows schematically the input and output streams of energy forms and substances of a HTSEL system where the symbols I and U stand for current and voltage, respectively.

Figure 5.2: Schematic of the input and output streams (directional arrows) of energy (diamond shape) and substances (circular shape) of a high-temperature steam electrolysis system (rectangular shape). The thick line around the grey shaded box represents the system boundary.



Source: JRC, 2023.

At its PoCs, the input energy streams to a HTSEL system are

- **Electricity** in the form of electric energy, see equation (5.1.1) using
  - DC power, see equation (5.1.2),
  - AC power ($P_{\text{el, ac}}$) whether symmetrical three-phase AC power:

$$P_{\text{el, 3p, ac}}\ (\text{kW}) \ = \ \sqrt{3} \cdot U_{\text{ac}}\ (\text{kV}) \cdot I_{\text{ac}}\ (\text{A}) \cdot \cos\varphi \tag{5.2.1}$$

    or single-phase AC power:

$$P_{\text{el, 1p, ac}}\ (\text{kW}) \ = \ U_{\text{ac}}\ (\text{kV}) \cdot I_{\text{ac}}\ (\text{A}) \cdot \cos\varphi; \tag{5.2.2}$$

    U_{ac}, I_{ac} and $\cos\varphi$ are respectively the root-mean-square (rms) AC voltage, rms alternating current and power factor (IEEE, 2010), or
  - both, AC power and DC power.
- **Heat/cold**, if any, in the form of thermal energy, see equation (5.1.3), carried by fluids i (input substance streams). For example, heat may be used to heat-up water to generate steam while cold may be used to cool down the generated hydrogen and oxygen gases.
- **Chemical energy**, if any, represented by the higher heating value (HHV) of gaseous fuel (HHV^{f}) with molar (q_{n}^{f}), for example, when natural gas (NG) is used to generate steam from water (H_2O). In this case, equation (5.1.4) reads

$$P_{\text{th}}\ (\text{kW}) \ = \ \text{HHV}^{\text{f}}\ (\text{kWh/mol}) \cdot q_{\text{n}}^{\text{f}}\ (\text{mol/h}) \ + \ \sum_{\text{i}} q_{\text{m}}^{\text{i}}\ (\text{kg/s}) \cdot c_{\text{p}}^{\text{i}}\ (\text{kJ/(kg K)}) \cdot (T^{\text{i}}\ (\text{K}) - T^{0}\ (\text{K})). \tag{5.2.3}$$

- **Mechanical energy**, if any, in the form of hydraulic energy conveyed, for example, by hydraulic oil and in the form of pneumatic energy, see equation (5.1.5), for example conveyed by compressed air, pressurised steam), or both. For example, stack compression may require hydraulic fluids, control devices may be actuated by compressed air and substances (steam, hydrogen or oxygen) may be compressed by supplied hydraulic fluid(s) or pneumatic fluid(s) as input substance streams.

The output streams of the system are

- **Hydrogen**,
- **Water/steam**,
- **Oxygen** in sweep gas (air for SOE and steam for PCE),
- Heat conveyed by these fluids and
- Exhaust gas mainly carbon dioxide, for example, when NG is used as fuel to generate steam.

6 Testing protocols

6.1 General

The operation of the test items, whether a HTE stack (Figure 5.1) or a HTSEL system (Figure 5.2), shall be in accordance with applicable safety requirements (Annex A) and the manufacturer's instructions.

The testing of the stack or system under given test conditions (section 6.2) consist of executing, usually at their beginning-of-life (BoL) ([9]), all or selected types of performance tests (**4.1.8**) according to a defined test plan (section 6.4) depending on the purpose(s) and objective(s) of the test campaign.

Note, the purpose of a test campaign could be, for example, establishing the performance and/or durability of a stack or system in a given application whether for assessing research progress, advancing product development or technology monitoring and assessment (TMA). The objective of a test campaign could be, for example, to determine under which conditions and modes of operation defined KPIs may or may not be achieved by the stack or system in the target application. For example, at a given input current, the hydrogen output rate, voltage, area-specific resistance and for PCE, the Faradaic efficiency may be chosen as KPIs for stacks subject to performance tests. For systems, the hydrogen output rate, the specific energy consumption, the specific electric energy consumption and the specific thermal energy consumption may be chosen as KPIs at a given input power according to the purpose(s) and objective(s) of the test campaign, see section 6.7.4 for KPIs regarding durability.

In a test campaign, performance tests (section 6.5) of a stack or system at BoL are usually followed by durability tests (section 6.7) conducted either at constant power (P), constant current (I) or constant voltage (U) for a prescribed period of use of the stack or system (section 6.7.2), or by employing application-oriented duty cycles (section 6.6) as appropriate for the intended use of the stack or system (section 6.7.3).

Intermittently, performance tests may be executed at specified intervals to assess how the stack or system has maintained or altered its performance characteristics. This also applies to the end of the test campaign when the final degree of the ability of the stack or system to maintain its performance characteristics is evaluated and alterations thereof are determined (section 6.7.4). Also, the test plan (section 6.4) may require to regularly perform safety checks (Annex A) on the stack and/or system. Testing shall not be continued for stacks and systems which are unsafe to operate.

The hydrogen output conditions (**4.1.6**) of the stack(s) and system including permissible variations shall be defined prior to testing and recorded in the test report (Annex C).

The change(s) in the performance characteristics are usually also graphically presented versus the total test duration or the number of performed duty cycles or sequence(s) of duty cycles (section 7).

Guidance on how to carry out an uncertainty analysis of the test results is provided by the Guide to the expression of uncertainty in measurement (GUM) (JCGM, 2009).

6.2 Test conditions

The test conditions including any permissible variation are

- the environmental conditions of the immediate surrounding (ambient) of the item under test such as air velocities, pressure, temperature, humidity, salinity, ultraviolet (UV) radiation and other weather conditions, as well as

- the actual operating conditions and operation mode(s) including start-up, normal operation, shut-down and quiescence (standby).

They shall be defined prior to testing in accordance with the purpose(s) and objective(s) of the test campaign and be in conformity with the specification of the stack or system as provided by the manufacturer.

Note, the TIPs used in the various performance and durability tests shall be based on these operating conditions and modes of stack or system operation. In the test plan, the individual set values of these TIPs shall be listed per test along with the related TOPs (test results) whether measured or calculated.

Reference test conditions may be agreed prior to testing to facilitate comparison of test results. Table 6.1 provides reference operating conditions recommended for HTE stacks of type SOE and PCE.

Table 6.1: Recommended reference operating conditions for HTE stacks

Description	**Symbol (unit)**	**SOE** ([1])	**PCE** ([2])
Anode gauge outlet pressure	p^{a} (kPa)	100 ($\pm$2 %)	300 ($\pm$2 %)
Cathode gauge outlet pressure	p^{c} (kPa)	100 ($\pm$2 %)	300 ($\pm$2 %)

Continue to next page

([9]) For a stack, BoL shall be the start of first-time operation following complete conditioning according to manufacture's instructions.

Table 6.1 – continued from previous page

Anode gas feed composition (3)	p^{H_2O}/p^{O_2} (kPa/kPa)	-	1,5 ($\pm$2 %)/0,5 ($\pm$2 %)
Cathode gas feed composition (3)	p^{H_2O}/p^{H_2} (kPa/kPa)	0,9 ($\pm$2 %)/0,1 ($\pm$2 %)	-
stack temperature (4)	T_{stack} (K)	973,15 ($\pm$2 K)	873,15 ($\pm$2 K)

Note: The test plan may list other reference operating conditions. It may also list reference operating conditions for systems.
(1) including rSOE when operated in electrolysis mode
(2) including rPCE when operated in electrolysis mode
(3) Inert gas additions (*e. g.* argon) are permitted, for example, to obtain a higher than ambient outlet pressure; p^{H_2O}, p^{O_2} and p^{H_2} are the partial pressures of water vapour, oxygen and hydrogen, respectively.
(4) The sensor position(s) to determine the stack temperature should be specified by the manufacturer.
Source: JRC, 2023

Note, while electrode gas feed compositions are TIPs to be set, the electrode gas pressures and the stack temperature are TOPs needing regulation. Other reference operating conditions can be the manufacturer specified rated stack power (P_{stack}), rated stack current (I_{stack}) or rated stack voltage (U_{stack}). In the first case, the stack power is a TIP to be set while stack current and voltage are measured TOPs. In the second case, stack current is the TIP to be set and stack voltage is a measured TOP while stack power is a calculated (derived) TOP. In the third and last case, stack voltage is the TIP to be set and stack current is a measured TOP while stack power is again a calculated (derived) TOP.

When agreed, the stack or system should first be subject to testing employing such reference test conditions before proceeding to their testing under other specified test conditions.

For example, clause 5.2.3.1 of ISO 22734:2019 (ISO, 2019) mentions common environmental conditions as reference test conditions. For SOEL technologies, the SRIA states as KPI target atmospheric pressure of hydrogen at a purity of 5 which is 99,999 vol-% of hydrogen in the yielded product gas (see online at `https://www.clean-hydrogen.europa.eu/knowledge-management/sria-key-performance-indicators-kpis_en`).

6.3 Measurement techniques

The test equipment, measuring instruments and measurement methods shall conform to the relevant standard (*e. g.* IEC 61010-1:2010+AMD1:2016 CSV (IEC, 2016)), test method or testing procedure employed. Instruments shall be calibrated in accordance with the applicable standard(s), measurement method(s) or procedure(s) recommended by the manufacturer of the stack or system to meet the targeted uncertainties of the concerned test parameters whether TIPs or TOPs.

The measurement set-up employed shall be documented in the test report (Annex C). Also, available calibration records and certificates of the measuring instruments should likewise be documented.

6.4 Test plan

For a test item, the test plan shall be drawn-up taking into account

(a) the item's specification and manufacturer's instructions (*e. g.* for the stack: maximum temperature, range of heating/cooling rates and electrode gas compositions, etc),

(b) the test conditions (section 6.2),

(c) the measurement techniques and instrumentation (section 6.3),

(d) test type (section 6.5 and section 6.7), sequence, frequency and duration,

(e) the DAQ including number, permissible range and frequency of data points,

(f) the state of calibration of the measuring instruments,

(g) post-processing of test results including data reduction and uncertainty analysis,

(h) one or more KPIs, whether measured or derived TOPs, as a result of performance tests (**4.1.8**) and

(i) one or more test stop criteria to (prematurely) end testing for preventing unintended failure or destruction.

One or more KPIs shall be defined to assess the durability (**4.1.4**) of the test item. For this purpose, TIPs and TOPs should be specified to obtain KPIs as functions of such parameters. For example, these parameters are, but not be limited to,

- the input power (P_{in}) whether

  - AC power ($P_{\text{el, ac}}$), or
  - DC power ($P_{\text{el, dc}}$),

- the input current (I_{in}) whether
  - alternating current (I_{ac}) or
  - direct current (I_{dc}),
- the input voltage (U_{in}) whether
  - AC voltage (U_{ac}) or
  - DC voltage (U_{dc}),
- the of hydrogen (p_{H_2}),
- the temperature of hydrogen (T_{H_2}),
- the stack temperature (T_{stack}) and
- the gas feed composition to the electrodes.

