Hands-on Seminar on Electrolysis and Fuel Cells for Life Support System Applications for Students at the University of Stuttgart

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At the Institute of Space Systems (IRS) at the University of Stuttgart, a hands-on seminar on electrolysis and fuel cells for Life Support System (LSS) applications is offered to the aerospace engineering master students. After an introduction of the electrochemical fundamentals of both, the electrolysis and the fuel cell process, the students learn about different fields of application. A special focus is set on LSS applications, e.g. oxygen production by water electrolysis. Additionally, terrestrial fields of application, e.g. fuel cell cars, are highlighted. After having learned all the basics, the students start their hands-on seminar by conducting their own experiments guided by the IRS staff. In a total of four experiments they learn about characteristic curves and efficiency levels of the different components. After the practical part, they write a report in which they evaluate their findings. Building on the knowledge gained throughout the seminar, they get a design task to calculate the baseline requirements for both, an electrolyzer and a fuel cell system to support humans in space. This paper introduces and summarizes the 2019 hands-on seminar on electrolysis and fuel cells for LSS applications and the results obtained by the students.

Nomenclature

AFC	=	alkaline fuel cell
AOCS	=	attitude and orbit control system
CO_2	=	carbon dioxide
el	=	electric
EPS	=	electrical power system
F	=	Faraday constant
Δh	=	energy
H_2	=	hydrogen
H_2O	=	oxygen
HHV	=	higher heating value
IRS	=	Institute of Space Systems
ISS	=	International Space Station
LHV	=	lower heating value
LSS	=	life support system
O_2	=	oxygen
OGA	=	oxygen generation assembly
P	=	power
PBR	=	photobioreactor
PEM	=	polymer electrolyte membrane
th	=	thermal
z	=	number of electrons

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I. Introduction

GETTING students closer to research and providing them practical training options to supplement theoretical knowledge is the idea behind the hands-on seminars carried out at the Institute of Space Systems (IRS) at the University of Stuttgart. IRS belongs to the faculty of Aerospace Engineering and Geodesy and is involved in both research and teaching. Each summer semester, the Institute offers several hands-on seminar options, from which 30 of the approximately 750 aerospace engineering master students have the opportunity to choose two in order to attend a three ECTS Credits course (90 hours workload equivalent). The hands-on seminar options offered in the previous years included: electrolysis and fuel cells, rendezvous and docking training using the Institute's Soyuz simulator, programming a spacecraft for the Soyuz simulator, neurofeedback-training, a mission analysis workshop, Earth observation using the Institute's Flying Laptop small satellite and a hands-on seminar on LSS technologies for human spaceflight.[1] All offered options are related to research conducted at IRS.

Today, with the growing interest in hydrogen technologies as an attractive option for the decarbonisation of global energy systems,[2,3] fuel cells and electrolyzers are gaining greatly in popularity. This can also be seen by the high demand from the students to participate in this hands-on seminar, which has already been offered several times in the past years.

A. Basic Fundamentals

A fuel cell is a galvanic cell, which converts the chemical reaction energy of a continuously supplied fuel (e.g. hydrogen, H_2) and an oxidant (e.g. oxygen, O_2) directly into electrical energy (by making use of the electrons transferred in the reaction) and thermal energy. The total energy released is $\Delta h_{released}$. The overall reaction scheme is:

$$2\ H_2 + O_2 \rightarrow 2\ H_2O + \Delta h_{released} \quad (1)$$

Although fuel cells had been described already in the 19th century,[4] they did not get beyond the textbooks of electrochemistry at that time. The theories were complicated and no correspondingly good materials to built them were available. With the invention of the combustion engine and the electro-dynamo at about the same time, electrical energy could be generated quickly and technically more easily, so that the fuel cell did not experience a renaissance until the 1960s with first applications developed for the space sector.[5] In the 1960s, General Electric developed the first proton-exchange membrane fuel cell, also known as polymer electrolyte membrane (PEM) fuel cell, which was used during the Gemini space missions. Two 1 kW systems were used on board the Gemini flights. The average power that was produced on the Gemini flights was 620 W.[6] At that time, due to their lower weight and volume requirements, fuel cells were superior compared to batteries that could not meet the high demands in terms of power output, mechanical load resistance and sufficient lifetime requirements in a compact and light-weight design for a two-man capsule.[5] The first PEM fuel cell flew successfully with Gemini 5 in August 1965 and was an integral part of the energy supply from then on until Gemini 12. The subsequent Apollo program continued to rely on fuel cells, but on the alkaline fuel cell (AFC) type from Pratt & Whitney because of its higher efficiency and higher output power compared to the PEM fuel cell. Its power range was 563 to 1,420 W with a peak power capability of 2,295 W at 20.5 V weighting 220 lb (about 100 kg).[6]

