Experimental Design, Operation, and Results of a 4 kW High Temperature Steam Electrolysis Experiment

Xiaoyu Zhang ^{a,*}, James E. O'Brien ^b, Greg Tao ^c, Can Zhou ^a, Gregory K. Housley ^b

^a Department of Mechanical & Aerospace Engineering, Old Dominion University, Norfolk, VA 23529, USA

^b Idaho National Laboratory, Idaho Falls, ID 83401, USA

^c Material & Systems Research, Inc., Salt Lake City, UT 84104, USA

* *Corresponding author. Kaufman Hall 238, Old Dominion University, Norfolk, VA 23529, USA. Tel.: +1 757-683-4913; fax: +1 757-683-5344. E-mail: x1zhang@odu.edu.*

Abstract

High temperature steam electrolysis (HTSE) is a promising technology for large-scale hydrogen production. However, research on HTSE performance above the kW level is limited. This paper presents the results of 4 kW HTSE long-term test completed in a multi-kW test facility recently developed at the Idaho National Laboratory (INL). The 4 kW HTSE unit consisted of two solid oxide electrolysis stacks electrically connected in parallel, each of which included 40 electrode-supported planar cells. A current density of 0.41 A cm^{-2} was used for the long-term operating at a constant current mode, resulting in a theoretical hydrogen production rate about 23 slpm. A demonstration of 830 hours stable operation was achieved with a degradation rate of 3.1% per 1000 hours. The paper also includes detailed descriptions of the piping layout, steam generation and delivery system, test fixture, heat recuperation system, hot zone, instrumentation, and operating conditions. This successful demonstration of multi-kW scale HTSE unit will help to advance the technology toward near-term commercialization.

Key words: High Temperature Steam Electrolysis; Solid Oxide Electrolysis Cell; Hydrogen Production; Multi-kW Test

1 Introduction

Hydrogen is a potentially renewable fuel that can help to meet the rapidly growing global energy demand. However, hydrogen is not a direct energy source. It is an energy carrier that must be produced from other energy resources such as fossil fuels, nuclear, solar, biomass, etc [1]. Currently, hydrogen production is mainly dependent on steam reforming of natural gas. However, from a long-term perspective, hydrogen needs to be produced from sustainable resources. High temperature steam electrolysis (HTSE) has emerged as a promising technology for large-scale sustainable hydrogen production ($> 500,000$ kg per day) [2]. Large-scale hydrogen production using HTSE coupled with the next generation nuclear plant (NGNP) was selected by the United States Department of Energy (DOE) as the leading candidate for carbon-free nuclear hydrogen production research and development (R&D) [3].

The HTSE process consumes electricity as well as heat, and is highly efficient. In terms of thermodynamics, the electrical energy requirement decreases while the thermal energy requirement increases with increasing temperature [4]. The total energy requirement is nearly constant. Therefore, at elevated temperatures (e.g. $800\text{ }^{\circ}\text{C}$), a large part of electricity input can be substituted by heat, leading to a higher efficiency than operating at low temperatures. Meanwhile, several restraining factors, e.g. activation, kinetics, and ohmic overpotentials decrease remarkably with rising temperature [5]. When powered by a high-temperature nuclear reactor system, HTSE has the potential to achieve 50% or even higher overall thermal-to-hydrogen efficiency [4]. Furthermore, according to a life cycle assessment (LCA), the global warming potential (GWP) and acidification potential (AP) of the HTSE process are one sixth and one-third, respectively, of those for hydrogen production by steam reforming of natural gas, and are competitive compared with the conventional water electrolysis powered by renewable energy [6].

