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THE DESIGN OF ALKALINE FUEL CELLS

K. STRASSER

Siemens AG, UB KWU, U9 261, Hammerbacherstrasse 12 + 14, P.O. Box 3220, D8520-Erlangen (F.R.G.)

Introduction

Since the beginning of the sixties different fuel cell systems have been investigated. They are characterized by using different

- Fuels
- Oxidants
- Electrolytes
- Catalysts
- Electrodes
- Cell design

Fuel cells with technical pure hydrogen or reformer gas as the fuel and oxygen or air as the oxidant are the most important. One of the different types — namely the low temperature fuel cell — may be applied as the electrical power source of a power storage system. This system is not suitable for power plant application, to which middle and high temperature fuel cells, *i.e.* PAFC, MCFC and SOFC are more adapted.

Low temperature fuel cells are cells with alkaline electrolyte and solid polymer electrolyte and have been approved as the electrical power supply in the U.S. Space programs Gemini and Apollo.

The following properties are advantageous:

- Overall efficiency is not limited by the Carnot factor
- Overall efficiency increases at part load
- Energy density is distinctly higher than that of the accumulator
- Series and parallel connections of the modules make good redundancy
- The fuel cell operates noiselessly, in the case of operating with technical pure reactants, without polluting gases, at low maintenance.

The typical principles of low temperature fuel cells

The operating principle of the low temperature fuel cell with mobile, alkaline electrolyte is shown Fig. 1. In the reaction hydrogen is oxidized at the anode, while oxygen is reduced at the cathode. The reaction products are water and heat, which dilute and heat up the liquid electrolyte and are removed from the cell by the electrolyte circulation. Usually 30% potassium hydroxide is used as the electrolyte.

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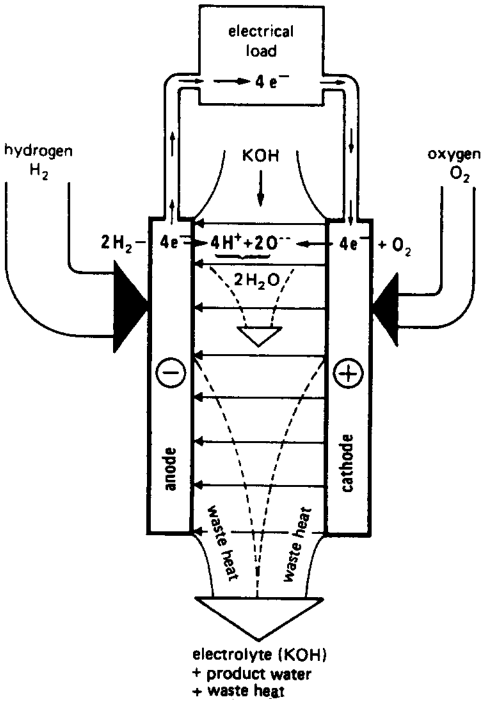


Fig. 1. Principle of the alkaline fuel cell with mobile electrolyte.

The principle of the second type of low temperature fuel cell, the alkaline fuel cell with base electrolyte is depicted in Fig. 2. In this case the electrolyte is based in a porous matrix for example in asbestos. The product water is removed from the cell by a hydrogen loop as water vapor, the waste heat by a coolant circulation. Using thin electrodes an additional porous sheet in the cell is necessary to store the product water during the heat up phase.

The principle of the third type of low temperature fuel cell, the PEM, fuel cell with polymer electrolyte, which is similar to the alkaline matrix cell, is shown in Fig. 3. The electrolyte of this cell is from a proton exchange material. Liquid water is produced at the cathode side and is removed from the cell by an oxygen loop or by static water management. Waste heat is directly removed by a coolant circulation.