Today, fuel cells are used to generate electricity in a very wide range of terrestrial applications, e.g. stationary and mobile applications.[7-10] Stationary applications include combined heat and power plants for in-house electricity and heat generation. Mobile applications include all kinds of vehicles, e.g. fuel cell cars. In mobile applications, the PEM fuel cell currently dominates, which as a low-temperature cell has the property of supplying electrical energy immediately after start-up.

Electrolysis is the splitting of a chemical compound under the influence of electric current. During water electrolysis, the water (H_2O) is split into H_2 and O_2 by supplying the electrical energy Δh_{supply}. The overall reaction scheme is:

$$2\ H_2O + \Delta h_{supply} \rightarrow 2\ H_2 + O_2 \quad (2)$$

Today on ISS water electrolysis is used for oxygen generation. The *Elektron* system, located in the Russian *Zwezda* module, and the *Oxygen Generation Assembly* (OGA) provide the required oxygen for the crew.

B. Research at IRS

At IRS, research on the synergetic integration of fuel cells in LSS was conducted.[5,11,12] Future LSS will have to focus on regenerative systems for water and oxygen regeneration. Combination options of the LSS, the electrical power system (EPS) and attitude and orbit control system (AOCS) are shown in Figure 1.

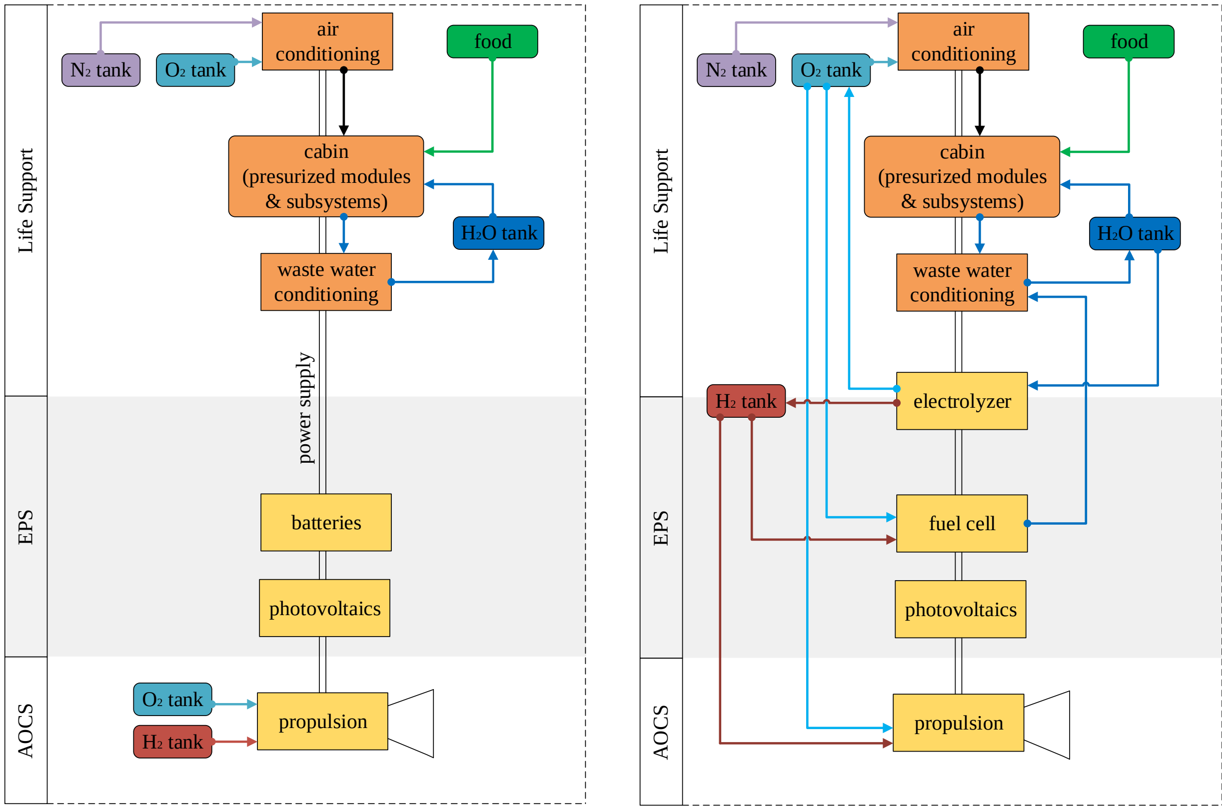


Figure 1. Left side: Separated subsystems with batteries. Right side: Integrated subsystems with electrolyzer and fuel cell. Adapted from S. Belz.[5,12]