The history of HTSE is related to the R&D of solid oxide fuel cell (SOFC). Back in 1980s, Doenitz and his German co-workers in 'Hot Elly' project published that the thermal efficiency of electrolytic hydrogen production can be as high as 40-50% when operating with water in the vapor phase [7]. Due to shorter sealing lengths and simpler fabrication technology, a serial tubular configuration was chosen

initially as the single cell for scaling up the design [8]. Subsequently, electrolysis units for modular integration were developed and tested successfully with respect to electricity consumption of $2.57 \text{ kWh Nm}^{-3} (\text{H}_2)$ [9]. Additionally, a 21.6 W tubular stack assembled by 10 series-connected cells was used to investigate the viability of high H_2 concentration at the outlet [9]. At the end of that project, the concepts of prototype plant with 3.5 kW hydrogen output power were proposed [10]. After that, the worldwide focus of solid-oxide R&D moved to SOFCs, which had gone through an impressive progress in recent two decades. Recently, energy supply and global warming concerns have renewed the research on HTSE using advanced technologies of solid-oxide cells.

There has been a growing interest globally on R&D of HTSE stacks for producing hydrogen as well as syngas in the past decade. The Idaho National Laboratory (INL) focused on the feasibility of using SOECs for large-scale hydrogen and syngas production [1, 11]. Both experimental investigations (single button cell tests, multi-cell stacks, and multi-stack systems) [12, 13] and computational simulations (1-D and 3-D) [14] were performed. In European Institute for Energy Research (EIFER), numerous experiments of HTSE stacks with test durations ranging from 1000 to 9000 hours were reported [15]. Researchers in Denmark used 6-cell and 10-cell stacks to investigate HTSE and co-electrolysis of steam and CO_2 , respectively. The results showed that absorption of impurities from inlet gas played a major role in polarization resistance degradation of stacks [16]. Aimed at improving performance and reducing cost, a French group in Alternative Energies and Atomic Energy Commission (CEA) designed a 3-cell short stack using thin interconnects. They achieved mitigation of the degradation rate below $3\% \text{ } 1000 \text{ hr}^{-1}$ [17, 18]. Institute of Nuclear and New Energy Technology (INET) in China has started the R&D of hydrogen production using HTSE coupled with High Temperature Gas-cooled Reactor (HTGR), similar to the work performed under the DOE NGNP program in the U.S. [19, 20]. In addition, optimization tests of a 30-cell HTSE stack were conducted in Ningbo Institute of Materials Technology and Engineering (NIMTE) in China. They achieved a maximum hydrogen production rate of 103.6 NL hr^{-1} and a system efficiency of 52.7% [21, 22]. Researchers in Korea Institute of Energy Research investigated a 3-cell

HTSE stack prepared by extrusion method, and confirmed that sufficient steam supply was feasible to facilitate water splitting and decrease activation energy [23]. Another group from Korea Institute of Science and Technology (KIST) tested a 200 W class solid oxide regenerative fuel cell (SORFC) stack. A degradation rate of 7.75% 1000 hr⁻¹ was observed when the stack was operated in the electrolysis mode [24].

HTSE stack tests have been reported extensively. However, many of them are constrained below the kW level. Consequently, evaluation of HTSE stacks at a scale larger than 1 kW is essential to demonstrate the commercialization feasibility. To our best knowledge, only a few groups performed HTSE stack tests in multi-kW scale. EIFER researchers reported a 25-cell stack (≥ 2 kW) with more than 2900-hour continuous operation in the electrolysis mode in 2012. Their objective of the long-term test was to identify the mechanisms leading to degradation of cells and stacks performance [15]. INL developed a 15 kW Integrated Laboratory Scale (ILS) HTSE experimental facility to investigate performance and degradation of steam electrolysis process back in 2009 [12]. The ILS system consisted of three modules (each module consists of 240 SOECs) and was tested for 1080h with hydrogen production rate about 1.2 Nm³ hr⁻¹. However, significant degradation was observed during the test.

This paper reports the results of a 4 kW HTSE stack test with more advanced electrode-supported SOECs developed by the Materials and Systems Research Inc (MSRI). This paper demonstrates the more durable SOEC stacks (degradation rate is 3.1% per one thousand hours) than the ones that were demonstrated before at INL [12]. A new stack test facility for multi-kW scale HSTE was designed and built at INL for this test. Long-term operation (920 hours) of a 4 kW HTSE stack with 80 SOECs was demonstrated.