The theoretical value of the cell voltage — dependent on the upper heat value of the hydrogen — amounts to 1.48 V. Measurable cell voltage at open circuit is a little higher than 1 V. As Fig. 4 shows, usable cell voltage decreases by increasing current, while voltage losses at low currents are caused primarily by the polarization of the cathode. At higher currents ohmic resistance increases and finally at high current, transport losses become significant. Usually transport losses at rated current may be neglected. Rated current depends on different operating conditions as well as on the fuel

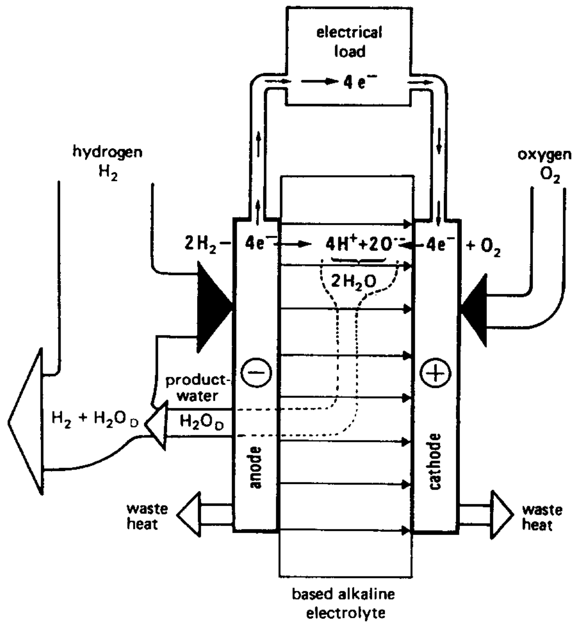


Fig. 2. Principle of alkaline matrix cell.

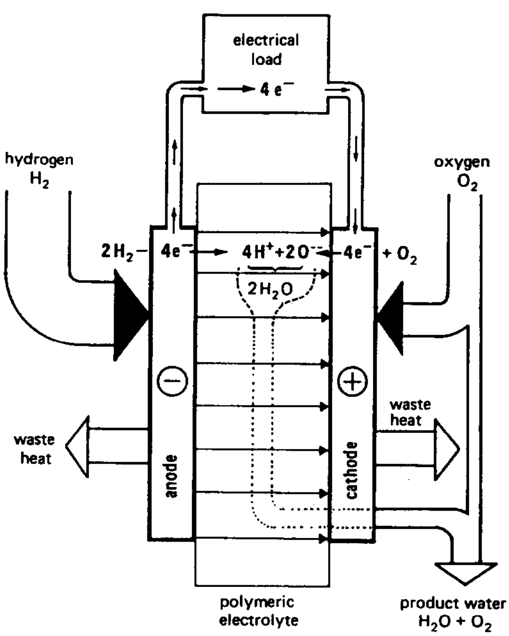


Fig. 3. Principle of the PEM fuel cell.

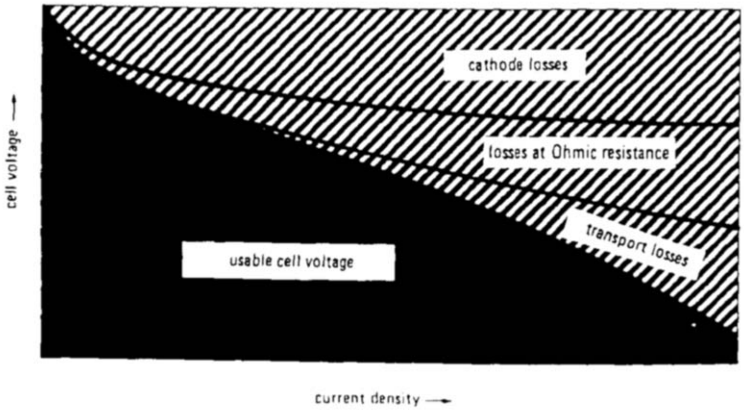


Fig. 4. Inner losses of cell voltage (schematic).

cell type, the electrode type or cell design. A current density of 0.5 A/cm^2 has been reached in complete fuel cell systems and more than 1.0 A/cm^2 in experimental cells.

Basic design of the fuel cell

Low temperature fuel cells are under development at different companies. Table 1 shows an overview of this activity.