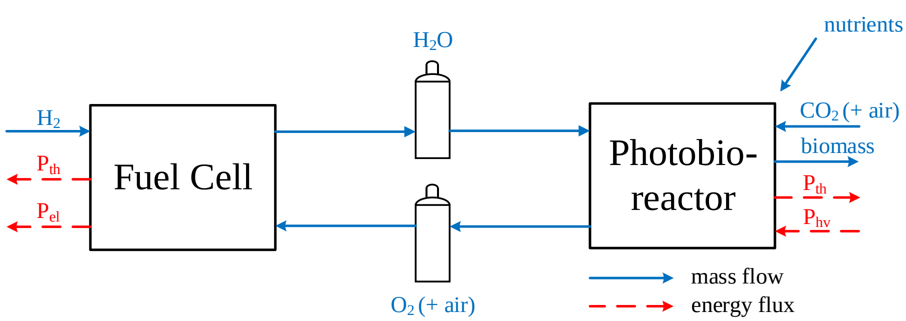


Figure 2. Combination of fuel cell and PBR. Adapted from S. Belz.[12]

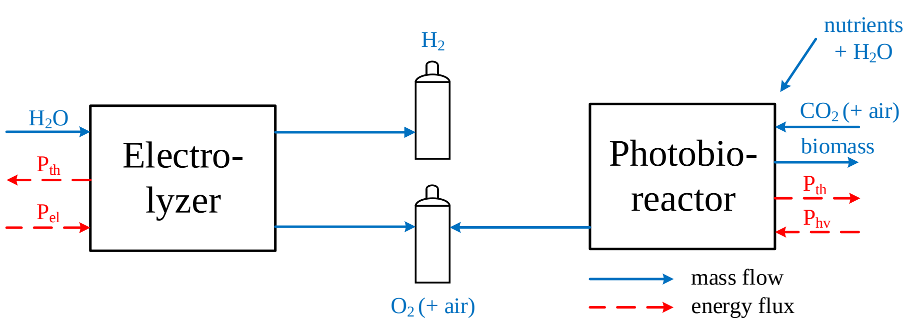


Figure 3. Combination of electrolyzer and PBR. Adapted from S. Belz.[12]

The option on the left-hand side of Figure 1 consists of separated systems. The replacement of the battery system and a shared infrastructure is shown on the right-hand side of Figure 1. The shared infrastructure means one tank for H_2, one tank for O_2 and one tank for H_2O for all system components. The fuel cell can contribute to the LSS because it is able to deliver water for the crew. This was already done for the US space shuttle fuel cell system, which was directed to the potable water storage subsystem.[13] The synergetic link between AOCS, EPS and LSS by sharing H_2 offers interesting aspects to save overall system mass.

Another focus was set on the coupling of fuel cells and electrolyzers with photobioreactors (PBR), see Figure 2 and Figure 3. A PBR utilizes a light source to cultivate phototrophic microorganisms such as microalgae. Microalgae are microscopic algae, typically found in freshwater and marine systems. They can generate biomass and oxygen from carbon dioxide (CO_2), water and inorganic components (e.g. phosphorus, nitrate) through photosynthesis. Although photobioreactors are not yet technologically advanced enough to replace conventional methods, they could be an attractive alternative in the future.

The studies conducted at IRS indicate, that the combination of physicochemical LSS components (e.g. fuel cells, electrolyzers) with simple biological components to create so called hybrid LSS might be very beneficial for long-term, deep space exploration missions. The hybrid approach with integrated subsystems might help to overcome considerable resupply mass issues that are linked with conventional systems.