2 Experimental

2.1 Experimental design

Designing multi-kW HTSE tests is not a simple scaling-up process of single cell or short stack tests. It often requires the multi-kW test facility coped with the management complexity of power, heat and feedstock flow rates, thus demanding significant modification or even redesign of many apparatus components. Table I lists the common design factors that need to be considered for multi-kW tests and the specifications used in this research.

The 4 kW HTSE experimental process is illustrated in a piping and instrumentation diagram (P&ID) presented in Figure 1. The P&ID shows the double SOEC stacks inside the furnace with supporting instrumentation, including mass-flow controllers (MFCs), steam generator, heat exchangers, dew point sensors, thermocouples, and pressure transducers. In a standard long-term test (1000 hours), the feedstock to the hydrogen-electrode side consists of water vapor produced by a steam generator and carrier gases (H_2 or H_2+N_2). The dew point sensors are used to measure the steam content in the inlet and outlet streams so that the H_2 production rate can be calculated independently, as compared to the data obtained from the current measurement. On the oxygen-electrode side, produced O_2 is purged with a sweep gas (N_2 or air). The SOEC stacks are located inside of a cylindrical clamshell ceramic-fiber furnace. The inlet gases are preheated before entering the furnace through heat recuperation from the hot outlet gases. The gases are heated to the stack operating temperature within the furnace by means of radiant heating. The inlet gases flow through coiled tubing inside the furnace upstream of the stack for this purpose. All the outlet gases are vented outside the building.

For the 4 kW long-term tests, a mixture of hydrogen, nitrogen, and steam is introduced to the hydrogen-electrode side of the electrolysis cells. Hydrogen is required on the inlet side in order to maintain reducing conditions for the nickel cermet electrode of the SOECs. Inlet hydrogen for these tests is supplied by a pressurized, low-temperature water electrolysis unit (Avalence LLC) at 6 slpm with additional hydrogen from compressed gas cylinders at 6 slpm. Nitrogen is included in the cathode gas

mixture to yield a total dry gas mole fraction of 30% with a hydrogen mole fraction of 17%. The inclusion of nitrogen reduces the required inlet hydrogen flow rate to a value that could be supported by the electrolyzer unit and the available mass flow controllers. Air or nitrogen flows across the oxygen-electrode side of the electrolysis cells as a sweep gas. Nitrogen is supplied by two cryogenic Dewars. Air is supplied using a shop air compressor at 50 slpm.

Steam is provided by an electrically heated steam generator. The steam generator includes two independently heated zones. The lower boiling zone is controlled at constant power, with the power value depending on the required steam production rate. The rate of steam production for these tests yields an inlet steam mole fraction of 70%. The upper zone is feedback-controlled on temperature in the single-phase steam region above the liquid. The two-zone strategy allows for steady steam production with a desired amount of superheat. The gas flow lines downstream of the steam generator are heat-traced to avoid condensation. The outlet gas flow mixture flows through a water-cooled condenser, where the majority of the residual steam is condensed, and then to the roof vent.

Stack power is provided by a 10 kW DC power supply rated at 100 V and 100 A. Nominal electrolysis power consumption during operation is 4.2 kW at 82 A and 50+ V. The stacks are instrumented with intermediate voltage taps on every eight cells.

The hydrogen/nitrogen inlet gas flow is mixed with steam downstream of the steam generator. After mixing, the dew point temperature of the resulting steam/hydrogen/nitrogen mixture is measured using a precision dew point sensor. Another dew point sensor is located downstream of the SOEC stacks. The two dew point measurements provide an independent direct measurement of the steam consumption rate in the SOEC stacks, which is equal to the hydrogen production rate on a molar basis.