An example of the basic design of the alkaline fuel cell with mobile electrolyte, as developed at Siemens, is shown in Fig. 5.

By the cell design the liquid electrolyte is separated from the gaseous reactants by asbestos diaphragms. The electrodes — anode from Raney-Nickel, cathode from doped silver — are connected uniformly to the electrolyte as well as to the current collecting side by pressing isostatically with pneumatic pressure cushions.

The active area of the cell is 340 cm^2. The single parts are sealed to each other by cementing as well as by an elastomer frame. The total network of the supplying channels is formed from the holes in the frames by mounting the stack.

At an operating temperature of 80 °C and a reactant pressure of about 2 bar a, the fuel cell can be loaded with a current density of 400 mA/cm^2 at ~0.8 V.

Figure 6 shows an expanded view of the cell.

The basic design of the Elenco fuel cell is not bipolar. It is edge-connected and stacks are assembled from modules.

Figure 7 shows an example of the matrix-type used at Siemens. The cell design is very similar to the cell with mobile electrolyte, as described. In principle there is no difference in the design of the matrix cell and the PEM cell. In Fig. 8 current voltage characteristics of Siemens fuel cells with a

TABLE 1

Current work on low temperature fuel cells

Type of fuel cell	Company	Application	Characteristics
Fuel cell with alkaline, mobile electrolyte	Siemens, F.R.G.	underwater application	H_2/O_2; about 2 bar a*; 80 °C Ni-anode/Ag-cathode
	Elenco, Belgium	electric vehicle (Bus)	H_2/air; low pressure anode and cathode with low Pt-loading
Fuel cell with alkaline matrix electrolyte	IFC, U.S.A.–Japan	space application	H_2/O_2; about 4 bar; 80 °C anode and cathode with high Pt-loading
	Siemens, F.R.G.	space	H_2/O_2; different conditions different electrode material
PEM fuel cell (for comparison)	Siemens, F.R.G.		H_2/O_2; about 2 bar a; 80 °C
	BTC, Canada		H_2/O_2; H_2/air; Methanol/air
	LANL, U.S.A.	different applications	H_2/O_2; H_2/air; Methanol/air
	GM, U.S.A.		Methanol/air
	Energenics, U.S.A.		H_2/O_2
	IFC, U.S.A.		Methanol/O_2

*a, absolute.

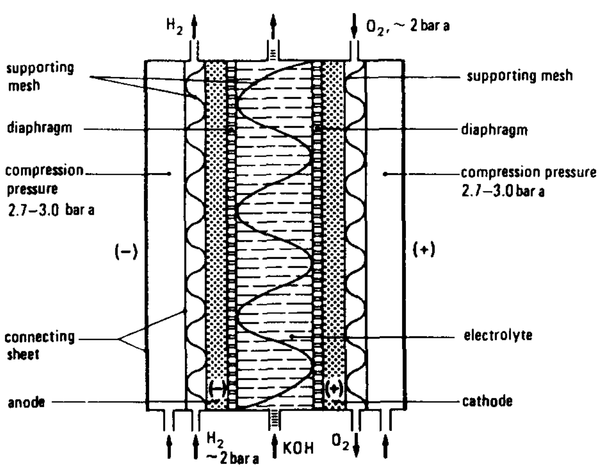


Fig. 5. Fuel cell with mobile electrolyte.

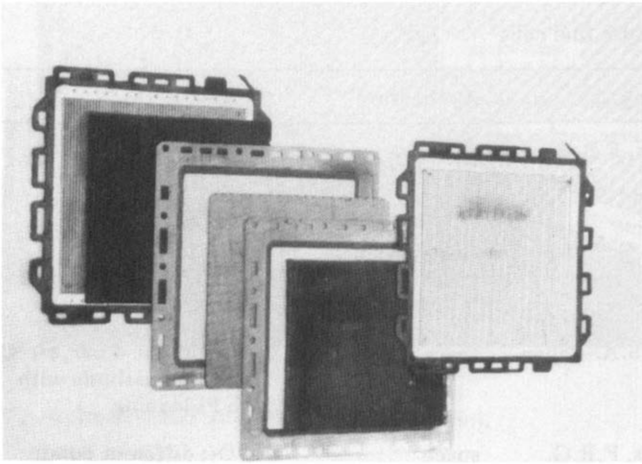


Fig. 6. Expanded view of the Siemens FC.

