Fuel Cells for Stationary, Automotive and Portable Applications

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Fuel Cell Testing

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Introduction

Fuel cells are considered clean and efficient power generators for various applications. Currently different fuel cell technologies are under investigation which are differentiated by the electrolyte used and the operating temperature:

Tab. 1: Fuel cell types

Low temperature FCs	AFC	Alkaline electrolyte
	PEMFC	Proton conducting polymer electrolyte
	DMFC	Proton conducting polymer electrolyte
Medium temperature FC	PAFC	Phosphoric acid
High temperature FCs	MCFC	Molten carbonate electrolyte
	SOFC	Solid oxid electrolyte

The main catagories of fuel cell applications could be divided into two major classes

Predominately dynamic load applications

These requiring fast and steep load changes even within fractions of a second. These are in particular:

- Vehicle traction
- Portable power generators
- Residential power generation

Predominately continuous load applications

These systems are typically run with limited load changes

- combined heat and power generation
- highly efficient baseline power generating stations

For more dynamic load operations the low temperature FCs are selected. The most promising low temperature fuel cell type is the Polymer electrolyte membrane fuel cell (PEFC). Considerable effort has been spent to develop PEFC for vehicle traction. However, portable power generation and residential fuel cells are an attractive opportunity for initial market penetration. ZSW is active in the development of PEFC technology. PEFC-stacks with an electric power in the range of 100 W to 10 kW (see Fig. 1) are available.

A B

Fig. 1: ZSW PEFC-Stacks (A: 1KW, B: 2,5 kW)

PEFC Operation Requirements

Low temperature fuel cell operation requires a supply of sufficiently pure hydrogen. Contamination by inert gasses or CO_2 can be tolerated with limited loss in performance. Contamination by trace amounts of CO up to 100 ppm requires special conditioning of the gas e.g. by addition of a small amount of air. CO contamination of levels above 500 ppm must be avoided.

In complete systems, hydrogen is either provided as a pure gas or produced on site from a more common fuel such as natural gas, naphta or methanol. These fuels must be processed by steam reforming or catalytic partial oxidation resulting in a mixture of H_2, CO_2, CO and N_2.

In addition to hydrogen a supply of oxidant, typically air or pure oxygen, is required.

In order to keep the high conductivity state of the common membrane electrolytes, humidification of the gasses is normally required. Operation of the fuel cell under elevated pressure increases the power density and considerably alleviates problems occurring from membrane water loss. Typical operating temperatures of PEFC`s in automotive applications are 80 °C and above at pressures above 2 bar. Residential and portable PEFC systems normally operate at temperatures around 60 °C close to atmospheric pressure.

Since the electrochemical electricity generation from hydrogen is not 100 % efficient, there is also production of heat which must be removed to prevent overheating of the fuel cell.

A schematic drawing of a FC-system is given in the next figure.

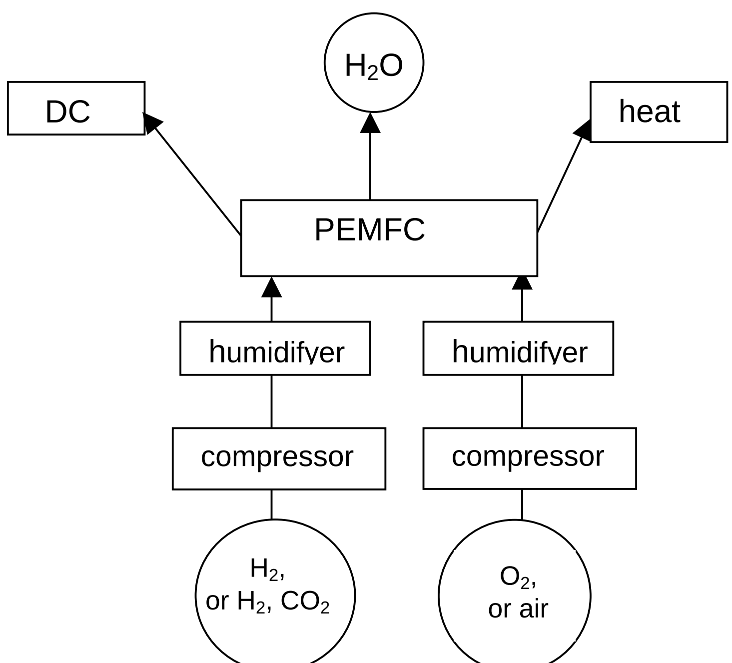

Fig. 2: Scheme of a PEFC-system

Under very low power load conditions fuel cells can be operated without using special control equipment. However, safe and reliable operation of the fuel cell does require control of:

- load
- gas flow
- gas utilization/stoichiometry
- gas humidification
- operating temperature
- pressure

Furthermore, differential pressure and single cell voltages need to be monitored in order to detect critical operation conditions.