Tests may also be conducted at environmental conditions other than standard ambient temperature and pressure (SATP) conditions; for example, system start-up and shut-down may be established for an ambient pressure (p) below standard ambient (p^0) and an ambient temperature (T) below or above standard ambient temperature (T^0) to simulate conditions at different installation sites.

Consistent with the purpose(s) and objective(s) of the test campaign, the test plan should specify the test methods and measurement techniques to be employed where standards, testing procedures and manufacturer's instructions provide for different possibilities. It may also list (micro-structural) characterisation methods, for example, to perform post-test analysis of the stack for gaining more insight into the obtained test results.

6.5 Performance tests

6.5.1 Input electric power

The input electric power ($P_{\text{el, in}}$) to a HTE stack or HTSEL system shall be determined in accordance with clause 5.2.1 of ISO 16110-2:2010 (ISO, 2010).

6.5.2 Input thermal power

The input thermal power ($P_{\text{th, in}}$) to a HTE stack or HTSEL system conveyed by heat transfer fluid(s) shall be determined in accordance with clause 5.2.2.1 of ISO 16110-2:2010 (ISO, 2010).

6.5.3 Input power of compression

The input power of compression ($P_{\text{compr, in}}$) to a HTE stack or HTSEL system conveyed by compression fluid(s) shall be determined in accordance with clause 5.2.2.1 of ISO 16110-2:2010 (ISO, 2010).

6.5.4 Start-up time and energy

The start-up time (t_{on}) of a HTSEL system to its rated hydrogen output rate (section 6.5.8) shall be determined in accordance with clause 5.6.1 of IEC 62282-8-201:2020 (IEC, 2020d) for positive ramp (heating) rate ($\dot{T}_{\text{heat}}$) consistent with the manufacturer's instructions. The heating rate is part of the test conditions (section 6.2).

System start-up is usually from cold state, commonly at SATP conditions. The test plan (section 6.4) may also foresee system start-up from a defined hot state (standby).

The start-up energy (E_{on}) for duration of the start-up time may also be determined in accordance with clause 14.5.4.2 of IEC 62282-3-201:2017+AMD1:2022 CSV (IEC, 2022) where reference to FC shall by analogy be replaced by HTSEL.

6.5.5 Response time and ramp energy

The response time (t_{resp}) of a HTSEL system to a given positive or negative ramp rate of a TIP shall be determined in accordance with clause 5.6.1 of IEC 62282-8-201:2020 (IEC, 2020d). Consistent with the manufacturer's instructions, the TIP may be

- the input power (P_{in}) whether
  - AC power ($P_{\text{el, ac}}$) or
  - DC power ($P_{\text{el, dc}}$),
- the input current (I_{in}) whether
  - alternating current (I_{ac}) or
  - direct current (I_{dc}), or
- the input voltage (U_{in}) whether
  - AC voltage (U_{ac}) or
  - DC voltage (U_{dc}).

In the test report (Annex C), the response time in relation to either of these TIPs shall be recorded separately. The same shall apply to the response time for positive and negative ramp rates.

In addition to the response time, the test plan may request to determine the ramp energy (E_{ramp}) for positive and/or negative ramps of the concerned TIP in accordance with clause 14.6.3.2 of IEC 62282-3-201:2017+AMD1:2022 CSV (IEC, 2022) where reference to FC shall by analogy be replaced by HTSEL.

In the test report, the ramp energy for positive and negative ramps shall be recorded separately.

Accordingly, the test plan should specify a set of symbols for response time and ramp energy, for example, by adding appropriate indices to both TOPs for differentiating between positive and negative ramp rates.

6.5.6 Shut-down time and energy

The shut-down time (t_{off}) of a HTSEL system shall be determined in accordance with clause 5.6.1 of IEC 62282-8-201:2020 (IEC, 2020d) for negative ramp (cooling) rate ($\dot{T}_{\text{cool}}$) consistent with the manufacturer's instructions. The cooling rate is part of the test conditions (section 6.2).

In addition to the shut-down time, the test plan (section 6.4) may request to determine the shut-down energy (E_{off}) in accordance with clause 14.9.3.2 of IEC 62282-3-201:2017+AMD1:2022 CSV (IEC, 2022) where reference to FC shall (by analogy) be replaced by HTSEL.

6.5.7 Switch-over time

For rSOE and rPCE, consistent with the manufacturer's instructions, the switch-over time (t_{switch}) of a HTSEL system to switch from FC mode to electrolysis mode and *vice versa* shall be determined in accordance with clause 5.7 of IEC 62282-8-201:2020 (IEC, 2020d).

In the test report (Annex C), the switch-over time for switching from FC mode to electrolysis mode and from electrolysis mode to FC mode shall be recorded. Also, the sequence of switching whether from FC mode to electrolysis mode or from electrolysis mode to FC mode shall be recorded in the test report.

Accordingly, the test plan (section 6.4) should specify, for example, appropriate indices to be added to t_{switch} to differentiate between the two modes and the sequence of switching.

6.5.8 Hydrogen output rate and quality

The product gas output rate also known as product gas ($q_{\text{n, out}}$) of a HTE stack or HTSEL system shall be determined in accordance with clause 5.2.11.1 of ISO 22734:2019 (ISO, 2019). From the product gas , the hydrogen output rate also known as of hydrogen ($q_{\text{n, H}_2}$) shall be calculated as follows

$$q_{\text{n, H}_2}\ \text{(mol/h)} = x_{\text{n, H}_2}\ \text{(mol/mol)} \cdot q_{\text{n, out}}\ \text{(mol/h)}; \qquad (6.5.1)$$

$x_{\text{n, H}_2}$ is the of hydrogen in the product gas to be determined by gas analysis in accordance with clause 5.2.2.2 of ISO 16110-2:2010 (ISO, 2010).

The hydrogen output quality of a HTE stack and HTSEL system other than the of hydrogen in the product gas, particular humidity, shall be determined in accordance with clause 5.2.11.2 of ISO 22734:2019 (ISO, 2019).

6.5.9 Oxygen output rate and quality

The oxygen output rate or of oxygen ($q_{\mathrm{n,O_2}}$) of a HTE stack and HTSEL system shall be determined in accordance with clause 5.2.11.1 of ISO 22734:2019 (ISO, 2019).

The oxygen output quality, particularly the of oxygen ($x_{\mathrm{n,O_2}}$) in the sweep gas, shall be determined in accordance with clause 5.2.11.2 of ISO 22734:2019 (ISO, 2019).

6.5.10 Polarisation curve measurements

The measurement of the current-voltage characteristics (I_{dc}-U_{dc} curves), known as polarisation curves, shall be determined for HTE stacks by applying the Solid Oxide Cell and Stack Testing, Safety and Quality Assurance (SOCTESQA) Test Module (TM) on current-voltage characteristics (de Marco *et al.*, 2017) or in accordance with clause 7.2 of IEC 62282-8-101:2020 (IEC, 2020c). The stack temperature (T_{stack}) shall be recorded as an additional TOP. Its average should be plotted versus the average of the stack direct current to check for temperature stability during the measurement.

From the I_{dc}-U_{dc} curves, the current-electric power characteristics (I_{dc}-P_{el} curves) of the stack may be derived by calculating its electric power ($P_{\mathrm{el,stack}}$) as follows

$$P_{\mathrm{el,stack}}\ (\mathrm{kW}) \ = \ U_{\mathrm{dc}}\ (\mathrm{kV}) \cdot I_{\mathrm{dc}}\ (\mathrm{A}). \tag{6.5.2}$$

The electric power density of the stack ($P_{\mathrm{el,d,stack}}$) is calculated as follows

$$P_{\mathrm{el,d,stack}}\ (\mathrm{kW/cm^2}) \ = \ U_{\mathrm{dc}}\ (\mathrm{kV}) \cdot J_{\mathrm{dc}}\ (\mathrm{A/cm^2}) \ \ \text{where} \tag{6.5.3}$$

$$J_{\mathrm{dc}}\ (\mathrm{A/cm^2}) \ = \ \frac{I_{\mathrm{dc}}\ (\mathrm{A})}{A_{\mathrm{act}}\ (\mathrm{cm^2})} \tag{6.5.4}$$

is the DC current density of the stack with active electrode area, A_{act}, specified by the stack manufacturer.

6.5.11 EIS measurements

The electrical impedance (Z) of individual SOCs in a HTE stacks shall be determined by applying the SOCTESQA TM on electrochemical impedance spectroscopy (EIS) (Lang *et al.*, 2017) or in accordance with clause 7.6 of IEC 62282-8-101:2020 (IEC, 2020c). Guidance on EIS measurements is provided by clause 10.7.2.2 of IEC 62282-7-2:2014 (IEC, 2014b) and clause 6.3.10 of IEC 62282-8-101:2020 (IEC, 2020c) while guidance on data-post processing of EIS data is provided by clause 7.6.3 of IEC 62282-8-101:2020 (IEC, 2020c). Useful software tools to perform data-post processing of EIS data are listed in term 403 on p. 66 (online version) of the recently published electrolysis terminology document (Malkow *et al.*, 2021).

From the EIS measurements, the ohmic resistance (R_{Ω}) and the polarisation resistance (R_{pol}) are estimated. In principle, the ohmic resistance is the high-frequency resistance (R_{∞}) that is the electrical impedance at high perturbation frequencies ($f \to \infty$) with vanishing reactance, $\mathfrak{Im} Z\,[f \to \infty] = 0$,

$$\lim_{f \to \infty} \mathfrak{Re} Z\,[f]\ (\Omega) \ = \ R_{\infty}\ (\Omega). \tag{6.5.5}$$

Practically, the high-frequency resistance is taken as the electrical impedance measured at the highest of the probed perturbation frequencies (f_{max}) where $\mathfrak{Im} Z\,[f \to f_{\mathrm{max}}] \to 0$,

$$\lim_{f \to f_{\mathrm{max}}} \mathfrak{Re} Z\,[f]\ (\Omega) \ \approx \ R_{\Omega}\ (\Omega). \tag{6.5.6}$$

The polarisation resistance is the difference between the low-frequency resistance and the high-frequency resistance (R_0),

$$R_{\mathrm{pol}}\ (\Omega) \ = \ R_0\ (\Omega) \ - \ R_{\infty}\ (\Omega). \tag{6.5.7}$$

The low-frequency resistance is the electrical impedance at low perturbation frequencies ($f \to 0$) with vanishing reactance, $\mathfrak{Im} Z\,[f \to 0] = 0$,

$$\lim_{f \to 0} \mathfrak{Re} Z\,[f]\ (\Omega) \ = \ R_0\ (\Omega). \tag{6.5.8}$$

Practically, the low-frequency resistance is taken as the electrical impedance measured at the lowest of the probed perturbation frequencies (f_{min}) where $\mathfrak{Im} Z\,[f \to f_{\mathrm{min}}] \to 0$,

$$\lim_{f \to f_{\mathrm{min}}} \mathfrak{Re} Z\,[f]\ (\Omega) \ \approx \ R_{\mathrm{lf}}\ (\Omega). \tag{6.5.9}$$

Consequently, the polarisation resistance is approximated as follows

$$R_{\text{pol}}\ (\Omega)\ \approx\ R_{\text{lf}}\ (\Omega)\ -\ R_{\Omega}\ (\Omega). \tag{6.5.10}$$

The area-specific resistance (R_{ASR}) is calculated as follows

$$R_{\text{ASR}}\ (\text{m}\Omega.\text{cm}^2)\ =\ R_{\text{lf}}\ (\Omega)\cdot A_{\text{act}}\ (\text{cm}^2)\cdot 1000\ \ \text{m}\Omega/\Omega. \tag{6.5.11}$$

In case EIS measurements and polarisation curve measurements (section 6.5.10) are conducted simultaneously, care should be taken in data post-processing of the test results as both, current and voltage, would contain AC and DC contributions.