2.2 Test stand

The 4 kW test stand is shown in Figure 2. A photograph of the completed assembled test stand is shown on the left and a rendering of the 3-D CAD design is shown on the right. A split-tube furnace

(40.6 cm ID $\times$ 54.3 cm height) is vertically mounted on a supporting shaft. The split-tube design provides convenient access during assembly and maintenance of test articles without physically removing the furnace. The furnace has an electrical power rating up to 15 kW and can be operated at temperatures up to 1000 °C.

The rendering in Figure 2 is labeled to show the top current collector rods, springs for stack compression, alumina load transfer tubes, furnace, SOEC stacks, base manifold plate, and recuperative heat exchangers. The base manifold plate is supported by an alumina tube, which acts as an electrical insulator as well. The stacks are shown in their uncompressed state. After conditioning and final compression, the height of the stacks is significantly reduced.

The test fixture is based on the kW stack design developed at MSRI for SOFC/SOEC applications. The compression apparatus is capable of providing compressive force to the top of a stack during testing via compression springs located outside the hot zone of the furnace. The compression load is transferred to the stack via an alumina load transfer tube and the upper electrode plates as shown in Figure 2. Once the stack is in place on the test fixture, alumina load transfer tubes are installed on top of the upper electrodes, onto which compression springs with pusher plates are placed. Compression of the stack to the desired loading is achieved by tightening nuts on the four threaded bars that stand in parallel to each load transfer tube and fixed to the lower test fixture portion running through the pusher plates. Upon achieving the desired initial compression of the springs and hence, forced loading of the stack, the furnace may be closed and a heatup procedure is executed. During heatup, springs are adjusted to ensure a constant compression loading.

A custom base manifold plate was designed and fabricated for the double-stack configuration. The plate provides mechanical support for the two SOEC stacks, serves as a bottom current collector, and distributes the inlet and outlet gas flows to and from the double stacks. There are only two gas inlet lines and two gas outlet lines on the underside of the manifold plate, whereas there are four inlet channels and

four outlet channels on the top side of the manifold plate. The inlet and outlet gas flows are distributed to/from the two stacks by means of flow channels that were milled into the base manifold plate and subsequently seal-welded.

As mentioned above, the base manifold plate serves as a bottom current collector, which electrically commons the bottom sides of two stacks. During operation, the top two current collectors are also connected to the same power terminal, resulting in the same voltage being applied onto both stacks. This arrangement may result in different values of current in the two stacks. The challenge of this configuration is that if one stack endures a catastrophic failure, it could significantly affect the other stack. In practice, a limiting voltage is programmed to prevent that instance. As an alternative strategy, independent current control of the two stacks was also evaluated in the initial design. However, independent control was deemed not feasible, due to its requirement of an additional power supply and a more complicated piping arrangement and instrument wiring.

2.3 SOEC stacks

The SOEC stacks used in this research were designed and manufactured by MSRI. An exploded view of a MSRI SOEC stack is provided in ref. [13]. The cells incorporate semi-elliptical cut-out gas flow channels around the outer periphery of the cells that mate with corresponding holes in the interconnect plates. The stack is internally manifolded with compliant seals. Treated metallic interconnects with integral flow channels separate the cells and electrode gases. The stack operates in cross-flow, with an inverted-U shaped overall flow pattern such that the gas flow inlets and outlets are all located underneath the stack. Stack mechanical compression is accomplished by means of the custom spring-loaded test fixture described previously [13].

The SOECs used for this study have a square profile with a cell active area of 100 cm^2 . The cells incorporate an electrode-supported multilayer configuration with nickel-zirconia cermet negative electrodes (Ni + YSZ), thin-film yttria-stabilized zirconia electrolytes (YSZ), and multilayer lanthanum

ferrite-based positive electrodes (LSCF). The nickel zirconia electrode has a support layer thickness of 700 μm and a graded functional layer with an overall thickness of 15 μm . The electrolyte thickness is 10 μm . The positive electrode has a graded functional layer with a thickness of 20 μm and a current collecting layer thickness of 50 μm .