Additionally, a safety interlock is required in order to handle critical conditions such as gas leakage, overheating or cell reversal.

The following sections describe fuel cell test equipment having two different levels of capability.

Fuel Cell Test Equipment for Educational Purposes

Fuel cells are increasingly integrated in the university curricula and used in the education of service personnel. Besides theoretical courses, fuel cell education should also provide practical training. For this purpose fuel cell test equipment is required facilitating the simulation of various operating conditions. This includes operation under favorable as well as unfavorable conditions. Furthermore, the user should be allowed to operate the fuel cell manually. However, setting of operating conditions that may lead to destruction of the fuel cell should always be prevented, e.g. by the system controller.

Typically, the influence of temperature, pressure, gas stoichiometry and humidity on the current-voltage curves are studied. Furthermore, the reaction to load changes as well as stability of operation under continuous load are investigated.

As indicated in the previous section, operation of fuel cells close to their limits requires a significant amount of controls and sensors. Furthermore, a safety interlock is required to prevent critical situations, e.g. in case of hydrogen leakage.

Fig. 3 shows an example of a simple test bench for PEFC-stacks designed for educational purposes. Control and monitoring functions are implemented in a programmable logic controller (PLC). The system includes mass flow controllers for hydrogen and air, an air humidifier, pressure control and a recirculation pump for hydrogen. Unattended operation is ensured by automatic refill of the humidifier and automaitc voltage monitoring. The test bench can be extended with single cell monitoring capability and additional mass flow controllers for CO_2, CO, or N_2.

Stack temperature control is achieved via a cooling loop using demineralized water. Low conductivity is maintained by an ion exchanger cartridge inside the cooling loop. Heat removal is achieved via a corrosion resistant heat exchanger.

The test bench is connected to an exhaust fan. Air flow and hydrogen concentration in the waste air are monitored during operation. A two stage alarm scheme is followed. In a first stage an acoustic alarm is activated when the air flow drops below a certain limit or the hydrogen concentration exceeds 20 % of the lower explosion limit. In the second stage the safety interlock is activated when the air flow drops further or the hydrogen concentration in the off gas exceeds 30% of the lower explosion limit. Further sensors can be added to the safety interlock.

The PLC allows fully automatic operation according to a specified parameter set. Standard startup and shutdown procedures are implemented. The bench also allows a complete manual operation of the fuel cell stack.

All relevant sensor data are displayed at the PLC operating panel. Additionaly, these data are provided as analog signals for further processing. Data acquisition and storage on a PC is possible via a special visualization tool dirctly connected to the PLC.

The test bench can handle PEFC stacks in a power range between 100 W and approximately 1 kW.

Optionally, a dc/ac inverter can be integrated into the system. This inverter has an efficiency above 85 %.

Such complete PEFC test systems will be manufactured and sold by ZSW. Several of these systems have been supplied to customers where tey are used e.g. in practical trainig of students.

Fig. 3: ZSW PEFC-test bench for educational purposes (1 kW)

Fuel Cell Test Equipment for Research Laboratories

Research laboratory fuel cell test equipment should also allow the operator flexibility in defining test operating conditions. The following requirements apply:

- Easy variation of operating parameters and test procedures
- High flexibility in parameter monitoring
- High flexibility in the definition of limit values
- High flexibility in gas compositions
- Definition of standard procedures
- Visualization of test results
- Test results stored in a database
- Customized reports of test results

Based on this set of requirements, a Laboratory PEFC-test system has been developed consisting of four main components:

- Stack testing system (STS) including gas and thermal management as well as the necessary safety features.
- Safety container
- Electric load system FCT
- System control FCT-600

Stack Test System STS

The test bench allows arbitrary mixing of anode and cathode gas compositions. Normally, hydrogen and nitrogen are provided to the anode from compressed gas storage. Gas flow is controlled by separate mass flow controllers for each gas. Up to five additional gasses (e.g. CO_2, CO, CH_4 etc.). can be added by separate mass flow controllers. The cathode is supplied with purified compressed air. Air feed is controlled by a mass flow controller. Optionally, additional media can be connected to the cathode. Pressure control is achieved by back pressure regulators installed after the exhaust gas cooler and dryer.

Normally, the gasses are fed in single pass where unused gas is not recovered. Optionally, recycling pumps for anode and cathode gasses can be included in order to operate the system under high total gas utilization at very homogeneous gas humidification.

Anode and cathode gas feed can be humidified. Normally, equilibrium humidification is achieved by feeding the gasses through bubblers held at a constant temperature by an electric heater. However, different humidifier options are available. The humidifiers are automatically refilled by high quality demineralized water. Humidified gas streams are led in heated tubing in order to avoid condensation losses.