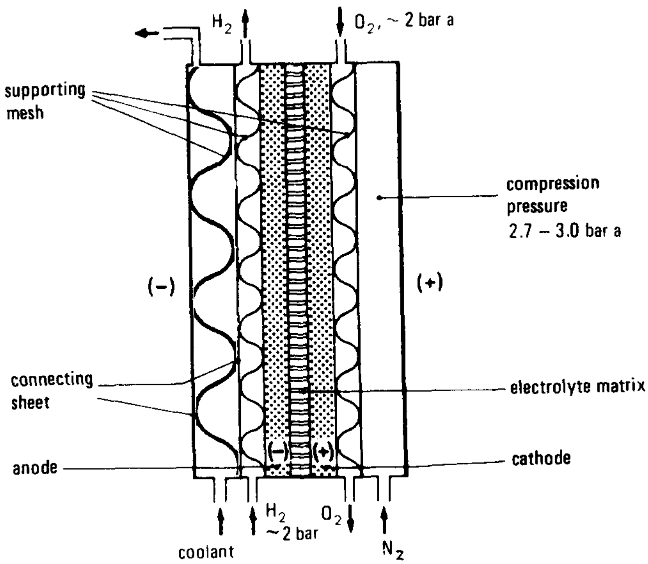


Fig. 7. Fuel cell with alkaline matrix electrolyte.

nickel anode and a silver cathode at different operating conditions are depicted.

The fuel cell system as developed at Siemens

To operate fuel cells, independent of the type, different components are necessary.

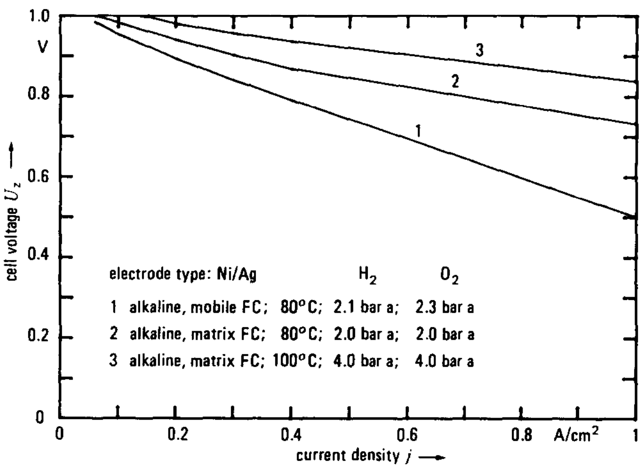


Fig. 8. Current voltage characteristics of Siemens fuel cells.

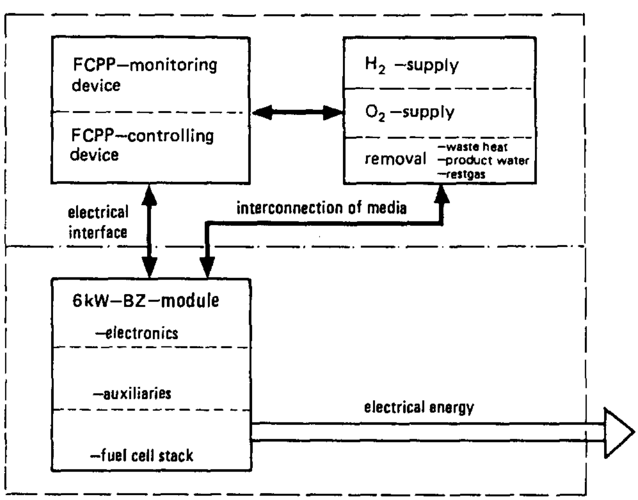


Fig. 9. Fuel cell power plant.