6.5.12 Specific energy consumption

The specific energy consumption per unit of hydrogen ($\varepsilon_{\text{e, V}}$) and the specific energy consumption per unit of hydrogen ($\varepsilon_{\text{e, m}}$) shall be determined for HTE stacks and HTSEL systems applying the recently published energy performance testing procedure (Malkow and Pilenga, 2023).

Also, the specific electric energy consumption per unit of hydrogen ($\varepsilon_{\text{el, V}}$) and the specific electric energy consumption per unit of hydrogen ($\varepsilon_{\text{el, m}}$) shall be determined for stacks and systems applying the same testing procedure.

Likewise, applying the said testing procedure, the specific thermal energy consumption per unit of hydrogen ($\varepsilon_{\text{th, V}}$) and the specific thermal energy consumption per unit of hydrogen ($\varepsilon_{\text{th, m}}$) shall also be determined for stacks and systems supplied with heat.

6.5.13 Efficiency

For a HTE stack or HTSEL system, the energy efficiency (η_{e}) based on the HHV of hydrogen ($\eta^0_{\text{HHV, e}}$) and the lower heating value (LHV) of hydrogen ($\eta^0_{\text{LHV, e}}$) should be determined applying the recently published energy performance testing procedure (Malkow and Pilenga, 2023).

Likewise, the electrical efficiency (η_{el}) based on the HHV and LHV of hydrogen, $\eta^0_{\text{HHV, el}}$ and $\eta^0_{\text{LHV, el}}$, should also be determined for stacks and systems applying the same testing procedure.

For PCE, the Faradaic (current) efficiency (η_{F}) ([10]) given by

$$\eta_{\text{F}}\ (\%)\ =\ \frac{2F\ (\text{C/mol})\cdot q_{\text{n, H}_2}\ (\text{mol/s})}{I\ (\text{A})}\cdot 100\ (\%), \tag{6.5.12}$$

should also be determined; F is the Faraday constant, I is the externally supplied current and $q_{\text{n, H}_2}$ is given by equation (6.5.1). The factor 2 in equation (6.5.12) stems from the fact that two electrons are exchanged in the PCEC electrode reactions (3.0.3).

6.6 Duty cycles

6.6.1 General

Duty cycles whether profiles of the input electric power ($P_{\text{el, in}}$), input current (I_{in}) or input voltage (U_{in}) versus time (t), are intended to simulate, under given test conditions (section 6.2), the operation of the stack or system for the use in the application concerned.

The time interval of a duty cycle is usually a fixed period of time. The duration of a duty cycle tests comprises the time required to carry out a given number of duty cycles of the same type or sequence of duty cycles of different types as specified in the test plan (section 6.4). This way, individual duty cycles constitute building blocks of a test sequence.

Duty cycles for rSOE may include periods of alternating operation in SOEC mode and SOFC mode. Likewise, duty cycles for rPCE may include periods of alternating operation in PCEC mode and PCFC mode.

In such case, the test plan (section 6.4) should provide details on switching between electrolysis mode and FC mode while also addressing safety concerns (Annex A), especially regarding high voltages and pressures, formation or release of harmful gases and occurrence of hot surfaces, as well as preventing excessive stack degradation or damage and sustained system dysfunction or failure.

([10]) Remark, as most PCCs in PCECs are mixed ionic and electronic conductors (MIECs), commonly acceptor doped barium zirconate ($BaZrO_3$) and barium cerate ($BaCeO_3$), electronic leakage occurs usually via small polarons ($\mathrm{M}^{\prime}_{\mathrm{M}}$) and electron holes ($\mathrm{h}^{\cdot}$) resulting in a reduced proton flux and thus, a lower hydrogen flow. As a result, the Faradaic efficiency is less than 100 %.

6.6.2 Graphical representation

Figure 6.1 shows the graphical representation of an idealised duty cycle (normalised set point versus cycle duration) as building block for a sequence of duty cycles to test the reactivity (**4.1.10**) of a stack or system (Tsotridis and Pilenga, 2021).

Similarly, Figure 6.2 Figure 6.3 and Figure 6.4 show the graphical representation of idealised duty cycles as building blocks for sequences of duty cycles to test the flexibility (**4.1.5**) of a stack or system (Tsotridis and Pilenga, 2021). Annex B contains the tabulated data of each of these cycles.

The duty cycle presented in Figure 6.2 simulates high flexibility while those presented in Figure 6.3 and Figure 6.4 simulate flexibility limited to 100 % and 200 % of the normalised set point, respectively.

The reactivity duty cycle is meant to simulate severe conditions in terms of set ramp rate(s) and frequency of change in the set point while the three flexibility duty cycles are meant to simulate at different degrees frequent periods of variation in the set point (Tsotridis and Pilenga, 2021).

For both, reactivity and flexibility, the total duration taken per completed cycle to (positive and negative) ramps should be determined (section 6.5.5) and recorded in the test report (Annex C). They may graphically be presented to show their evolution versus the total sequence(s) of the performed duty cycles and/or the number of duty cycles or sequence(s) of duty cycles performed. In the above mentioned figures, the normalised set point expressed in percentage is the ratio of either

- the specified input electric power ($P_{\text{el, in}}$) to its nominal (rated) value ($P_{\text{el, nom}}$) namely

$$\text{Normalised electric power set point (\%)} = \frac{P_{\text{el, in}}\ (W)}{P_{\text{el, nom}}\ (W)} \cdot 100\ \%,$$

- the specified input current (I_{in}) to its nominal (rated) value (I_{nom}) namely

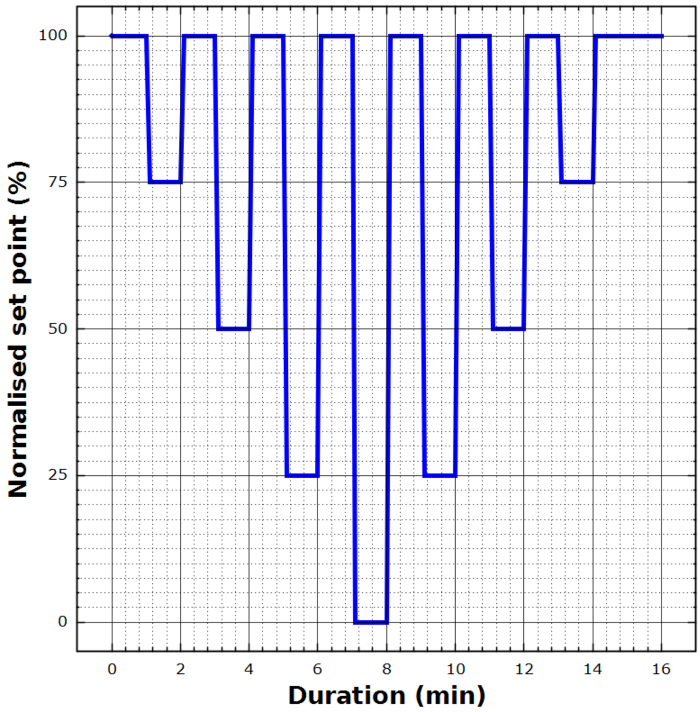
$$\text{Normalised current set point (\%)} = \frac{I_{\text{in}}\ (A)}{I_{\text{nom}}\ (A)} \cdot 100\ \% \ \text{ or}$$

- the specified input voltage (U_{in}) to its nominal (rated) value (U_{nom}) namely

$$\text{Normalised voltage set point (\%)} = \frac{U_{\text{in}}\ (V)}{U_{\text{nom}}\ (V)} \cdot 100\ \%.$$

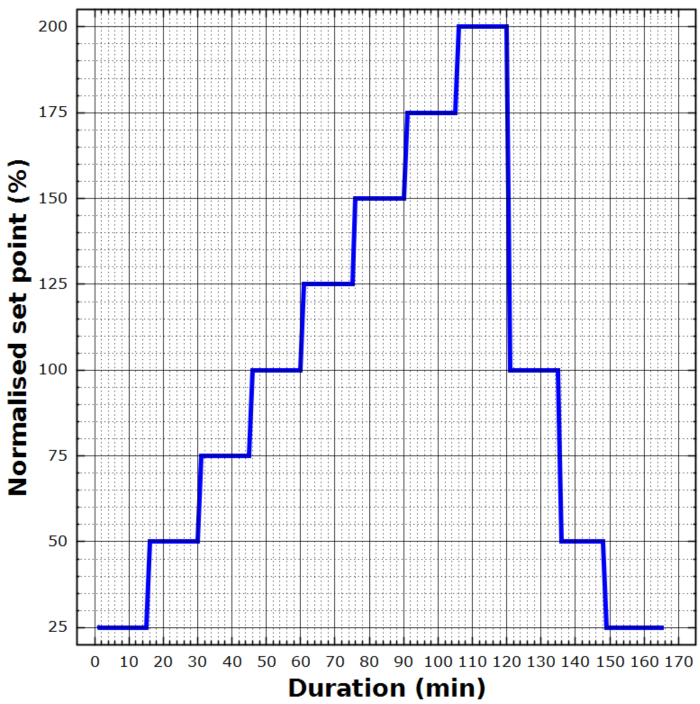
The TIP (power, current or voltage) is specified in the test plan (section 6.4) as part of the test conditions (section 6.2) and the value of the corresponding nominal quantity is specified by the manufacturer of the stack/system in accordance with IEC 60204-1:2016+AMD1:2021 CSV (IEC, 2021).

Figure 6.1: Graph of a duty cycle (normalised set point versus cycle duration) for testing the reactivity of a stack or system (Table B.1).