Temperature control of the stack under test is achieved by a liquid cooling loop filled with distilled water. An ion exchanger cartridge is included in the temperature control loop in order to keep the conductivity below 0.1 μS/cm. For constant temperature operation under all load conditions, an electrical heater is included in the temperature control loop. Excess heat is removed via a heat exchanger into a secondary cooling loop. Media flow in the temperature control loop is measured by a flow sensor. Temperature sensors at the inlet and outlet of the stack allow for exact thermal balancing of the stack.

A picture of the STS is shown in Fig 4.

Basic functions of the STS are controlled by a programmable logic controller (PLC). This unit allows fast and precise control of all relevant parameters. All relevant data are displayed on a touchpad panel. Furthermore, the STS can be operated manually from this touchpad panel as well as automatically by the system control software FCT-600. The PLC also provides independent monitoring and safety features. Limiting values triggering an emergency shutdown procedure can be defined for all relevant parameters and sensor inputs. Furthermore, the PLC ensures a minimum gas flow even under extremely low load conditions.

Safety Container

Normally, the STS is operated inside a separately vented container. The venting system is explosion-proof. It ensures a 30 fold air change per hour. Gas valves outside the test container remain closed in case the air flow sensor in the exhaust pipe indicates low flow conditions. This procedure efficiently prevents the accumulation of potentially dangerous gas concentrations. Furthermore, the container is equipped with sensors monitoring the concentration of hydrogen, CO, CO_2 and oxygen in the atmosphere. Acoustical and optical signals indicate the buildup of potentially dangerous gas concentrations. As soon as a second limit is exceeded, the gas supply to the container is cut by an independent safety circuit. This procedure ensures safety inside the container without influencing testing activities outside the container. Optionally, a third alarm level can be defined cutting off the gas supply to the entire building.

Electronic Load System FCT

The Fuel Cell Test System incorporates a freely programmable electronic load required to simulate a wide range of potential fuel cell applications.

Depending upon the application the power section utilizes transistor-controlled, thyristor-controlled or a highly sophisticated converter with IGBT-technology. Dynamic features, input current ripple and harmonics should be considered when choosing the appropriate load to be connected to the stack.

Using the technologies described hereafter individually or combined the FCT can simulate the load profiles of a wide variety of. fuel cell applications.

Transistor technology

Using transistor-controlled current drains equipped with bipolar transistors or metal oxyd transistors (MOS-FET), harmonic free direct current with high slew rates can be provided.
Transistor-controlled drains are used for low power applications where the energy taken is converted into heat.

Thyristor-technology

Rectifiers using thyristor-technology are suited for applications with high voltages and high currents. The direct current contains ripple and harmonics. Subsequently, filters are used to reduce ripple and harmonics which may result in slower slew rates.
Thyristor technology allows energy feed back into the mains and are typically used in continuous load applications.

IGBT-technology

IGBT-technology provides high dynamic load changes at high voltage and high current levels, e.g. simulation of electric and hybrid vehicle.. IGBT is a combination of FET and bipolar transistors. The basic design is similar to thyristor-technology but provides the advantages of a full sine wave energy feed back and high efficiency.

A seperate controller per unit is embedded for accurate regulation and data acquisition. Control of additional inputs and outputs is available.

System Control FCT-600

The requirements of experimental operation requires multiple system control modes. When combined with the concept of two independent microprocessors manual operation and automatic operation are possible.

Set values and process data are transferred to and from a Pentium PC with Windows operating system.The communication between PC and the individual microprocessors is accomplished via a 4-wire communication line. Downloading the complete test program with all its regulator and load profiles to the individual microprocessors guarantees that the process can be continued safely even in case of a computer breakdown.

The operation depends substantially on the regulator profiles, load profiles and the system control. Regulator profiles contain the appropriate regulator settings for the stack test system where load profiles contain data to simulate standard load cycles or customized load algorithms. System control allows the combination of a variety of different profiles, sequentially.
Profiles are stored in a library and available for manual and automatic operation (see Fig.5). Profile parameters are also displayed clearly in a graphical schematic of the entire process (see Fig.6)