Integrating MSRI stacks with the test facility is a relatively simple procedure. Correct alignment of the process gas (steam/ H_2) and air inlets and outlets of the stack to the corresponding flow channels of the test section is most critical. Seal gasket and contact aids are placed between the stack and manifold plates.

2.4 Steam generator

For the 4 kW HTSE tests, the inlet steam flow rate will be relatively high (about 50 slpm). Commercial lab-scale steam generators usually are not able to meet the requirement of this research. Therefore, a steam generator was designed and built in house at INL. The custom steam generator shown in Figure 3 consists of a heated vertical tube with two independently heated sections—a lower constant-power boiler section and an upper constant-temperature superheater section. The boiler portion vaporizes the water while the smaller superheater section heats the saturated steam from the boiler to a temperature of about 150°C. It was fabricated by attaching a combination of twenty 200 and 300-watt clamp-on electric heaters to the outside of a stainless steel tube (2.54 cm OD). The heaters are wrapped with 3.08 cm thick thermal insulation then covered by an aluminum outer shell. The heaters are spaced such that a higher heat flux is obtained in the boiling region with lower heat flux in the single-phase regions. The tube interior is filled with a copper foam material that reduces the flow perturbations and increases temperature uniformity in the boiling region. Three thermocouples are mounted to the outside wall of the boiler/superheater assembly. The superheater outlet temperature is feedback-controlled based on the desired superheater outlet temperature. Input power to the boiler section is set via computer and is not feedback controlled. The required boiler power is calculated via the data acquisition software based on the inlet water flow rate and temperature.

2.5 Operating conditions

Typical operating conditions for the 4 kW HTSE tests are listed in Table II. At the nominal operating conditions, the hydrogen production rate is 23 slpm or 1380 NL hr⁻¹. This production rate is determined from the measurement of the electrical current supplied to the electrolysis cells using Faraday's law and is also independently verified based on the change in dew point values between the inlet and outlet dew point sensors. The voltage and current across the electrolysis cell(s) is continuously monitored. Typical per-cell operating voltage will be 1.12 V.

3 Results

3.1 Preliminary test – two 10-cell stacks

A preliminary test using two 10-cell stacks was performed in the 4 kW test apparatus. The purpose of this test was to evaluate the functionality of all the components of the test apparatus, including gas supplies (H₂, N₂, air, steam), flow control, temperature control, heat recuperation, data acquisition and instrumental control. The results would ensure that the 4 kW HTSE test stand would operate correctly in an integrated fashion. The cells and stacks were subjected to the usual heatup and conditioning procedure, followed by initial DC potential sweeps and long-term operation of 100 hours duration. The preliminary 100-hour test demonstrated a stable operation. As a conclusion, all the components of the test apparatus functioned properly and therefore were ready for the 4 kW HTSE tests.

3.2 4 kW HTSE test

For the 4 kW HTSE tests, two 40-cell stacks were installed in the test apparatus. A current density of 0.41 A cm⁻² was required in order to achieve 4 kW of electrolysis power. Operating conditions for this test are shown in Table II. The two 40-cell stacks installed in the test fixture are shown in Figure 4. Following stack installation, cell conditioning was performed for curing seals and the Ni-based hydrogen-electrode reduction. For a typical HTSE conditioning procedure, one can refer to ref. [13]. However, during the conditioning period, there was a loss of nitrogen flow to the stack that lasted for

several hours due to depletion of nitrogen source. The stacks were consequently exposed to a deficient flow only at 10% of the designated flow rate, bearing only pure hydrogen gas during this time. This event probably led to a redox of the Ni-based electrode, affecting the bottom cell groups the most which subsequently exhibited relatively high resistance. After completion of the preconditioning, the stacks were further treated with a reducing gas with a gradually increased hydrogen concentration to ensure a complete reduction of the Ni-based electrode.