II. The Hands-on Seminar Approach

The goal of the hands-on seminar is to provide the students an opportunity to supplement theoretical knowledge by practical training. At the beginning of the semester, a two-hours lecture is held to convey theoretical knowledge. In order to consolidate this theoretical knowledge, lecture notes are provided to the students. Besides containing all the required theory, the 20-page lecture notes also include descriptions of all experiments to be performed in the practical part. Students are expected to prepare for this laboratory module in self-study. During the self-study part, students can contact the lecturer at any time.

After about four weeks of self-study, the practical training is carried out. The four-hour hands-on experience starts with a short oral exam. Therefore, each student draws a question card from a deck. Besides the question, the card also contains a number that later determines their group partner for the laboratory module. Afterwards the students present the question written on their card and answer it in front of the audience. Thereby, the students are encouraged to support and complement each other. The oral examination does not aim to grade the students individually, but to ensure that all participants have the same level of knowledge required for the laboratory module of the seminar. Usually the students are very well prepared for this exam and master the challenge without problems.

Before the practical training starts, the lecturer presents the individual experiment setups and gives a safety briefing. Additionally, the handling of the measuring instruments is explained. For the practical part, the students work in pairs. Together with their partner, each student conducts four experiments in total, see Section IV.

The experiments include their setup as well as the integration of the required measuring instruments. If required, guidance is provided by the lecturer. Before the students can start conducting their experiments, the experimental setup has to be approved by the lecturer for safety reasons.

Once all groups have finished their experiments, the lecturer briefly summarizes what has been done throughout the training session in order to consolidate what has been learnt. The training session ends with information on the final report the students have to write for examination.

The evaluation of each student is based on their final report which has about 20 pages and includes the description and evaluation of all experiments performed, see Section IV. Additionally, two given design tasks must be solved in the report, see Section V. During the writing phase, students can contact the lecturer at any time.

To ensure a dedicated guidance and tutoring by the lecturer and his two assistants, the number of participants is limited to eight per training session. During the semester, there are two training sessions, so that a total of 16 students can participate in the hands-on seminar. Students who could not be accepted into the seminar will be selected on a preferred basis next year.

III. Equipment used for the Hands-on Seminar

A. Fuel Cells and Electrolyzers

Figure 4 shows the fuel cells and electrolyzers used for the hands-on seminar. They were purchased from the company H-TEC Education. The electrolyzer (product code T203) has an H_2 production rate of up to 10 cm³ per minute. The fuel cell (product code F103) can provide 200 mW in H_2/air-mode and up to 500 mW in H_2/O_2-mode.

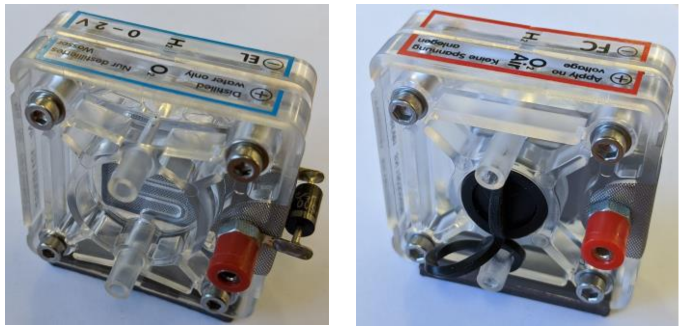


Figure 4. Left: H-TEC electrolyzer (product code T203). Right: H-TEC fuel cell (product code F103).

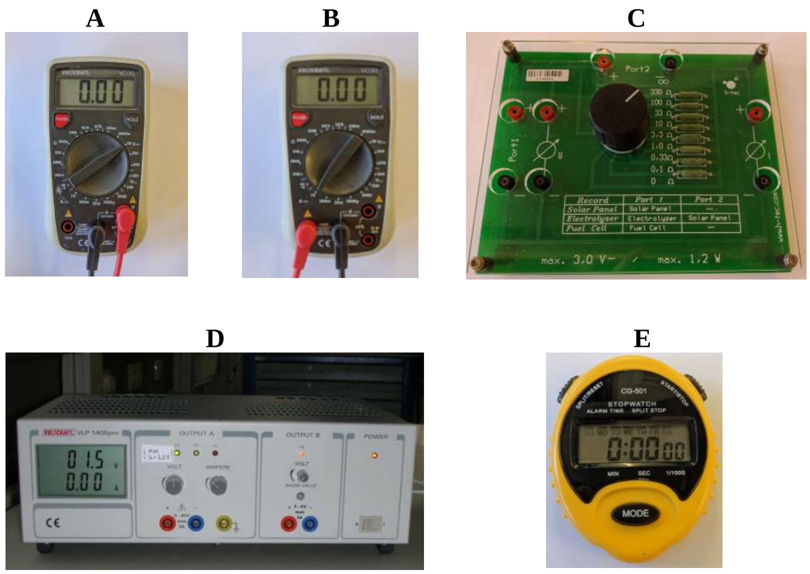


Figure 5. Equipment used for the hands-on seminar. A: multimeter used as voltmeter. B: multimeter used as ammeter. C: adjustable resistance. D: power supply unit. E: stopwatch.