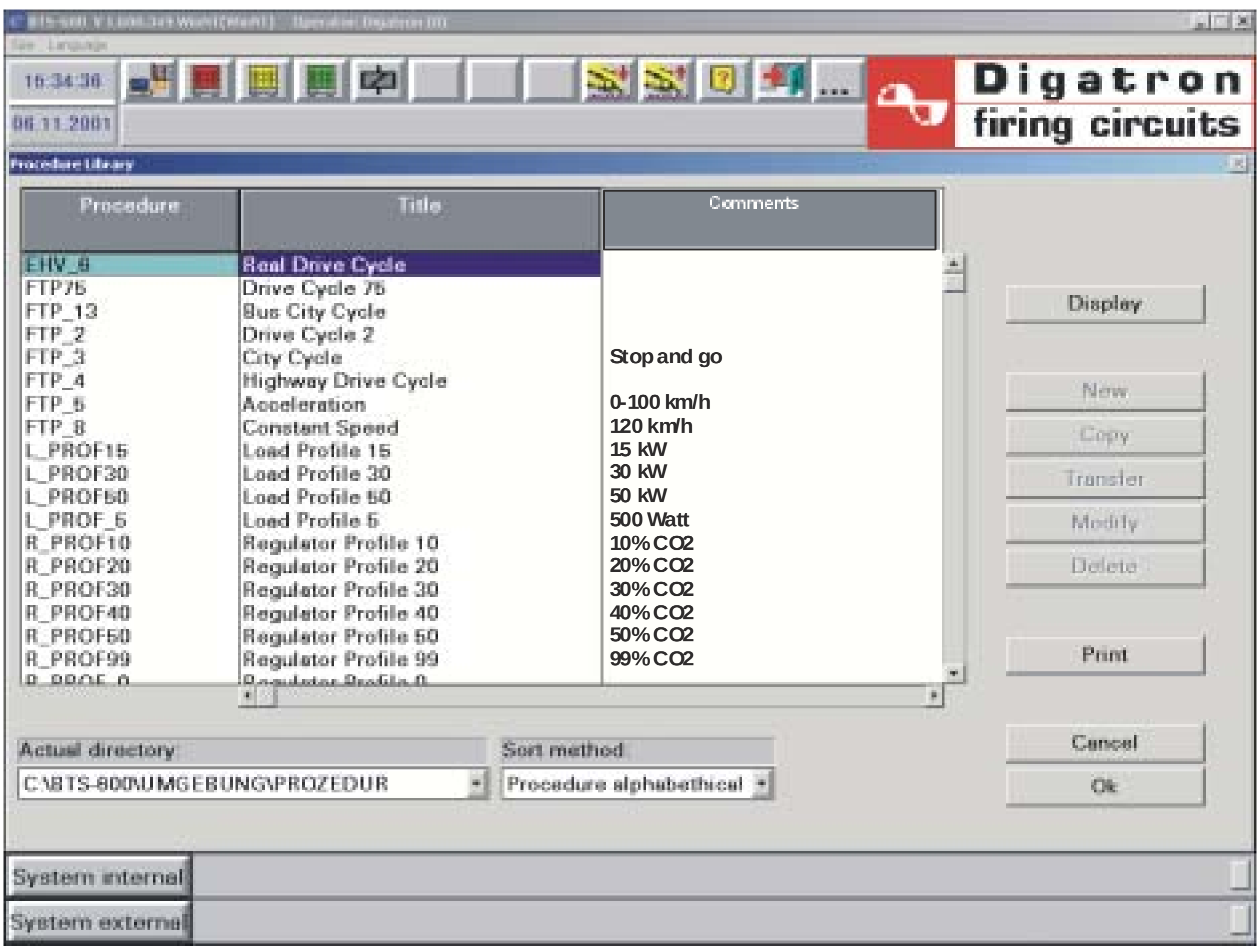

Fig.5: Profile Library

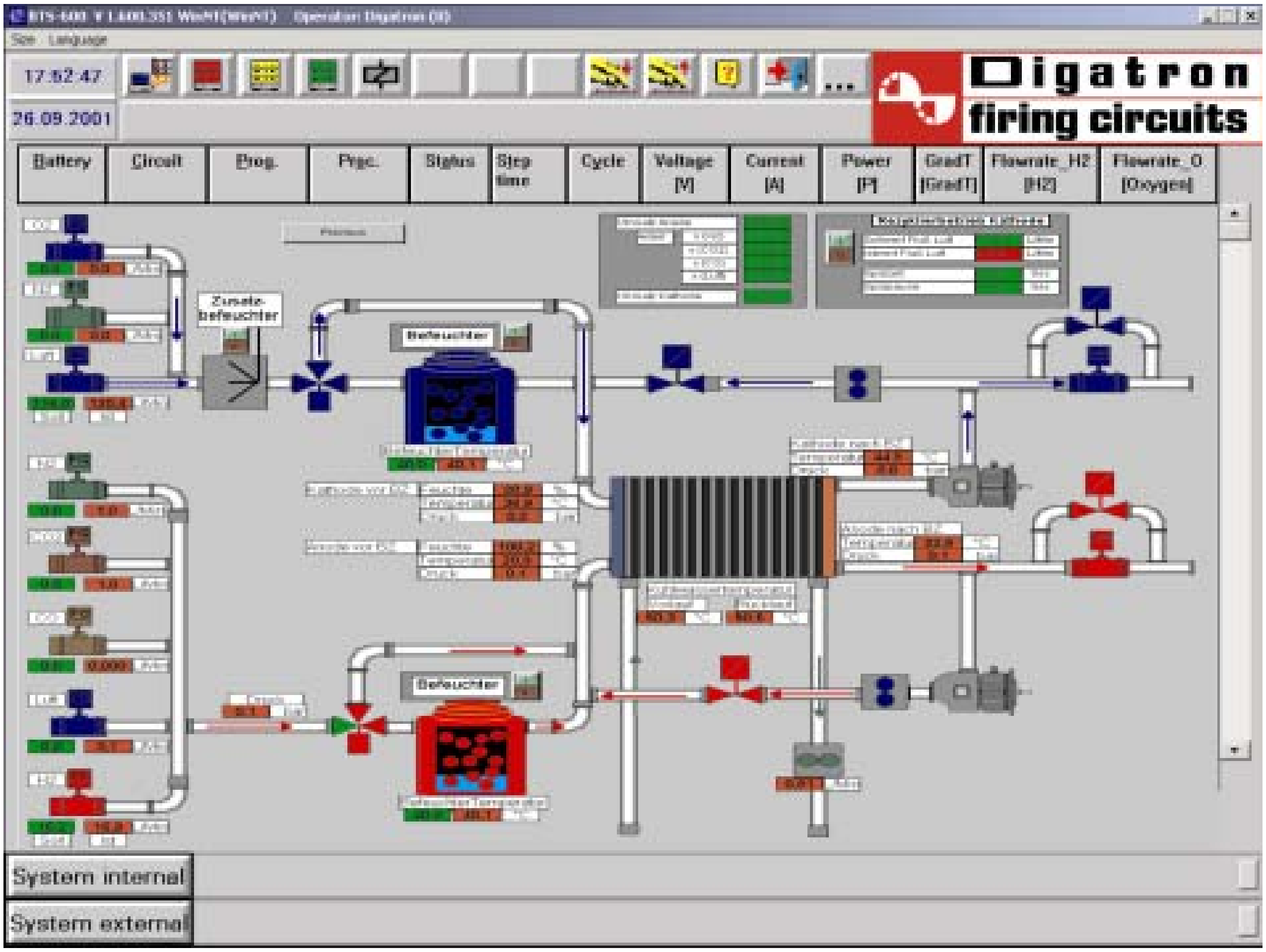

Fig.6: Graphical User Interface

In combination with the FCT-600 system control it is possible to create complex test procedures for almost any application in the field of fuel cell testing (see Fig.7). When used in conjunction with appropriate hardware, i.e. electronic load using IGBT technology, testing can be performed in compliance with standards such as FTP 75 load profile (see Fig. 8).