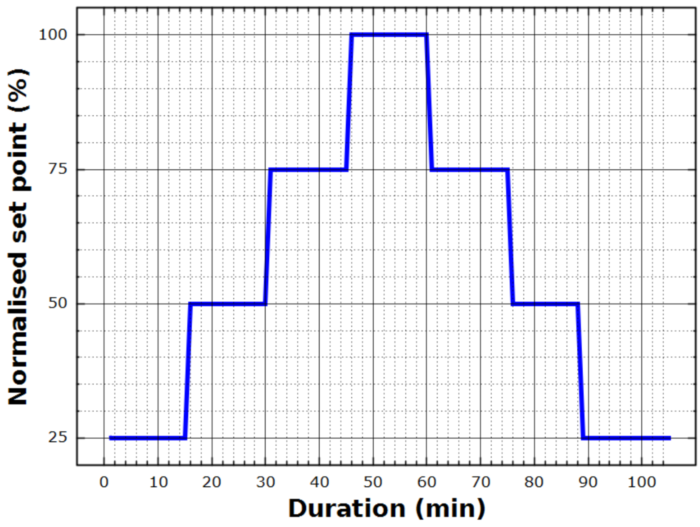
Source: JRC, 2023.

Figure 6.2: Graph of a duty cycle (normalised set point versus cycle duration) for testing the high flexibility of a stack or system (Table B.2).



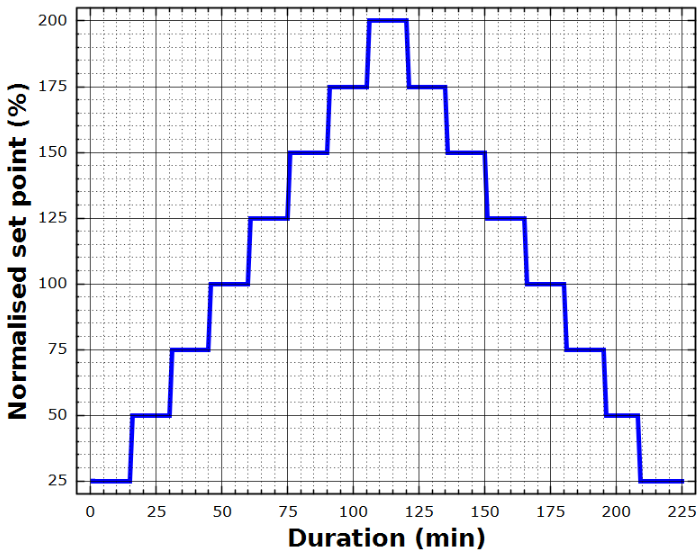
Source: JRC, 2023.

Figure 6.3: Graph of a duty cycle (normalised set point versus cycle duration) for testing 100 % flexibility of a stack or system (Table B.3).



Source: JRC, 2023.

Figure 6.4: Graph of a duty cycle (normalised set point versus cycle duration) for testing 200 % flexibility of a stack or system (Table B.4).



Source: JRC, 2023.

667 ## 6.7 Durability tests

6.7.1 General

Durability tests (**4.1.8**) on HTE stacks evaluate the ability of the stack to maintain its performance characteristics under specified test conditions (section 6.2) for a given time interval when subjected to testing either at constant “steady-state” operation (section 6.7.2) or variable operation (section 6.7.3) applying appropriate duty cycles (section 6.6). The two operation modes may also be combined, for example, they may be applied alternatively or applied in a specified sequence typical to a stack in a system for use in a given application.

For HTSEL systems, durability tests evaluate the ability of the system to maintain its reliability (**4.1.11**) under specified test conditions (section 6.2) for a given time interval when subjected to testing either at constant “steady-state” operation (section 6.7.2) or variable operation (section 6.7.3) applying duty cycles (section 6.6). As for stacks, the two operation modes may be combined, for example, alternatively or by a specified sequence typical for the intended use of the system in a given application.

In addition to beginning-of-test (BoT) and end-of-test (EoT) as specified in the test plan (section 6.4), performance tests (section 6.5) are also conducted intermittently at intervals k=1,2,... in accordance with the test plan to determine one or more KPIs.

The inability of a stack to maintain its performance characteristics during testing in accordance a specified test stop criterion may be regarded as stack failure. Likewise, the inability of a system to perform as required during testing in accordance with a specified test stop criterion may be regarded as a reliability failure of the system.

6.7.2 Constant operation

Durability testing of a HTE stack under constant power (P), constant current (I) or constant voltage (U) shall be conducted in accordance with clause 7.4 of IEC 62282-8-101:2020 (IEC, 2020c).

6.7.3 Variable operation

Durability testing of a HTE stack under variable power, variable current or variable voltage using duty cycles (section 6.6) shall be conducted in accordance with clause 7.7 of IEC 62282-8-101:2020 (IEC, 2020c).

6.7.4 KPI estimation

For a specified current (I_{stack}) or current density (J_{stack}), the durability of the stack at an elapsed time interval t_{k} is assessed from the difference (deviation) of the stack voltage at that instant and at BoT (t_0) by calculating the total rate of change of voltage ($\Delta_{\text{tot}} U$) as follows

$$\Delta_{\text{tot}} U \text{ (mV/h)} = \frac{U(t_{\text{k}}) \text{ (V)} - U(t_0) \text{ (V)}}{t_{\text{k}} \text{ (h)} - t_0 \text{ (h)}} \cdot 1000 \text{ mV/V} \tag{6.7.1}$$

where $U(t_{\text{k}})$ and $U(t_0)$ are the stack voltage at respectively time, t_{k} and time, t_0; t_{k} is the time elapsed from BoT at t_0 until the time at the end of interval k whether for constant stack operation (section 6.7.2) or variable stack operation (section 6.7.3). At both instants, t_0 and t_{k}, the stack voltages are determined from polarisation curve measurements (section 6.5.10). The relative rate of change of voltage ($\Delta_{\text{rel}} U$) corresponding to one thousand hours of operation is calculated as follows (McPhail *et al.*, 2022)

$$\Delta_{\text{rel}} U \text{ (\%)} = \frac{U(t_{\text{k}}) \text{ (V)} - U(t_0) \text{ (V)}}{U(t_0) \text{ (V)}} \cdot \frac{1000 \text{ (h)}}{t_{\text{k}} \text{ (h)}} \cdot 100 \text{ \%}. \tag{6.7.2}$$

The specified current is usually the current occurring at the thermal-neutral voltage (U_{tn}) of the stack when operated under given conditions at BoT. According to the test plan, it may also be the current which occurs at a voltage different from the thermal-neutral voltage.

Stack durability may also be assessed by means of the area-specific resistance (R_{ASR}) (de Marco *et al.*, 2017) at a specified current density (J_{stack}). Then, the durability of the stack at t_{k} is assessed from the difference of the area-specific resistance at that instant and at t_0 by calculating the total rate of change of ($\Delta_{\text{tot}} R_{\text{ASR}}$) as follows

$$\Delta_{\text{tot}} R_{\text{ASR}} \text{ (m}\Omega \text{ cm}^2\text{/h)} = \frac{R_{\text{ASR}}(t_{\text{k}}) \text{ (}\Omega \text{ cm}^2\text{)} - R_{\text{ASR}}(t_0) \text{ (}\Omega \text{ cm}^2\text{)}}{t_{\text{k}} \text{ (h)} - t_0 \text{ (h)}} \cdot 1000 \text{ m}\Omega/\Omega. \tag{6.7.3}$$

The relative rate of change of ($\Delta_{\text{rel}} R_{\text{ASR}}$) corresponding to one thousand hours of operation is calculated as follows (McPhail *et al.*, 2022)

$$\Delta_{\text{rel}} R_{\text{ASR}} \text{ (\%)} = \frac{R_{\text{ASR}}(t_{\text{k}}) \text{ (}\Omega \text{ cm}^2\text{)} - R_{\text{ASR}}(t_0) \text{ (}\Omega \text{ cm}^2\text{)}}{R_{\text{ASR}}(t_0) \text{ (}\Omega \text{ cm}^2\text{)}} \cdot \frac{1000 \text{ (h)}}{t_{\text{k}} \text{ (h)}} \cdot 100 \text{ \%}. \tag{6.7.4}$$

The total rate of change of Faradaic (current) efficiency ($\Delta_{\text{tot}}\,\eta_{\text{F}}$) is calculated as follows

$$\Delta_{\text{tot}}\,\eta_{\text{F}}\ (\%/\text{h}) \;=\; \frac{\eta_{\text{F}}(t_{\text{k}})\ (\%) \;-\; \eta_{\text{F}}(t_0)\ (\%)}{t_{\text{k}}\ (\text{h}) \;-\; t_0\ (\text{h})} \tag{6.7.5}$$

where $\eta_{\text{F}}(t_{\text{k}})$ and $\eta_{\text{F}}(t_0)$ are the Faradaic efficiency at t_{k} and t_0, respectively. The relative rate of change of Faradaic (current) efficiency ($\Delta_{\text{rel}}\,\eta_{\text{F}}$) corresponding to one thousand hours of operation is calculated as follows

$$\Delta_{\text{rel}}\,\eta_{\text{F}}\ (\%) \;=\; \frac{\eta_{\text{F}}(t_{\text{k}})\ (\%) \;-\; \eta_{\text{F}}(t_0)\ (\%)}{\eta_{\text{F}}(t_0)\ (\%)} \cdot \frac{1000\ (\text{h})}{t_{\text{k}}\ (\text{h})} \cdot 100\ \%. \tag{6.7.6}$$

For a specified input power (P_{in}), the durability of the HTSEL system at an elapsed time interval t_{k} is assessed from the difference of the specific energy consumption (ε_{e}), whether per unit of volume (V) of hydrogen ($\varepsilon_{\text{e,V}}$) or mass (m) of hydrogen ($\varepsilon_{\text{e,m}}$), at that instant and at BoT (t_0) by calculating the total rate of change of of hydrogen ($\Delta_{\text{tot}}\,\varepsilon_{\text{e,V}}$) and the total rate of change of of hydrogen ($\Delta_{\text{tot}}\,\varepsilon_{\text{e,m}}$) as follows

$$\Delta_{\text{tot}}\,\varepsilon_{\text{e,V}}\ ((\text{J/m}^3)/\text{h}) \;=\; \frac{\varepsilon_{\text{e,V}}(t_{\text{k}})\ (\text{kWh/m}^3) \;-\; \varepsilon_{\text{e,V}}(t_0)\ (\text{kWh/m}^3)}{t_{\text{k}}\ (\text{h}) \;-\; t_0\ (\text{h})} \cdot 3600\ \text{s/h} \cdot 1000\ \text{J/kJ} \ \ \text{and} \tag{6.7.7a}$$

$$\Delta_{\text{tot}}\,\varepsilon_{\text{e,m}}\ ((\text{J/kg})/\text{h}) \;=\; \frac{\varepsilon_{\text{e,m}}(t_{\text{k}})\ (\text{kWh/kg}) \;-\; \varepsilon_{\text{e,m}}(t_0)\ (\text{kWh/kg})}{t_{\text{k}}\ (\text{h}) \;-\; t_0\ (\text{h})} \cdot 3600\ \text{s/h} \cdot 1000\ \text{J/kJ}; \tag{6.7.7b}$$