B. Measuring instruments and other equipment

Figure 5 gives an overview of the measuring instruments and other equipment used for the hands-on seminar on electrolysis and fuel cells. The required equipment includes multimeters, power supply units, adjustable resistances, and a stopwatch. Additionally, a barometer and a thermometer are required for experiment evaluation.

IV. Laboratory Experiments and Results

A. Laboratory Experiments

During the hands-on seminar, the students conduct four experiments, each one lasting about half an hour. Two experiments focus on electrolysis and two experiments focus on the fuel cell. This section briefly explains the experimental setups, see Figure 6, and the experimental goals.

1. Electrolysis experiment 1 – current-voltage characteristics of an electrolyzer

The first electrolysis experiment focuses on determining the current-voltage characteristics of an electrolyzer. The students start with setting up the electrical circuit shown on the left-hand side of Figure 6. The setup consists of an adjustable power supply, an ammeter, a voltmeter and an electrolyzer. The students then adjust the voltage and measure the current. In case of a single cell electrolyzer, they adjust the voltage in steps of 0.2 V until they reach 1.2 V. Afterwards, they use 0.05 V steps until they reach the upper limit of 2.0 V. After having adjusted the voltage, the students need to wait about 10 s until the measurement values are constant. They write their measured current and voltage values in their lab notes.

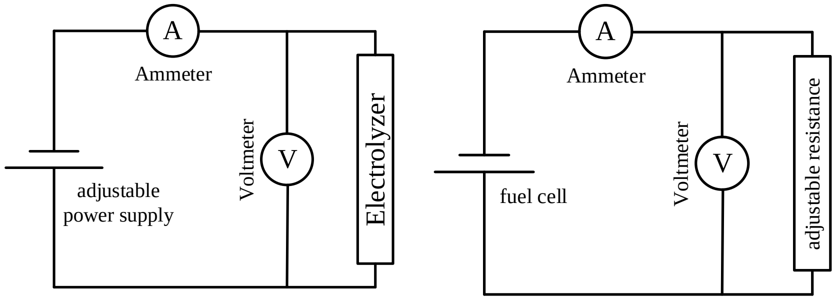


Figure 6. Left side: circuit diagram for the electrolysis experiments. Right side: circuit diagram for the fuel cell experiments.

2. Electrolysis experiment 2 – efficiency of an electrolyzer

The second electrolysis experiment focuses on determining different efficiency levels (e.g. energetic efficiency, Faraday efficiency). The same experimental setup as for the first experiment is used. Each group has a predefined operation point for their electrolyzer. For a single cell electrolyzer the operation point is about 1.0 to 1.4 W. The students must then adjust the voltage until the product of voltage and current reaches their predefined operation point. Once they have found their operation point, they can start with their measurements. Therefore, they observe the amount of produced hydrogen over time. Typically, they start with a tank level of 0 cm^3 at timepoint 0 s. Each time when a fixed amount of hydrogen, e.g. 2 cm^3, has been produced by the electrolyzer, they write down time, current and voltage. The experiment ends when they have at least 5 to 6 measurement points. The measurement of current and voltage is important to observe if the fixed operation point is kept over the whole experiment duration. Usually the electrolyzers work very stable and keep the operation point fixed over time.

3. Fuel cell experiment 1 – current-voltage characteristics of a fuel cell

As in the first electrolysis experiment, the aim of this experiment is to determine the characteristic curve of a fuel cell. Again, the students start with setting up the electrical circuit shown on the right-hand side of Figure 6. The setup consists of the fuel cell, an ammeter, a voltmeter, and an adjustable resistance. The fuel cell is supplied with H_2 and O_2 by an external electrolyzer (not shown in the circuit diagram). During the experiment, the students adjust the resistance to simulate different electronic consumers. By changing the resistance, also the voltage and current changes. For each resistance (e.g. 330, 100, 33, 10, 3.3, 1, 0.3 Ohm) the students measure current and voltage and write down their measurement values into their lab notes.