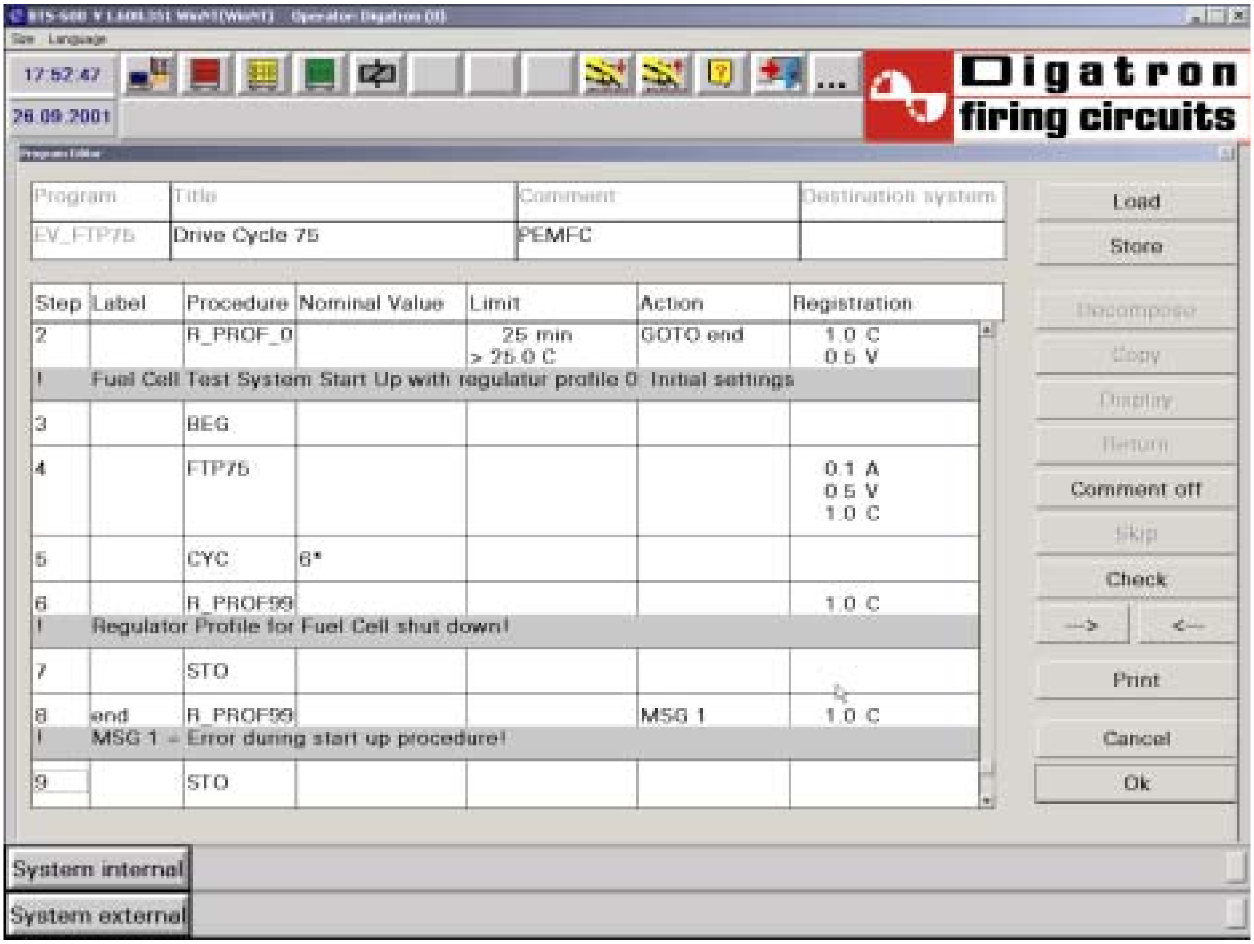

Fig. 7: Programm Editor

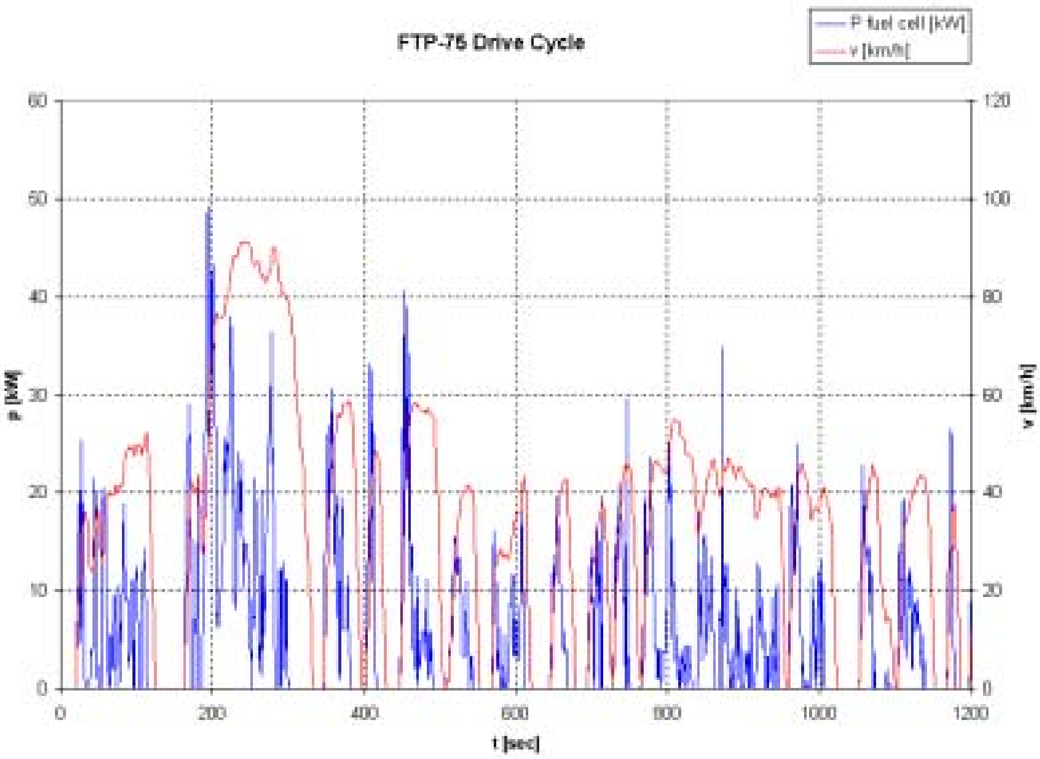

Fig. 8: FTP 75 Drive Cycle

Due to high speed data acquisition capabilities the voltages of single cells, high dynamic load changes, gas flow rates, temperatures and pressures can be captured. Each of those values can interrupt the test program at any time. In the same way that external limits can influence the test program run via digital inputs outputs can be activated by the program to switch on or off humidifiers or heaters.