Initial performance characterization was achieved by executing individual DC potential sweeps for each stack, followed by an overall sweep for the two stacks operating in parallel. These sweeps were performed at a stack temperature of 780°C. Results of the individual stack sweeps are presented in Figure 5. The figures show the intermediate voltages of five groups with eight cells per group, and per-cell area-specific resistance (ASR) as a function of current density up to 0.42 A cm⁻². During the VI sweeps for Stack 1, the intermediate voltages for the three top cell groups exhibited very similar behavior. The highest voltages during the sweeps were observed for the bottom two cell groups due to the pressure gradient through the flow channels. The bottom cells of the stack 2 behaved abnormally, which is believed to be caused by the redox event described earlier in §3.2. Since the flow channels of two stacks and not perfectly identical, the imbalance of flow distribution at lower flow rate might significantly affect the redox reactions of stack 2. The initial overall ASR for Stack 1 decreased with current density to a value of 0.86 Ω cm² at 0.42 A cm⁻². The sweep results for Stack 2 show that the intermediate voltages for the four top cell groups exhibited similar behavior. The highest voltages during the sweeps were also observed for the bottom cell group, probably due to the same reason. Voltages for the bottom cell group in Stack 2 were by far the highest of all the cell groups. The initial overall ASR for Stack 2 also decreased with current density to a value of 1.15 Ω cm² at 0.42 A cm⁻². The overall stack voltage increased nearly linearly with current density to a maximum value of 53.3 V at 0.42 A cm⁻². The corresponding total current was 84 A, with a total electrolysis power consumption of 4.52 kW.

The long-term 4 kW HTSE stack test was performed immediately after the initial performance sweeps. The furnace temperature was reduced to 750 °C to maintain the stack operating temperature at 800 °C due to the resistance heating during the long-term operation. The long-term test results are shown in Figure 6, which depicts the time history of total current for the two stacks operating in parallel, the total electrolysis power consumption, the stack voltage and the per cell ASR value. The initial current was ramped from 40 A to 60 A over the first day of the long-term test to ensure all the components functioned correctly. Thereafter, the current were ramped up to 82 A. The stacks were controlled galvanostatically at a constant current density of 0.41 A cm⁻², in order to maintain the electrolysis power just over the 4 kW level. The test duration target was 1000 hours operation at the 4 kW level.

Figure 6 shows the results for the first 920 hours of operation. Stack operation in the long-term mode was generally very stable, with minimum degradation in performance through 830 hours. The overall stack average ASR was 0.81 Ω cm², which is an excellent value in the stack configuration, compared to our previous stack tests [13]. The overall degradation rate of the 4kW test is 3.1%, which is calculated based on the stable period. The large fluctuations in the plotted values that began at 836 hours were related to the malfunction of the deionized (DI) water delivery system. The pressure across the reverse osmosis (RO) device increased, resulting in a sudden loss of water flow delivery to the stacks, which thus were operated in the electrolysis mode without steam. The RO system was subsequently bypassed, but stable operation could not be fully restored.

Figure 7 shows the data of hydrogen production rate measured independently by the Faraday current and the dew points. In general, both measurements indicate a stable production of hydrogen prior to the unrecoverable event, which dramatically influenced the stack performance subsequently. The malfunction of the RO system significantly destabilized steam generation, resulting in fluctuations of the inlet pressure, as shown in Figure 7. In addition, the discrepancy between those two measurements indicates a gas leakage in the system. Therefore, further improvement of sealing materials was suggested.

The long-term behaviors of the parallel stacks intermediate voltages are plotted in Figure 8. The intermediate voltages were measured across eight consecutive cells, resulting in 5 voltage measurements for each stack. As discussed previously, nitrogen flow loss affected the initial conditioning process. The intermediate voltages measured from the stacks clearly indicated that stack 2, especially the bottom 8 cells, suffered more from the interruption in nitrogen flow. Because of parallel operation, the stacks were compensating each other, so that the degradation cannot be evaluated individually for each stack.