4. Fuel cell experiment 2 – efficiency of a fuel cell

The second fuel cell experiment focuses on determining efficiency levels. The same experimental setup as for the first fuel cell experiment is used. A photograph of the experimental setup is shown in Figure 7. Each group has a predefined operation point for their fuel cell. This time, the operation point is defined by a fixed resistance value (e.g. 3.3 or 1 Ohm). Once the students have set their operation point, and the H_2 supply tank is filled, measurement can start. At experiment start, they disconnect the external electrolyzer in order to stop the H_2 resupply to the fuel cell. The students then observe the amount of consumed H_2 over time. Additionally, they observe the current and voltage. The experiment ends when they have at least 5 to 6 measurement points. Especially for the fuel cell experiment, the observation of current and voltage is extremely important. Since the cathode of these fuel cells is blocked by a stopper, product water from the fuel cell process might accumulate and limit the active cell area thereby leading to power losses. If a loss of power is observed during the measurement, the stopper must be shortly removed from the cathode to release the water. After putting the stopper back on again, the measurements must be repeated.

B. Results obtained by the students

As an example, the results from one student group are briefly presented, see Figure 8. Part A of Figure 8 shows the characteristic voltage-current curve of an electrolyzer. As can be seen in the diagram, a voltage of about 1.5 V is required to start the electrolysis process. In theory (concerning an ideal electrolyzer), we would expect that only 1.23 V would be needed because this is the required potential difference to split water. Since we do not have ideal conditions, a higher potential is needed to start the process. The curve then rises constantly until to the upper limit of 2.0 V.

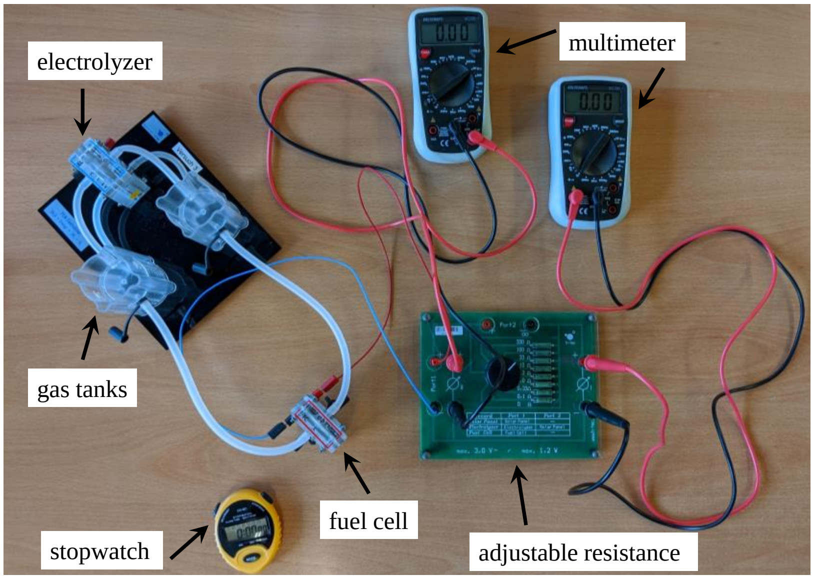
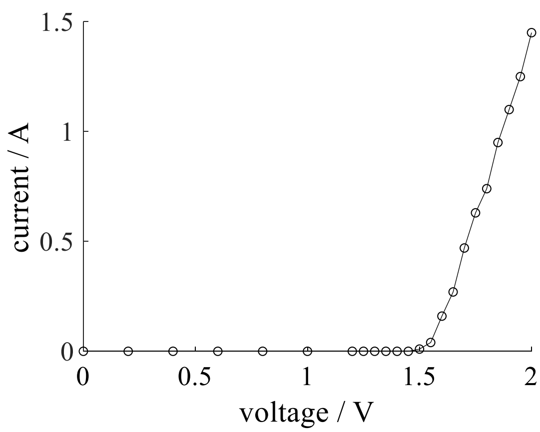


Figure 7. Experimental setup of the second fuel cell experiment.