Cycles within cycles make it easy to run any complex test against a range of current, voltage, power and resistance parameters. The FCT-600 Fuel Cell Test Software allows the creation of customised functions and their integration into the overall test program. Digatron/Firing-Circuits offers a detailed programming manual for experienced users to create their own extensions in Turbo Pascal. Less experienced users, however, should entrust these changes to Digatron/Firing-Circuits software specialists.

A number of special features have been included to make the evaluation of test results more user-friendly:

- Data export to ASCII, EXCEL, Dia-PC, etc.
- Programming with the fuel cell data or parameters
- Use of logical channels (i.e. calculated values, such as “Internal Resistance”, “Supplied Energy”) in the program.
- Creation of test processes with values from existing ASCII or EXCEL tables
- Prints of customised cycle reports during long term test program run
- Graphs with characteristic curves current/voltage, gas combinations, gas utilisation, etc..(see Fig. 9, Fig. 10)

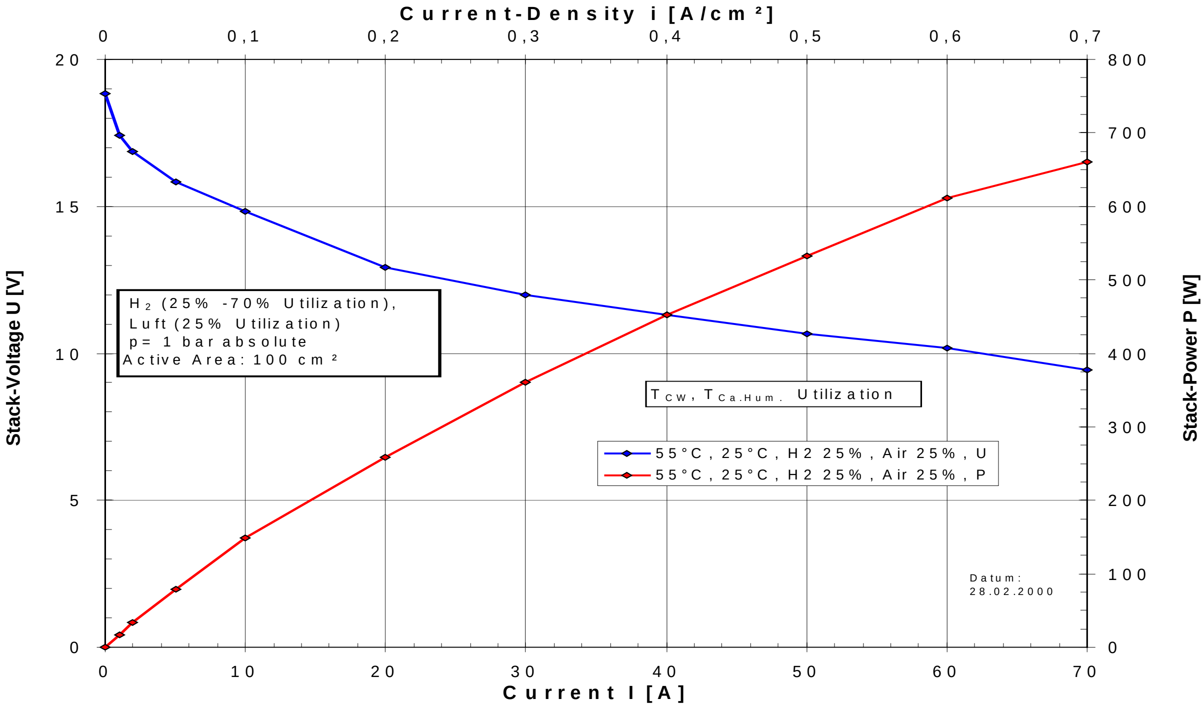

Fig. 9: Stack Voltage vs. Current

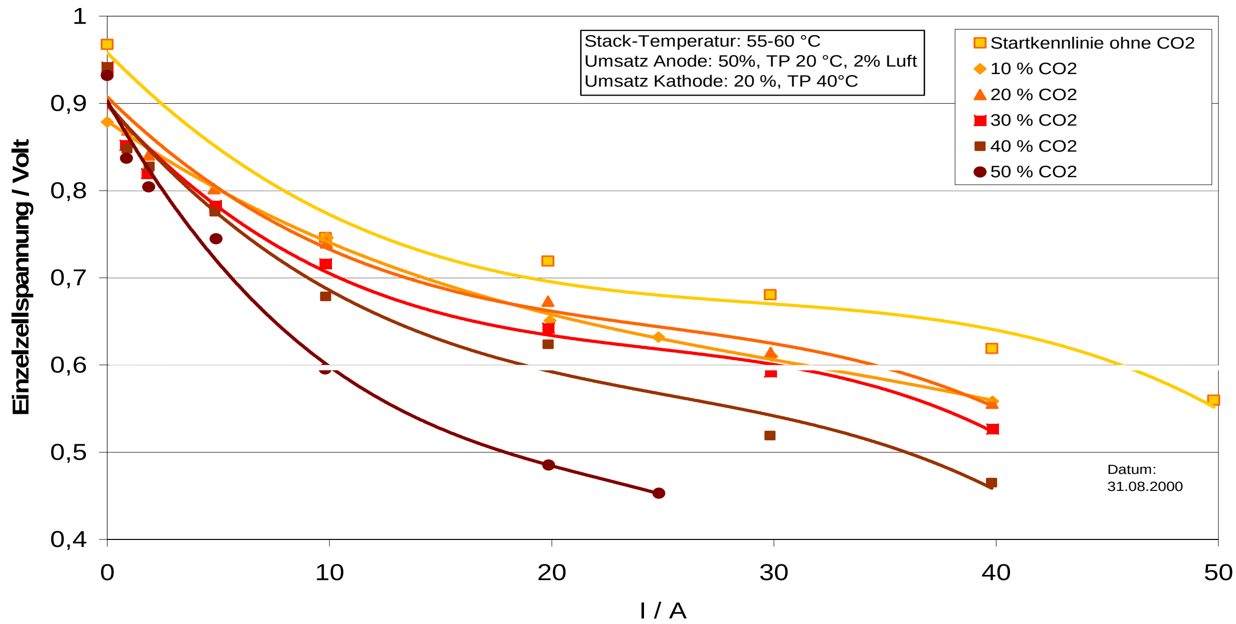

Fig. 10: Single Cell Voltage vs. Current using different CO_2 concentration

Test Setup

Automatic start-up including a self check procedure is provided by the system. Initially, the electronic load is disabled and the gas flow to the stack is bypassed.

Subsequently, a self test of the pressure control system is carried out at all relevant values of gas flow and pressure. Particular emphasis is given to conditions of high pressure at low overall gas flow and minimum pressure at high gas flow. Pressure variations caused by inappropriate time constants under these conditions must be minimized. Furthermore, the function of the gas humidifiers is checked. Additional tests are run on temperature, flow and pressure sensors.

The electronic load is enabled only after a successful self test of the STS. After detection of the “load ready” signal, gas flow to the stack is enabled.

Initial regulator profiles and set values for stack start-up defined in the library of FCT-600 are transferred to the PLC. Modification of regulator profiles and set values is possible at any time during the following test.

Fuel Cell Operation