$\varepsilon_{\text{e,V}}(t_{\text{k}})$ and $\varepsilon_{\text{e,m}}(t_{\text{k}})$ are respectively the specific energy consumption per unit and the specific energy consumption per unit of the system at t_{k} while $\varepsilon_{\text{e,V}}(t_0)$ and $\varepsilon_{\text{e,m}}(t_0)$ are respectively the specific energy consumption per unit and the specific energy consumption per unit at t_0. The relative rate of change of of hydrogen ($\Delta_{\text{rel}}\,\varepsilon_{\text{e,V}}$) and the relative rate of change of of hydrogen ($\Delta_{\text{rel}}\,\varepsilon_{\text{e,m}}$) are calculated as follows

$$\Delta_{\text{rel}}\,\varepsilon_{\text{e,V}}\ (\%) \;=\; \frac{\varepsilon_{\text{e,V}}(t_{\text{k}})\ (\text{kWh/m}^3) \;-\; \varepsilon_{\text{e,V}}(t_0)\ (\text{kWh/m}^3)}{\varepsilon_{\text{e,V}}(t_0)\ (\text{kWh/m}^3)} \cdot 100\ \ \% \ \ \text{and} \tag{6.7.8a}$$

$$\Delta_{\text{rel}}\,\varepsilon_{\text{e,m}}\ (\%) \;=\; \frac{\varepsilon_{\text{e,m}}(t_{\text{k}})\ (\text{kWh/kg}) \;-\; \varepsilon_{\text{e,m}}(t_0)\ (\text{kWh/kg})}{\varepsilon_{\text{e,m}}(t_0)\ (\text{kWh/kg})} \cdot 100\ \ \%. \tag{6.7.8b}$$

Similar to stack operation, t_{k} is the time elapsed from BoT until the time at the end of interval k, whether for constant system operation (section 6.7.2) or variable system operation (section 6.7.3). At both instants, the specific energy consumption per unit of hydrogen ($\varepsilon_{\text{e,V}}$) and per unit of mass of hydrogen ($\varepsilon_{\text{e,m}}$) are determined from measurements of the specific energy consumption (section 6.5.12).

For a specified input electric power ($P_{\text{el,in}}$), the durability of the HTSEL system at the elapsed time interval t_{k} may also be assessed from the difference of the specific electric energy consumption (ε_{el}), whether per unit of volume (V) of hydrogen ($\varepsilon_{\text{el,V}}$) or mass ($m$) of hydrogen ($\varepsilon_{\text{el,m}}$), at t_{k} and t_0 by calculating the total rate of change of of hydrogen ($\Delta_{\text{tot}}\,\varepsilon_{\text{el,V}}$) and the total rate of change of of hydrogen ($\Delta_{\text{tot}}\,\varepsilon_{\text{el,m}}$) as follows

$$\Delta_{\text{tot}}\,\varepsilon_{\text{el,V}}\ ((\text{J/m}^3)/\text{h}) \;=\; \frac{\varepsilon_{\text{el,V}}(t_{\text{k}})\ (\text{kWh/m}^3) \;-\; \varepsilon_{\text{el,V}}(t_0)\ (\text{kWh/m}^3)}{t_{\text{k}}\ (\text{h}) \;-\; t_0\ (\text{h})} \cdot 3600\ \text{s/h} \cdot 1000\ \text{J/kJ} \ \ \text{and} \tag{6.7.9a}$$

$$\Delta_{\text{tot}}\,\varepsilon_{\text{el,m}}\ ((\text{J/kg})/\text{h}) \;=\; \frac{\varepsilon_{\text{el,m}}(t_{\text{k}})\ (\text{kWh/kg}) \;-\; \varepsilon_{\text{el,m}}(t_0)\ (\text{kWh/kg})}{t_{\text{k}}\ (\text{h}) \;-\; t_0\ (\text{h})} \cdot 3600\ \text{s/h} \cdot 1000\ \text{J/kJ}. \tag{6.7.9b}$$

The relative rate of change of of hydrogen ($\Delta_{\text{rel}}\,\varepsilon_{\text{el,V}}$) and the relative rate of change of of hydrogen ($\Delta_{\text{rel}}\,\varepsilon_{\text{el,m}}$) are calculated as follows

$$\Delta_{\text{rel}}\,\varepsilon_{\text{el,V}}\ (\%) \;=\; \frac{\varepsilon_{\text{el,V}}(t_{\text{k}})\ (\text{kWh/m}^3) \;-\; \varepsilon_{\text{el,V}}(t_0)\ (\text{kWh/m}^3)}{\varepsilon_{\text{el,V}}(t_0)\ (\text{kWh/m}^3)} \cdot 100\ \% \ \ \text{and} \tag{6.7.10a}$$

$$\Delta_{\text{rel}}\,\varepsilon_{\text{el,m}}\ (\%) \;=\; \frac{\varepsilon_{\text{el,m}}(t_{\text{k}})\ (\text{kWh/kg}) \;-\; \varepsilon_{\text{el,m}}(t_0)\ (\text{kWh/kg})}{\varepsilon_{\text{el,m}}(t_0)\ (\text{kWh/kg})} \cdot 100\ \%. \tag{6.7.10b}$$

For a specified input thermal power ($P_{\text{th,in}}$), the durability of the HTSEL system at the elapsed time interval t_{k} may additionally be assessed from the difference of the specific thermal energy consumption (ε_{th}), whether per unit of volume (V) of hydrogen ($\varepsilon_{\text{th,V}}$) or mass ($m$) of hydrogen ($\varepsilon_{\text{th,m}}$), at t_{k} and t_0 by calculating the total rate of change of of hydrogen ($\Delta_{\text{tot}}\,\varepsilon_{\text{th,V}}$) and the total rate of change of of hydrogen ($\Delta_{\text{tot}}\,\varepsilon_{\text{th,m}}$) as follows

$$\Delta_{\text{tot}}\,\varepsilon_{\text{th,V}}\ \text{((J/m}^3\text{)/h)} = \frac{\varepsilon_{\text{th,V}}(t_{\text{k}})\ \text{(kWh/m}^3\text{)} - \varepsilon_{\text{th,V}}(t_0)\ \text{(kWh/m}^3\text{)}}{t_{\text{k}}\ \text{(h)} - t_0\ \text{(h)}} \cdot 3600\ \text{s/h} \cdot 1000\ \text{J/kJ} \quad \text{and} \qquad (6.7.11a)$$

$$\Delta_{\text{tot}}\,\varepsilon_{\text{th,m}}\ \text{((J/kg)/h)} = \frac{\varepsilon_{\text{th,m}}(t_{\text{k}})\ \text{(kWh/kg)} - \varepsilon_{\text{th,m}}(t_0)\ \text{(kWh/kg)}}{t_{\text{k}}\ \text{(h)} - t_0\ \text{(h)}} \cdot 3600\ \text{s/h} \cdot 1000\ \text{J/kJ}. \qquad (6.7.11b)$$

The relative rate of change of of hydrogen ($\Delta_{\text{rel}}\,\varepsilon_{\text{th,V}}$) and the relative rate of change of of hydrogen ($\Delta_{\text{rel}}\,\varepsilon_{\text{th,m}}$) are calculated as follows

$$\Delta_{\text{rel}}\,\varepsilon_{\text{th,V}}\ (\%) = \frac{\varepsilon_{\text{th,V}}(t_{\text{k}})\ \text{(kWh/m}^3\text{)} - \varepsilon_{\text{th,V}}(t_0)\ \text{(kWh/m}^3\text{)}}{\varepsilon_{\text{th,V}}(t_0)\ \text{(kWh/m}^3\text{)}} \cdot 100\ \% \quad \text{and} \qquad (6.7.12a)$$

$$\Delta_{\text{rel}}\,\varepsilon_{\text{th,m}}\ (\%) = \frac{\varepsilon_{\text{th,m}}(t_{\text{k}})\ \text{(kWh/kg)} - \varepsilon_{\text{th,m}}(t_0)\ \text{(kWh/kg)}}{\varepsilon_{\text{th,m}}(t_0)\ \text{(kWh/kg)}} \cdot 100\ \%. \qquad (6.7.12b)$$

Note, the specified input power (electric and/or thermal) is usually the rated power of the system as defined by the manufacturer. According to the test plan, it may also be a fraction or a multiple of the rated power.

7 Presentation of test results

Table 7.1 and Table 7.2 list the TOPs as results of the performance and durability tests, respectively.

Table 7.1: Test results of performance tests

Symbol (unit)	**Description**	**Test method**
$P_{\text{el, ac, in}}$ (kW)	input	6.5.1
$P_{\text{el, dc, in}}$ (kW)	input	6.5.1
$P_{\text{th, in}}$ (kW)	input thermal power (1)	6.5.2
$P_{\text{compr, in}}$ (kW)	input power of compression (2)	6.5.3
t_{on} (s)	start-up time	6.5.4
E_{on} (J)	start-up energy	6.5.4
t_{off} (s)	shut-down time	6.5.6
E_{off} (J)	shut-down energy	6.5.6
t_{resp} (s)	response time (3)	6.5.5
E_{ramp} (J)	ramp energy (4)	6.5.5
t_{switch} (s)	switch-over time (5)	6.5.7
x_{n, H_2} (mol/mol)	product gas of hydrogen	6.5.8
q_{n, H_2} (mol/h)	of hydrogen (6)	6.5.8
x_{n, O_2} (mol/mol)	sweep gas of oxygen	6.5.9
q_{n, O_2} (mol/mol)	of oxygen (7)	6.5.9
I_{stack} (A)	stack current (8)	6.5.10
J_{stack} (A/cm^2)	stack current density (8)	6.5.10
U_{stack} (kV)	stack voltage (9)	6.5.10
$P_{\text{el, stack}}$ (kW)	stack electric power	6.5.10
$P_{\text{el, d, stack}}$ (kW/cm^2)	stack	6.5.10
T_{stack} (K)	stack temperature	6.5.10
Z (Ω) (10)	electrical impedance (11)	6.5.11
Y (S)	electrical admittance (12)	6.5.11
R_{Ω} (Ω) (10)	ohmic resistance	6.5.11
R_{pol} (Ω) (10)	polarisation resistance	6.5.11
R_{ASR} (mΩ.cm^2)	area-specific resistance	6.5.11
$\varepsilon_{\text{e, V}}$ (kWh/m^3)	specific energy consumption per unit	6.5.12
$\varepsilon_{\text{e, m}}$ (kWh/kg)	specific energy consumption per unit	6.5.12
$\varepsilon_{\text{el, V}}$ (kWh/m^3)	specific electric energy consumption per unit	6.5.12
$\varepsilon_{\text{el, m}}$ (kWh/kg)	specific electric energy consumption per unit	6.5.12
$\varepsilon_{\text{th, V}}$ (kWh/m^3)	specific thermal energy consumption per unit	6.5.12
$\varepsilon_{\text{th, m}}$ (kWh/kg)	specific thermal energy consumption per unit	6.5.12
$\eta^0_{\text{HHV, e}}$ (%)	energy efficiency based on HHV under SATP conditions	6.5.13
$\eta^0_{\text{LHV, e}}$ (%)	under SATP conditions	6.5.13
$\eta^0_{\text{HHV, el}}$ (%)	under SATP conditions	6.5.13
$\eta^0_{\text{LHV, el}}$ (%)	under SATP conditions	6.5.13
η_{F} (%)	Faradaic efficiency	6.5.13

Note: TOPs may be obtained as functions of TIPs or other TOPs as well as time (test duration), number of duty cycles or sequence(s) of duty cycles. By adding appropriate indices to the TIP and TOP symbols, the test plan should accordingly specify a set of indexed TIPs and TOPs when of same type.