As the lessons learned from this 4 kW HTSE stack test, the following improvements are suggested for large-scale HTSE tests in the future. First, a backup system for gas supplies is needed for all the gases to minimize the impacts from human errors and malfunctions of the main supply system. Second, a backup pressurized water storage tank is needed in order to minimize the instability of the water supply system. The backup tank should be able to supply pressurized water independently between regular work shifts, giving enough time for troubleshooting the main system.

4 Conclusion

A new test facility has been developed for testing of HTSE stacks at a multi-kW level. This facility has provided a demonstration of HTSE operation at the 4 kW scale with advanced cell and stack technology. The 4 kW test included two stacks (40 cells per stack) operating in parallel in a single hot zone. The 4 kW HTSE stacks were successfully operated for 830 hours with low degradation (3.1% per 1000 hours). As a reference for future research, the factors used to design and develop multi-kW HTSE test facilities are provided. This successful large-scale demonstration of HTSE will help to advance the technology toward near-term commercialization.

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Table I. Design factors of multi-KW high temperature steam electrolysis experiments.

Design Factor	Elements for Consideration	Specs used in this research
Power requirement	<ul style="list-style-type: none"> DC power supply for electrolysis AC power supplies for the steam generator, heat traces, and the furnace. 	DC power supply: TDK-Lambda Gen 100-100; 3-phase 208 V input. Furnace: Applied Test Systems Series 3210, 15 KW Heat trace power control: Watlow Din-a Mites, 110 V input. Steam generator: Watlow clamp heater, 240 V input.
Gas supplies and distribution	<ul style="list-style-type: none"> Gas consumption rates Gas flow rates 	H ₂ : compressed bottles and H ₂ generator. N ₂ : Dewar. Air: air compressor.
Steam generation	<ul style="list-style-type: none"> Steam flow rate Power consumption 	Steam is produced from a homemade steam generator.
Heat recuperation	<ul style="list-style-type: none"> Preheating requirement for the inlet gases Heat exchanger design 	Tube-in-tube heat exchangers for preheating and cooling.
Data acquisition (DAQ)	<ul style="list-style-type: none"> DAQ system for collecting the data of temperature, voltage, current, pressure, and humidity. 	Agilent DAQ system.
Safety	<ul style="list-style-type: none"> Hazardous gases Overtemperature protection High voltage DC protection 	Gas monitor: Draegergard CCS 3000 to monitor CO, CO ₂ , H ₂ , and O ₂ . Overtemperature protection: usually 20-50 °C above the setting points.

Table II. Operating conditions for 4 kW HTSE stack test (80 cells).

Electrolysis power input (kW)	4.01
Stack current (parallel double stacks) (A)	82
Current density (A cm^{-2})	0.41
Stack voltage (V)	48.9
Stack temperature ($^{\circ}\text{C}$)	750
Stack pressure	ambient
Gas flow rates (slpm)	
▪ Inlet hydrogen	14.9
▪ Hydrogen production rate	23.0
▪ Inlet steam	52
▪ Inlet nitrogen	7.4
▪ Sweep air	70
Steam utilization (%)	45
Inlet steam mole fraction	0.70
Inlet hydrogen mole fraction	0.20
Inlet nitrogen mole fraction	0.10

Captions of Figures

Figure 1. 4 KW high temperature steam electrolysis P&ID.

Figure 2. 4 KW test stand. The actual test stand prior to the tests (left) and the 3D CAD design (right).

Figure 3. Schematics of custom steam generator and the actual steam generator right next to the test stand.

Figure 4. Two 40-cell stacks installed in the test apparatus.

Figure 5. Initial VI sweeps of a) stack 1 and b) stack 2. The intermediate voltages were measured the voltage across 8 cells.

Figure 6. Long-term 4 kW HTSE test results through 920 hours of operation.

Figure 7. The hydrogen production rates and the inlet and outlet pressure during the long-term test (Figure 6).

Figure 8. Intermediate voltages of a) stack 1 and b) stack 2 during 920 hours operation. The intermediate voltages were measured the voltages across 8 consecutive cells.