The main components of the system are shown in Fig. 9.

- Fuel cell modules
- H_2 supply
- O_2 supply
- Device for removing waste heat, product water and restgas
- Installation for controlling and monitoring

The main components of the FC system are connected at the electrical interface and the interconnection of the different media. Because of the modular design, the adaption of the fuel cell system to special requirements of the application is relatively simple.

The FC module

The FC module is assembled from a 60-celled FC stack, the electrolyte evaporator stack, the electromechanical and electronic control unit.

For stack operation auxiliaries are necessary, which have to be assigned to the FC module (Fig. 10). They envelop the following device for

- Supplying with H_2, O_2 and N_2 gas
- Removing product water and waste heat from the fuel cells via electrolyte circulation
- Separating product water and waste heat from the electrolyte by a slit-type evaporator
- Removing waste heat from the electrolyte evaporator by a coolant circulation

The FC module block is incorporated in a pressure tank. It is operated at 3 bar a with N_2 as a protecting atmosphere, preventing a mixture of reactants in the surroundings by leakages, and has to be supplied with defined static pressures for H_2, O_2, N_2 and coolant.

Figure 11 shows the technical data for the FC module at defined conditions, and the outline dimensions.

Removal of product water and heat

The principle applied in the electrolyte regenerator for water and heat removal is shown in Fig. 12. The spaces through which electrolyte flows alternate with those containing coolant. A gas-filled gap separates each electrolyte and coolant space. The electrolyte spaces are surrounded with asbestos diaphragms and the coolant spaces with thin, non-porous sheets.

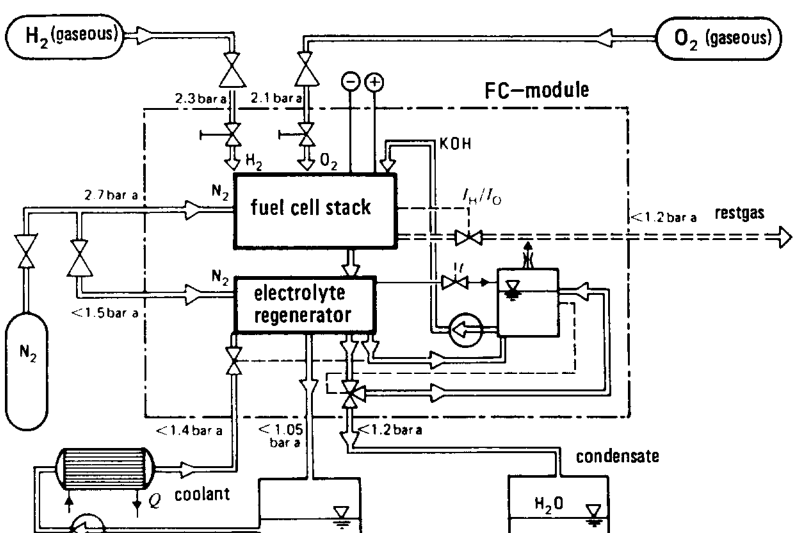
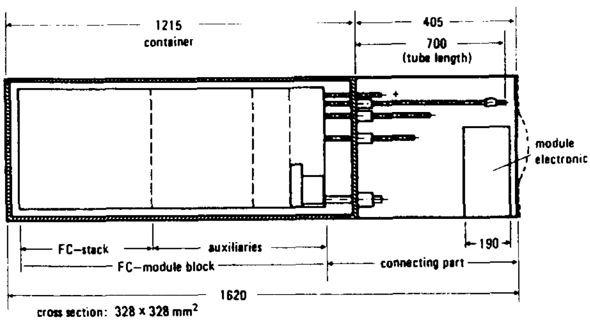


Fig. 10. Fuel cell power plant, consisting of the FC module, pressure gas bottles and coolant circulation.



power	6 kW
voltage	46–48 V
efficiency	61–63%
efficiency at ~20% load	71–72%
temperature	~80° C
H_2–pressure	2.3 bar a
O_2–pressure	2.1 bar a
dimensions	0.328 x 0.328 x 1.62 m^3
weight, total	215 kg
weight of the container	125 kg

Fig. 11. Technical data of the 6 kW FC module BZA 4-2.