(1) conveyed by heat transfer fluids such as air and steam
(2) conveyed by compressible fluids such as compressed air and pressurised steam
(3) in relation to input power (P_{in}), input current (I_{in}) or input voltage (U_{in}), see section 6.5.5
(4) for positive and negative ramps
(5) from FC mode to electrolysis mode and from electrolysis mode to FC mode
(6) hydrogen output rate
(7) oxygen output rate
(8) When the polarisation curve measurement is conducted under potentiostatic conditions or by a set voltage ramp rate ($\dot{U}$).
(9) When the polarisation curve measurement is conducted under galvanostatic conditions or by a set current ramp rate ($\dot{I}$).
(10) Ω.cm^2 may be used as an alternative unit.
(11) When the EIS measurement uses small amplitude AC voltage perturbations.
(12) When the EIS measurement uses small amplitude alternating current (AC) perturbations.

Source: JRC, 2023

Table 7.2: Test results of durability tests

Symbol (unit)	Description	Test method
	Constant stack operation [1]	
$\Delta_{\mathrm{tot}} U$ (mV/h)	total rate of change of voltage	6.7.2
$\Delta_{\mathrm{rel}} U$ (mV/h)	relative rate of change of voltage	6.7.2
$\Delta_{\mathrm{tot}} R_{\mathrm{ASR}}$ (mΩ cm^2/h)	total rate of change of	6.7.2
$\Delta_{\mathrm{rel}} R_{\mathrm{ASR}}$ (mΩ cm^2/h)	relative rate of change of	6.7.2
$\Delta_{\mathrm{tot}} \eta_{\mathrm{F}}$ (mΩ cm^2/h)	total rate of change of Faradaic (current) efficiency	6.7.2
$\Delta_{\mathrm{rel}} \eta_{\mathrm{F}}$ (mΩ cm^2/h)	relative rate of change of Faradaic (current) efficiency	6.7.2
	Variable stack operation [1]	
$\Delta_{\mathrm{tot}} U$ (mV/h)	total rate of change of voltage	6.7.3
$\Delta_{\mathrm{rel}} U$ (mV/h)	relative rate of change of voltage	6.7.3
$\Delta_{\mathrm{tot}} R_{\mathrm{ASR}}$ (mΩ cm^2/h)	total rate of change of	6.7.3
$\Delta_{\mathrm{rel}} R_{\mathrm{ASR}}$ (mΩ cm^2/h)	relative rate of change of	6.7.3
$\Delta_{\mathrm{tot}} \eta_{\mathrm{F}}$ (mΩ cm^2/h)	total rate of change of Faradaic (current) efficiency	6.7.3
$\Delta_{\mathrm{rel}} \eta_{\mathrm{F}}$ (mΩ cm^2/h)	relative rate of change of Faradaic (current) efficiency	6.7.3
	Constant system operation [1]	
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{e,V}}$ ((J/m^3)/h)	total rate of change of	6.7.2
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{e,V}}$ ((J/m^3)/h)	relative rate of change of	6.7.2
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{e,m}}$ ((J/kg)/h)	total rate of change of	6.7.2
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{e,m}}$ ((J/kg)/h)	relative rate of change of	6.7.2
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{el,V}}$ ((J/m^3)/h)	total rate of change of	6.7.2
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{el,V}}$ ((J/m^3)/h)	relative rate of change of	6.7.2
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{el,m}}$ ((J/kg)/h)	total rate of change of	6.7.2
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{el,m}}$ ((J/kg)/h)	relative rate of change of	6.7.2
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{th,V}}$ ((J/m^3)/h)	total rate of change of	6.7.2
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{th,V}}$ ((J/m^3)/h)	relative rate of change of	6.7.2
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{th,m}}$ ((J/kg)/h)	total rate of change of	6.7.2
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{th,m}}$ ((J/kg)/h)	relative rate of change of	6.7.2
	Variable system operation [1]	
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{e,V}}$ ((J/m^3)/h)	total rate of change of	6.7.3
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{e,V}}$ ((J/m^3)/h)	relative rate of change of	6.7.3
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{e,m}}$ ((J/kg)/h)	total rate of change of	6.7.3
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{e,m}}$ ((J/kg)/h)	relative rate of change of	6.7.3
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{el,V}}$ ((J/m^3)/h)	total rate of change of	6.7.3
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{el,m}}$ ((J/kg)/h)	total rate of change of	6.7.3
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{el,m}}$ ((J/kg)/h)	relative rate of change of	6.7.3
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{th,V}}$ ((J/m^3)/h)	total rate of change of	6.7.3
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{th,V}}$ ((J/m^3)/h)	relative rate of change of	6.7.3
$\Delta_{\mathrm{tot}} \varepsilon_{\mathrm{th,m}}$ ((J/kg)/h)	total rate of change of	6.7.3
$\Delta_{\mathrm{rel}} \varepsilon_{\mathrm{th,m}}$ ((J/kg)/h)	relative rate of change of	6.7.3

Note: TOPs may be obtained as functions of time (test duration), number of duty cycles or sequence(s) of duty cycles. By adding appropriate indices to the TIP and TOP symbols, the test plan should accordingly specify a set of indexed TIPs and TOPs when of same type.

([1]) The test results are meant for each interval k of a duty cycle or sequence of duty cycles. Accordingly, subscript or superscript k should be added to TIPs and TOPs as specified in the test plan.

Source: JRC, 2023

The test results should, as appropriate, be reported along with their uncertainties in accordance with the GUM (JCGM, 2008, JCGM, 2009, JCGM, 2020).

In addition to tabulated test results, TOPs may also graphically be presented (Annex C), for example, showing their evolution with time or the number and sequence(s) of duty cycles as well as presenting them as functions of TIPs (*i. e.* power, current, voltage, etc). Standard uncertainties (u) of base quantities and combined standard uncertainties (u_{c}) of derived quantities may be displayed as error bars for a specified level of confidence.

8 Conclusions with final remarks

This report provides testing protocols for establishing the performance and durability of HTE stacks and HTSEL systems generating hydrogen in P2H2 applications for HtP, hydrogen-to-mobility (HtM) and H2I processes. They rely on test methods of ISO and IEC standards as well as on testing procedures previously developed in FCH2JU funded projects and those published as part of the EU electrolysis harmonisation activities.

These protocols allow for an adequate comparison of SOC technologies in stacks whether of SOEC type in SOE including rSOE, or PCEC type in PCE including rPCE. They also allow to compare the performance and durability of different HTSEL systems. Intended for use by the research community and industry alike, these protocols provide for built-in flexibility as performance tests may selectively be executed and application-oriented duty cycles may be added to the exemplified duty cycles.

Also, the user is free to add other performance tests for a particular test campaign as well as to substitute one or another test method or testing procedure when deemed more appropriate for the intended use of the stack or system in the application concerned. This is provided all tests are conducted safely (Annex A) and with due care, the recording of all relevant test parameters whether TIPs or TOPs is followed as required and the test results including uncertainties and measurement set-up(s) are adequately reported.

The performance and durability tests may be used to conduct accelerated stress testing (AST) (**4.1.2**) of a test item when degradation mechanisms and their triggering test conditions are known to affect the test item the same way as long exposures under normal conditions of use would do. This is a current subject of ongoing HTE research.

Durability tests may be used to conduct accelerated life testing (ALT) (**4.1.1**) of a test item for determining the item's useful life when aggravated conditions of use have previously been identified. This is yet to become a subject of electrolyser R&D.

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List of Abbreviations and Acronyms

AC alternating current
AC/DC alternating current-to-direct current
ALT accelerated life testing
AMD amendment
AS Aktsiaselts
ASR area-specific resistance
AST accelerated stress testing
ATEX Appareils destinés à être utilisés en atmosphères explosibles
AWE alkaline water electrolyser
AWI approved working item
BoL beginning-of-life
BoP balance of plant
BoT beginning-of-test
BV besloten vennootschap
CC BY 4.0 Creative Commons Attribution 4.0 International
CEA Commissariat à l'énergie atomique et aux énergies alternatives
CGO ceria-doped gadolinium oxide
CH Switzerland
CH2 compressed hydrogen
Clean H_2 JU Clean Hydrogen Joint Undertaking
CORDIS Community Research and Development Information Service
CSV consolidated version
DAQ data acquisition
DC direct current
DC/DC direct current-to-direct current
DLR Deutsches Zentrum für Luft- und Raumfahrt e. V.
doi digital object identifier
e. V. eingetragener Verein
EC European Commission
EEA European Economic Area
EHC electrochemical hydrogen compressor
EIS electrochemical impedance spectroscopy
EMC electromagnetic compatibility
EN English
EoT end-of-test
ES energy-storage
EU European Union
EUR European Union Report
FC fuel cell
FCH2JU Fuel Cells and Hydrogen second Joint Undertaking
GAMER Game changer in high temperature steam electrolysers with novel tubular cells and stacks geometry for pressurized hydrogen production
GUM Guide to the expression of uncertainty in measurement
H2I hydrogen-to-industry
HER hydrogen evolution reaction
HHV higher heating value
HOR hydrogen oxidation reaction
HTE high-temperature electrolyser
HTEL high-temperature electrolysis
HtM hydrogen-to-mobility
HtP hydrogen-to-power
HTSEL high-temperature steam electrolysis
IEC International Electrotechnical Commission
IEEE Institute of Electrical and Electronics Engineers
ISBN international standard book number
ISO International Organization for Standardization
JCGM Joint Committee for Guides in Metrology
JRC Joint Research Centre
KPI key performance indicator