The control concept, realised by FCT-600, provides quite unlimited flexibility. Gas handling and temperature control systems are controlled by regulator profiles. The regulator profiles accept set values from 0-100% of the parameter in question. Monitoring of global limits e.g. maximum flow rates of mass flow controllers prevents consequences of inadvertent entry errors in the test program.

The test procedure is defined by a sequence of load profile instructions which are then transferred to the electronic load. Appropriate gas flow is ensured by the PLC following the regulator profiles. System control can sequentially activate several regulator profiles influencing the gas handling system e.g. different regulator profiles can be used for cold start, highly dynamic or steady state operation and system shutdown.

Fuel Cell Test Center at ZSW

At ZSW, a fuel cell test center is established. Currently the following test benches for low temperature fuel cells such as AFC, PEFC and DMFC are available:

5 manually operated test benches for single cells and small stacks up to 500 W

2 test benches for PEFC up to 1 kW of the educational type described above equipped for H_2/air-operation

6 test benches of the professional type as shown above including
- 2 x 10 kW test benches,
- 2 x 3 kW test benches,
- 2 x 1 kW test benches.

These benches are equipped for operation under synthetic reformate (H_2, CO_2, CO, N_2, O_2/air-bleed, CH_4) in arbitrary mixtures. Cathode operation can be chosen from compressed air, pure oxygen and synthetic air.

1 DMFC test bench for single cells and short stacks

An additional 100 kW test bench will be installed in the year 2002. Furthermore, various methods of post test characterization of components are available. Additionally, a room for safety tests possibly leading to stack or system destruction will be available by end of 2002.

The following picture shows the gas infrastructure of the ZSW

Besides tests of fuel cell stacks and components, the test facility can also be used for the test of complete systems as well as components of the balance of plant (e.g. catalytic burners).

ZSW is offering these test capacities including well trained personnel for independent tests of fuel cell performance, endurance and safety.

Fig. 11: ZSW Buildings and fuel infrastructure (H_2, O_2, CO_2, N_2, CO, CH_3OH)