A



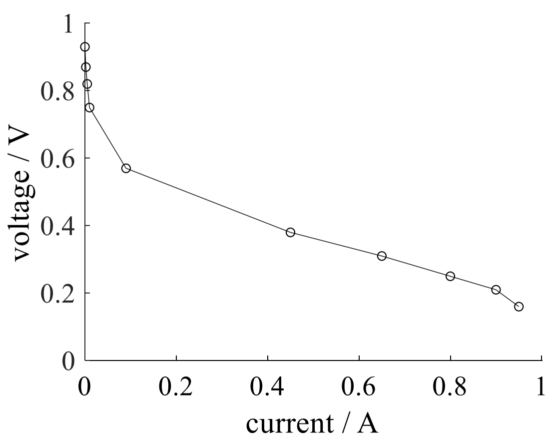
B

Ambient pressure:	963 mbar
Ambient temperature:	293 K
Mean voltage:	1.71 V
Mean current:	0.82 A
Produced H_2:	18 cm³
Experiment time:	214 s

$$\eta_E = \frac{V_{H_2} \cdot HHV_{H_2}}{\bar{V} \cdot \bar{A} \cdot t} = 0.765 \qquad (3)$$

$$\eta_F = \frac{V_{H_2}}{R \cdot \bar{I} \cdot T \cdot t /_{F \cdot p \cdot z}} = 0.782 \qquad (4)$$

C



D

Ambient pressure:	963 mbar
Ambient temperature:	293 K
Mean voltage:	0.35 V
Mean current:	0.79 A
Consumed H_2:	18 cm³
Experiment time:	164 s

$$\eta_E = \frac{\bar{U} \cdot \bar{I} \cdot t}{V_{H_2} \cdot LHV_{H_2}} = 0.233 \qquad (5)$$

$$\eta_F = \frac{R \cdot \bar{I} \cdot T \cdot t /_{F \cdot p \cdot z}}{V_{H_2}} = 0.947 \qquad (6)$$

Figure 8. A: Characteristic curve of a single cell electrolyzer. B: Efficiency levels of a single cell electrolyzer. C: Characteristic curve of a single cell fuel cell. D: Efficiency levels of a single cell fuel cell.

Part B of Figure 8 shows measurement values and efficiency calculations for the electrolyzer. Eq. (3) shows how the energetic efficiency of the electrolyzer is calculated. The term HHV represents the higher heating value of H_2, which is 12.745 MJ/m³. An energetic efficiency of about 76.5 % was calculated. Eq. (4) shows the calculation of the Faraday efficiency where F is the Faraday constant and z the number of electrons transferred in the reaction. The term R represents the universal gas constant. A Faraday efficiency of about 78.2 % was calculated.

Part C of Figure 8 shows the characteristic curve of the fuel cell. An open cell voltage of about 0.93 V was measured. As the current increases slightly above zero, the voltage drops significantly. This is caused by activation losses. Afterwards, a linear correlation between current and voltage can be determined. Here, ohmic losses dominate. The voltage drops as high currents are reached. This is caused by mass transfer inhibitions.

Part D of Figure 8 shows measurement values and efficiency calculations for the fuel cell. Eq. (5) shows how the energetic efficiency of the fuel cell is calculated. The term LHV represents the lower heating value of H_2, which is 10.8 MJ/m³. The energetic efficiency of the fuel cell is about 23.3 %. Eq. (6) shows the calculation of the Faraday efficiency. The fuel cell reaches a Faraday efficiency of about 94.7 %.

V. Design Task and Results

A. Design task description

1. Design of an electrolyzer system to support humans during long-term exploration missions

In the first design task, the students size an electrolyzer system that shall provide oxygen to a crew of seven during a 540 days mission to Mars. Data from single cell testing of a PEM electrolyzer is provided. Each cell has an operational power of 22 W, the electrical efficiency is 94 % and the Faraday efficiency is 98 %. Losses of 7 % from stacking the single cells, and losses of 6 % due to peripherals can be assumed. Additionally, it is assumed that the overall system efficiency after 30,000 hours of operation will linearly decrease down to 25 %. The student’s task is to calculate the required power of the electrolyzer system and the number of cells in order to generate enough oxygen for the crew (0.84 kg/CM-day) whilst keeping in mind the system degradation over time.