L Luxembourg
LH$_2$ liquefied hydrogen
LHV lower heating value
LSCF strontium-doped lanthanum cobalt iron oxide
LSM strontium-doped lanthanum manganite
LTWE low-temperature water electrolysis
LVD Low-Voltage Directive
MIEC mixed ionic and electronic conductor
NG natural gas
NY New York
O-SOE oxygen ion-conducting solid oxide electrolyser
OCV open circuit voltage
OER oxygen evolution reaction
OHS occupational health and safety
OJ Official Journal
ORR oxygen reduction reaction
P-SOE proton-conducting solid oxide electrolyser
P2C power-to-chemical
P2F power-to-fuel
P2G power-to-gas
P2H2 power-to-hydrogen
P2L power-to-liquid
P2M power-to-mobility
P2P power-to-power
P2X power-to-X
PCC proton-conducting ceramic
PCCEL proton-conducting ceramic steam electrolysis
PCE proton-conducting ceramic electrolyser
PCEC proton-conducting ceramic electrolysis cell
PCFC proton-conducting ceramic fuel cell
PDF portable document format
PED Pressure Equipment Directive
PEM proton exchange polymer membrane
PEMWE proton exchange polymer membrane water electrolyser
PoC point of connection
PV photovoltaic
R&D research and development
R&I research and innovation
REFLEX Reversible solid oxide Electrolyzer and Fuel cell for optimized Local Energy miX
RES renewable energy source
rFC reversible fuel cell
rms root-mean-square
rPCE reversible proton-conducting ceramic electrolyser
rSOE reversible solid oxide electrolyser
SATP standard ambient temperature and pressure
SI Système International d'Unités
SINTEF Stiftelsen for industriell og teknisk forskning
SOC solid oxide cell
SOCTESQA Solid Oxide Cell and Stack Testing, Safety and Quality Assurance
SOE solid oxide electrolyser
SOEC solid oxide electrolysis cell
SOEL solid oxide steam electrolysis
SOFC solid oxide fuel cell
SRIA strategic research and innovation agenda 2021-2027 of the Clean Hydrogen Partnership for Europe
TC Technical Committee
TIP test input parameter
TM Test Module
TMA technology monitoring and assessment
TNO Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek
TOP test output parameter
TR Technical Report

TRL technology readiness level
URL uniform resource locator
UV ultraviolet
WG working group
YSZ yttria-stabilised zirconia

1106 # List of Symbols

Notation	**Description**
(ed)	subscript denoting electrode
(el)	subscript denoting electrolyte
(g)	subscript denoting gaseous phase
A_{act}	active electrode area
$\mathrm{CO_2}$	carbon dioxide
$c_{\mathrm{p}}^{\mathrm{i}}$	of fluid i
$c_{\mathrm{p}}^{\mathrm{j}}$	of fluid j
$c_{\mathrm{V}}^{\mathrm{j}}$	of fluid j
$\Delta_{\mathrm{rel}}\,\varepsilon_{\mathrm{e,V}}$	relative rate of change of
$\Delta_{\mathrm{rel}}\,\eta_{\mathrm{F}}$	relative rate of change of Faradaic (current) efficiency
$\Delta_{\mathrm{rel}}\,R_{\mathrm{ASR}}$	relative rate of change of
$\Delta_{\mathrm{rel}}\,U$	relative rate of change of voltage
$\Delta_{\mathrm{rel}}\,\varepsilon_{\mathrm{el,m}}$	relative rate of change of
$\Delta_{\mathrm{tot}}\,\varepsilon_{\mathrm{el,m}}$	total rate of change of
$\Delta_{\mathrm{rel}}\,\varepsilon_{\mathrm{el,V}}$	relative rate of change of
$\Delta_{\mathrm{tot}}\,\varepsilon_{\mathrm{el,V}}$	total rate of change of
$\Delta_{\mathrm{rel}}\,\varepsilon_{\mathrm{e,m}}$	relative rate of change of
$\Delta_{\mathrm{tot}}\,\varepsilon_{\mathrm{e,m}}$	total rate of change of
$\Delta_{\mathrm{tot}}\,\varepsilon_{\mathrm{e,V}}$	total rate of change of
$\Delta_{\mathrm{rel}}\,\varepsilon_{\mathrm{th,m}}$	relative rate of change of
$\Delta_{\mathrm{tot}}\,\varepsilon_{\mathrm{th,m}}$	total rate of change of
$\Delta_{\mathrm{rel}}\,\varepsilon_{\mathrm{th,V}}$	relative rate of change of
$\Delta_{\mathrm{tot}}\,\varepsilon_{\mathrm{th,V}}$	total rate of change of
$\Delta_{\mathrm{tot}}\,\eta_{\mathrm{F}}$	total rate of change of Faradaic (current) efficiency
$\Delta_{\mathrm{tot}}\,R_{\mathrm{ASR}}$	total rate of change of
$\Delta_{\mathrm{tot}}\,U$	total rate of change of voltage
E	energy
e'	electron (in Kröger-Vink notation)
e^{-}	electron
E_{compr}	pneumatic energy
E_{el}	electric energy
E_{off}	shut-down energy
E_{on}	start-up energy
ε_{e}	specific energy consumption
$\varepsilon_{\mathrm{el}}$	specific electric energy consumption
$\varepsilon_{\mathrm{el,m}}$	specific electric energy consumption per unit
$\varepsilon_{\mathrm{el,V}}$	specific electric energy consumption per unit
$\varepsilon_{\mathrm{e,m}}$	specific energy consumption per unit
$\varepsilon_{\mathrm{e,V}}$	specific energy consumption per unit
$\varepsilon_{\mathrm{th}}$	specific thermal energy consumption
$\varepsilon_{\mathrm{th,m}}$	specific thermal energy consumption per unit
$\varepsilon_{\mathrm{th,V}}$	specific thermal energy consumption per unit
E_{ramp}	ramp energy
η_{e}	energy efficiency
$\eta_{\mathrm{HHV,e}}^{0}$	energy efficiency based on HHV under SATP conditions
η_{el}	electrical efficiency
$\eta_{\mathrm{HHV,el}}^{0}$	under SATP conditions
$\eta_{\mathrm{LHV,e}}^{0}$	under SATP conditions
$\eta_{\mathrm{LHV,el}}^{0}$	under SATP conditions
η_{F}	Faradaic efficiency
E_{th}	thermal energy
F	Faraday constant
f	perturbation frequency
f_{max}	maximum frequency
f_{min}	minimum frequency
γ^{j}	of fluid j

Notation	Description
H	hydrogen
H^+	proton
$h^{\cdot}$	electron hole
H_2	molecular hydrogen
H_2O	steam
HHV^f	higher heating value of fuel
I	current
I_{ac}	alternating current
I_{dc}	direct current
$\dot{I}$	current ramp rate
I_{in}	input current
I_{nom}	nominal (rated) current
I_{stack}	stack current
J	current density
J_{dc}	DC current density
J_{stack}	stack current density
m	mass
$M^{\cdot}_M$	singly negatively charged metal ion lattice site
O	oxygen
O_2	molecular oxygen
O^{2-}	oxygen ion
$OH^{\cdot}_O$	hydroxide ion at singly positively charged oxygen lattice site
O^x_O	neutral oxygen ion lattice site
P	power
p	pressure
p^0	standard ambient
p^a	at the anode
p^c	at the cathode
P_{compr}	power of compression
$P_{compr, in}$	input power of compression
P_{el}	electric power
$P_{el, 1p, ac}$	single-phase AC power
$P_{el, 3p, ac}$	symmetrical three-phase AC power
$P_{el, ac}$	AC power
$P_{el, ac, in}$	input
$P_{el, d}$	electric power density
$P_{el, dc}$	DC power
$P_{el, dc, in}$	input
$P_{el, d, stack}$	stack
$P_{el, in}$	input electric power
$P_{el, nom}$	nominal (rated) electric power
$P_{el, stack}$	stack electric power
$\cos\varphi$	power factor
p^{H_2}	partial of hydrogen
p_{H_2}	of hydrogen
p^{H_2O}	partial of water vapour (steam)
P_{in}	input power
p^j	of fluid j
p^{O_2}	partial of oxygen
P_{stack}	stack power
P_{th}	thermal power
$P_{th, in}$	input thermal power
q	flow rate
q^i_m	of fluid i
q_n	molar
q^f_n	of fuel
q_{n, H_2}	of hydrogen
q^j_n	of fluid j
q_{n, O_2}	of oxygen

Notation	**Description**
$q_{\mathrm{n,out}}$	product gas
R_0	low-frequency resistance
R_{ASR}	area-specific resistance
R_{g}	universal gas constant
R_∞	high-frequency resistance
R_{lf}	low-frequency resistance
R_Ω	ohmic resistance
R_{pol}	polarisation resistance
T	temperature
t	time
T^0	standard ambient temperature
t_{0}	time at BoT
$\dot{T}_{\mathrm{cool}}$	cooling rate
$T_{\mathrm{H_2}}$	temperature of hydrogen
$\dot{T}_{\mathrm{heat}}$	heating rate
T^{i}	temperature of fluid i
t_{k}	time at interval k
t_{off}	shut-down time
t_{on}	start-up time
t_{resp}	response time
T_{stack}	stack temperature
t_{switch}	switch-over time
U	voltage
u	standard uncertainty
U_{ac}	AC voltage
u_{c}	combined
U_{dc}	DC voltage
$\dot{U}$	voltage ramp rate
U_{in}	input voltage
U_{nom}	nominal (rated) voltage
U_{stack}	stack voltage
U_{tn}	thermal-neutral voltage
V	volume
$\mathrm{V}_{\mathrm{O}}^{\cdot\cdot}$	doubly positively charged oxygen ion lattice vacancy
V_{AC}	AC voltage
$x_{\mathrm{n,H_2}}$	of hydrogen
$x_{\mathrm{n,O_2}}$	of oxygen
Y	electrical admittance
Z	electrical impedance
$\bar{Z}^{\mathrm{j}}$	of fluid j

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Annex A Test safety

In HTE stacks and HTSEL systems, hazards arises especially from

- generated hydrogen and oxygen gases,
- use of steam and other fluids (combustible fuel, compressed air, hydraulic oil, etc) and
- high temperature, high pressure and high voltage.

During installation, commissioning, operation including quiescence (standby) and maintenance as well as decommissioning, the safety of persons requires due care and vigilance by all parties.

The entity carrying out the testing should comply with the occupational health and safety (OHS) requirements of ISO 45001:2018 (ISO, 2018).

Tests on HTE stacks and HTSEL systems shall be conducted in accordance with the applicable legislation, granted licenses and issued permits not to pose harm or unacceptable risk to humans, property and the environment.

ISO has published guidance regarding basic safety considerations for systems (ISO, 2015) ([11]) which shall be observed while testing HTE stacks and HTSEL systems ([12]). Additionally, IEC published guidance on the classification of areas where explosive atmospheres may occur (IEC, 2014a, IEC, 2013, IEC, 2017, IEC, 2020a) which shall also be followed.

Note, IEC published standards on FC safety (IEC, 2019, IEC, 2020b) which may be applied by analogy as appropriate ([13]).

In the European Economic Area (EEA) ([14]), the ATEX Directives 2014/34/EU (EP and Council, 2014b) and 94/9/EC (EP and Council, 1994) apply ([15]).

In addition, the HTSEL system should comply with other EU legislation such as the electromagnetic compatibility (EMC) Directive 2014/30/EU (EP and Council, 2014a) ([16]), the Low-Voltage Directive (LVD) 2014/35/EU (EP and Council, 2014c) ([17]), the general product safety Directive 2001/95/EC (EP and Council, 2001) ([18]), the machinery Directive 2006/42/EC (EP and Council, 2006) ([19]) and the Pressure Equipment Directive (PED) 2014/68/EU (EP and Council, 2014d) ([20]).

Generally, test items which do not conform to these EU legislation shall not be used within the EEA.

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(11) WG 29 of TC 197 currently reviews this technical report.

(12) WG 34 of TC 197 currently prepares the AWI entitled "ISO 22734-1 Hydrogen generators using water electrolysis - Industrial, commercial, and residential applications — Part 1: General requirements, test protocols and safety requirements".

(13) In the future, IEC TC 105 may draft IEC 62282-8-200 on safety of power-to-power (P2P) systems using electrolyser complementing IEC 62282-8-201:2020 (IEC, 2020d).

(14) At present, this comprises the territories of the EU, Island, Norway and Liechtenstein. It also applies to Switzerland under a mutual recognition agreement and Türkiye under a customs union agreement with the EU.

(15) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/single-market/european-standards/harmonised-standards/equipment-explosive-atmospheres-atex_en.

(16) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/sectors/electrical-and-electronic-engineering-industries-eei/electromagnetic-compatibility-emc-directive_en.

(17) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/sectors/electrical-and-electronic-engineering-industries-eei/low-voltage-directive-lvd_en.

(18) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/single-market/european-standards/harmonised-standards/general-product-safety_en.

(19) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/sectors/mechanical-engineering/machinery_en.

(20) The EC publishes guidance online at https://single-market-economy.ec.europa.eu/sectors/pressure-equipment-and-gas-appliances/pressure-equipment-sector/pressure-equipment-directive_en.

Annex B Tabulated data of duty cycles

B.1 Reactivity duty cycle

Table B.1 contain the tabulated data of the reactivity duty cycle (Figure 6.1).

Table B.1: Reactivity duty cycle data.

Duration (s)	Normalised set point (%)
0	100
1	100
2	100
3	100
4	100
5	100
6	100
7	100
8	100
9	100
10	100
11	75
12	75
13	75
14	75
15	75
16	75
17	75
18	75
19	75
20	75
21	100
22	100
23	100
24	100
25	100
26	100
27	100
28	100
29	100
30	100
31	50
32	50
33	50
34	50
35	50
36	50
37	50
38	50
39	50
40	50
41	100
42	100
43	100
44	100
45	100
46	100
47	100
48	100
49	100

Continue to next page

Table B.1 – continued from previous page

50	100
51	25
52	25
53	25
54	25
55	25
56	25
57	25
58	25
59	25
60	25
61	100
62	100
63	100
64	100
65	100
66	100
67	100
68	100
69	100
70	100
71	0
72	0
73	0
74	0
75	0
76	0
77	0
78	0
79	0
80	0
81	100
82	100
83	100
84	100
85	100
86	100
87	100
88	100
89	100
90	100
91	25
92	25
93	25
94	25
95	25
96	25
97	25
98	25
99	25
100	25
101	100
102	100
103	100
104	100
105	100
106	100

Continue to next page

Table B.1 – continued from previous page

107	100
108	100
109	100
110	100
111	50
112	50
113	50
114	50
115	50
116	50
117	50
118	50
119	50
120	50
121	100
122	100
123	100
124	100
125	100
126	100
127	100
128	100
129	100
130	100
131	75
132	75
133	75
134	75
135	75
136	75
137	75
138	75
139	75
140	75
141	100
142	100
143	100
144	100
145	100
146	100
147	100
148	100
149	100
150	100
151	100
152	100
153	100
154	100
155	100
156	100
157	100
158	100
159	100
160	100

Source: JRC, 2020 (Tsotridis and Pilenga, 2021).

B.2 Flexibility duty cycles

Table B.2, Table B.3 and Table B.4 contain the tabulated data of the high flexibility duty cycle (Figure 6.2), the 100 % flexibility duty cycle (Figure 6.3) and the 200 % flexibility duty cycle (Figure 6.4), respectively.

Table B.2: High flexibility duty cycle data.

Duration (min)	Normalised set point (%)
1	25
2	25
3	25
4	25
5	25
6	25
7	25
8	25
9	25
10	25
11	25
12	25
13	25
14	25
15	25
16	50
17	50
18	50
19	50
20	50
21	50
22	50
23	50
25	50
26	50
27	50
28	50
29	50
30	50
31	75
32	75
33	75
34	75
35	75
37	75
38	75
39	75
40	75
41	75
42	75
43	75
44	75
45	75
46	100
47	100
48	100
49	100
50	100
51	100
52	100
53	100

Continue to next page

Table B.2 – continued from previous page

54	100
55	100
56	100
57	100
58	100
60	100
62	125
63	125
65	125
66	125
67	125
68	125
69	125
70	125
71	125
73	125
74	125
75	125
76	150
77	150
78	150
79	150
80	150
81	150
82	150
83	150
84	150
85	150
87	150
88	150
89	150
90	150
91	175
92	175
93	175
94	175
95	175
96	175
97	175
98	175
99	175
100	175
101	175
102	175
103	175
104	175
105	175
106	200
108	200
109	200
110	200
112	200
113	200
114	200
115	200
116	200
117	200

Continue to next page

Table B.2 – continued from previous page

118	200
119	200
120	200
121	100
122	100
123	100
124	100
125	100
126	100
127	100
128	100
129	100
130	100
131	100
132	100
133	100
134	100
135	100
136	50
137	50
138	50
139	50
140	50
141	50
142	50
143	50
144	50
145	50
146	50
147	50
148	50
149	25
151	25
153	25
155	25
156	25
157	25
158	25
159	25
160	25
161	25
162	25
163	25
164	25
165	25

Source: JRC, 2020 (Tsotridis and Pilenga, 2021).

Table B.3: 100 % flexibility duty cycle data.

Duration (min)	Normalised set point (%)
1	25
2	25
3	25
4	25
5	25
6	25

Continue to next page

Table B.3 – continued from previous page

7	25
8	25
9	25
10	25
11	25
12	25
13	25
14	25
15	25
16	50
17	50
18	50
19	50
20	50
21	50
22	50
23	50
24	50
25	50
26	50
27	50
28	50
29	50
30	50
31	75
32	75
33	75
34	75
35	75
36	75
37	75
38	75
39	75
40	75
41	75
42	75
43	75
44	75
45	75
46	100
47	100
48	100
49	100
50	100
51	100
52	100
53	100
54	100
55	100
56	100
57	100
58	100
59	100
60	100
61	75
62	75
63	75

Continue to next page

Table B.3 – continued from previous page

64	75
65	75
66	75
67	75
68	75
69	75
70	75
71	75
72	75
73	75
74	75
75	75
76	50
77	50
78	50
79	50
80	50
81	50
82	50
83	50
84	50
85	50
86	50
87	50
88	50
89	25
90	25
91	25
92	25
93	25
94	25
95	25
96	25
97	25
98	25
99	25
100	25
101	25
102	25
103	25
104	25
105	25

Source: JRC, 2020 (Tsotridis and Pilenga, 2021).

Table B.4: 200 % flexibility duty cycle data.

Duration (min)	Normalised set point (%)
1	25
2	25
3	25
4	25
5	25
6	25
7	25
8	25
9	25

Continue to next page

Table B.4 – continued from previous page

10	25
11	25
12	25
13	25
14	25
15	25
16	50
17	50
18	50
19	50
20	50
21	50
22	50
23	50
24	50
25	50
26	50
27	50
28	50
29	50
30	50
31	75
32	75
33	75
34	75
35	75
36	75
37	75
38	75
39	75
40	75
41	75
42	75
43	75
44	75
45	75
46	100
47	100
48	100
49	100
50	100
51	100
52	100
53	100
54	100
55	100
56	100
57	100
58	100
59	100
60	100
61	125
62	125
63	125
64	125
65	125
66	125

Continue to next page

Table B.4 – continued from previous page

67	125
68	125
69	125
70	125
71	125
72	125
73	125
74	125
75	125
76	150
77	150
78	150
79	150
80	150
81	150
82	150
83	150
84	150
85	150
86	150
87	150
88	150
89	150
90	150
91	175
92	175
93	175
94	175
95	175
96	175
97	175
98	175
99	175
100	175
101	175
102	175
103	175
104	175
105	175
106	200
107	200
108	200
109	200
110	200
111	200
112	200
113	200
114	200
115	200
116	200
117	200
118	200
119	200
120	200
121	175
122	175
123	175

Continue to next page

Table B.4 – continued from previous page

124	175
125	175
126	175
127	175
128	175
129	175
130	175
131	175
132	175
133	175
134	175
135	175
136	150
137	150
138	150
139	150
140	150
141	150
142	150
143	150
144	150
145	150
146	150
147	150
148	150
149	150
150	150
151	125
152	125
153	125
154	125
155	125
156	125
157	125
158	125
159	125
160	125
161	125
162	125
163	125
164	125
165	125
166	100
167	100
168	100
169	100
170	100
171	100
172	100
173	100
174	100
175	100
176	100
177	100
178	100
179	100
180	100

Continue to next page

Table B.4 – continued from previous page

181	75
182	75
183	75
184	75
185	75
186	75
187	75
188	75
189	75
190	75
191	75
192	75
193	75
194	75
195	75
196	50
197	50
198	50
199	50
200	50
201	50
202	50
203	50
204	50
205	50
206	50
207	50
208	50
209	25
210	25
211	25
212	25
213	25
214	25
215	25
216	25
217	25
218	25
219	25
220	25
221	25
222	25
223	25
224	25
225	25

Source: JRC, 2020 (Tsotridis and Pilenga, 2021).

Annex C Test report

C.1 General

The test report shall accurately, clearly and objectively present all relevant information to demonstrate whether or not the purpose(s) and objective(s) of the test is/are attained. As a minimum requirement, the test report shall contain a title page (section C.2) and a summary report (section C.3) with the measured or estimated TIPs and TOPs at least as mean values along with their (combined) standard uncertainties whether absolute, relative or both. The test plan (section 6.4) as executed may be appended to the report. Calibration records and/or certificates of the measuring instruments used may also be appended to the report.

C.2 Title page

The titlepage shall present the following information:

(a) report identification, *i. e.* report number (optional),

(b) type of report (summary, detailed or full),

(c) author(s) of the report,

(d) entity issuing the report with name and address,

(e) date of the report,

(f) person(s) conducting the test when different from the reporting author(s),

(g) organisation conducting the test when different from report issuing entity,

(h) date and time per test run,

(i) location per test run when different from the address of the report issuing entity,

(j) descriptive name per test and

(k) identification (model name, serial number, type and specification) of the HTE stack and/or HTSEL system tested including their manufacturer(s).

The titlepage may be followed by a contents page before the summary report.

C.3 Summary report

The summary report shall include the following information:

(i) test purpose(s) and objective(s),

(ii) description of the test(s) with sufficient information on the test conduct and measurement set-up including test methods, measurement techniques (section 6.3) and test conditions (section 6.2),

(iii) all relevant test parameters namely TIPs and TOPs including uncertainties (section 7) as well as

(iv) conclusion(s) including graphical presentation of test results (section 7) and discussion with remark(s) and/or observation(s) as appropriate.

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