2. Design of a fuel cell system to support humans during long-term exploration missions

In the second design task, the students size a fuel cell system that shall provide energy to a crew of seven during a 540 days mission to Mars. Oxygen supply to the fuel cell shall be provided by an algae photobioreactor. It is assumed, that the whole amount of exhaled CO_2 (1 kg/CM-day) is consumed by the PBR. Further, it is assumed that the PBR provides seven ninths kilogram of O_2 per kilogram consumed CO_2. Measurement data from single cell testing of a PEM fuel cell at IRS is provided to the students. The data contains flow rates of H_2 and O_2, temperature, pressure, voltage, and current measurement. Again, information about system losses due to periphery and degradation behavior of the fuel cell system over time are given. The student’s task is to calculate the amount of electrical energy provided by the fuel cell system.

B. Results obtained by the students

1. Electrolyzer system

Without degradation and an overall efficiency of 79.7 %, the fictive electrolyzer system would require 1,540 W and consist of 70 single cells to meet the oxygen demand of the crew. Since the system performance degrades over time, the initial system power must be increased, to ensure enough oxygen production even after 540 days into the mission. Therefore, the system must initially be oversized to 1,804 W resulting in 82 single cells. With this configuration, a surplus of about 23 kg of O_2 is produced during the mission, the overall O_2 demand is 3,175.2 kg.

2. Fuel cell system

With the given measurement data from single cell characterization, an ideal operation point at 0.493 V and 22.1 A is determined. Due to the over-stoichiometric operation of the fuel cell, the electrical efficiency is only about 19 % for the single cell. Considering further losses by stacking the single cells, losses caused by the periphery, and degradation over time, the total energy provided by the fuel cell system during the entire mission is about 800 kWh.

VI. Students Feedback

After the hands-on seminar took place, the students were asked to provide feedback to the lecturer regarding organization, content, learning methodology, and practical training. For each question the students had to provide a score from 1 (best) to 5 (worst). Feedback questions were divided into generic questions and into specific questions defined by the lecturer.

Generic questions included (some examples): Is the seminar well organized? Are the learning objectives of this seminar transparent? Were the contents explained in an understandable way? Am I motivated to think along? Does the lecturer focus on the interests of the students? Does it become clear to me what significance the topics dealt with have for my field of study? For these questions, scores between 1.0 and 1.89 with an average score of 1.47 were achieved.

Since the seminar is very practical, specific questions considering this kind of course were asked including (some examples): Am I actively involved in the course? Am I encouraged to ask questions? Was I well supervised during the seminar? Do I gain deeper understanding through the practical part? Do I feel qualified to solve problems on the topics dealt with in the future? For these questions, scores between 1.22 and 2.22 with an average of 1.61 were achieved. The students especially praised the practical approach, the good supervision and organization, their high involvement in the course and the encouragement to ask questions but they did not feel completely confident whether they are qualified to solve future problems on the topics dealt with in the seminar.

The students' lack of confidence to solve future problems related to hydrogen technologies might be coupled with the complexity of the topics dealt with and the relatively short timeframe (in total 45 hours work equivalent) as well as the fact that most of the students had their first contact with fuel cells and electrolyzers during the seminar. Expanding the content of practical examples in the theoretical part might help to give students better guidance for future problems related to the topic and also serve as a reference guide.

VII. Conclusion

The goal of the hands-on seminars offered to the aerospace engineering master students at the University of Stuttgart is to provide an opportunity to supplement theoretical knowledge by practical training. The students can choose from a wide range of different hands-on seminar options (e.g. mission analysis, Soyuz simulator, LSS, Flying Laptop, etc.) that are all related to research conducted at IRS.

In the hands-on seminar on electrolysis and fuel cells, the students get in touch with hydrogen technologies used in human space flight. The seminar starts with a theoretical lecture in which all the required basics are explained. Additionally, lecture notes are provided to the student to support them in self-study. At the beginning of the practical training session, a short oral exam is performed with questions discussed in public in order to bring everyone to the same level of knowledge. For the practical training, students are divided into groups of two. Together with their partner they perform four experiments (two concerning electrolysis, two concerning fuel cells). After the practical training, they write a report in which they describe, analyze and evaluate the experiments. Additionally, they solve two given design tasks. Evaluation is done through a final report.

Students have evaluated the seminar very positively. They especially liked the good organization and the practical aspect of the seminar. The training will continue to take place in the coming years, if required means are available.

Acknowledgments

The authors of this paper would like to thank the University of Stuttgart, which through the "Studienkommisionsmittel" (SKM) has provided the required budget to carry out this hands-on training in the summer semester 2019.

A special thanks goes to Dr. Stefan Belz who established and conducted this hands-on seminar for many years.

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