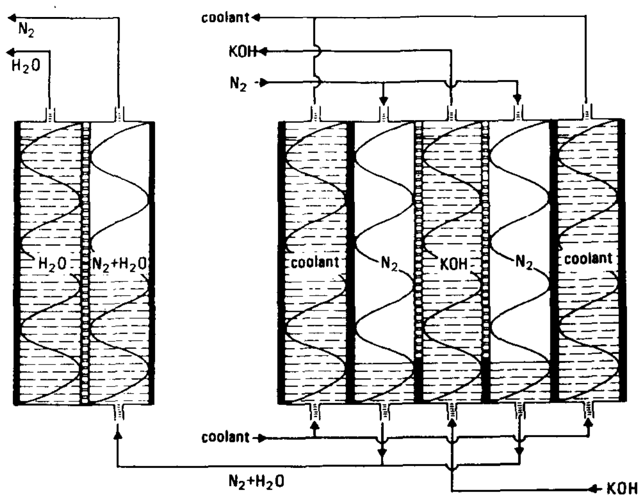


Fig. 12. Principle of the water and heat removal system in FC module BZA 4-2.

The product water is removed by evaporation and condensation, caused by the different water vapor partial pressures at the electrolyte-side and coolant-side surfaces. The static pressure in the gas gap and a pressure lock aid removing the condensate.

Removal of inert gas

The principle applied in removing inert gases from the fuel cell is depicted in Fig. 13. H_2 and O_2 are streamed through the FC stack in opposite directions in a cascading manner. Inert gases are collected in the last step of the cascading system. This is the gas space in a cell which is electrically connected in parallel with another cell, as shown in Fig. 14.

This configuration is responsible for the fact that the load current in a cell changes when the inert gas concentration in the gas space in the cell is increased. Current sensors record this deviation. An electronic device switches on a valve at the stack outlet, releasing the inert gases, when the current through the H_2 reference cell is decreased to 95%, and through the O_2 reference cell to 80%.

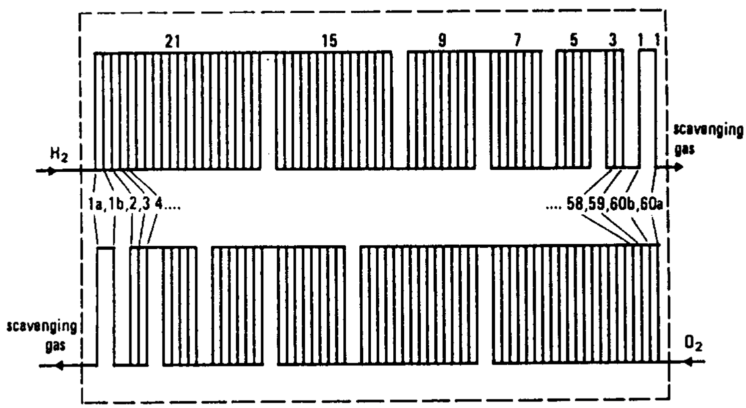
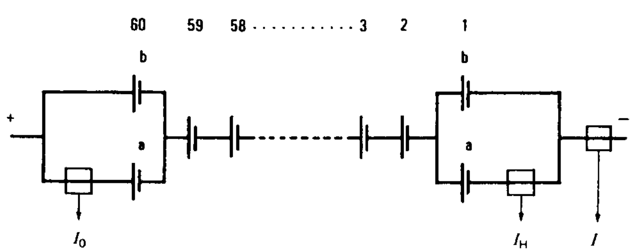


Fig. 13. Gas flow of H_2 and O_2 in FC module BZA 4-2.



purging conditions: O_2: $2 I_O / I = 0.80$

H_2: $2 I_H / I = 0.95$

Fig. 14. Electrical connection of the fuel cells and location of the current sensors for current controlled purge gas removal in FC module BZA 4-2.

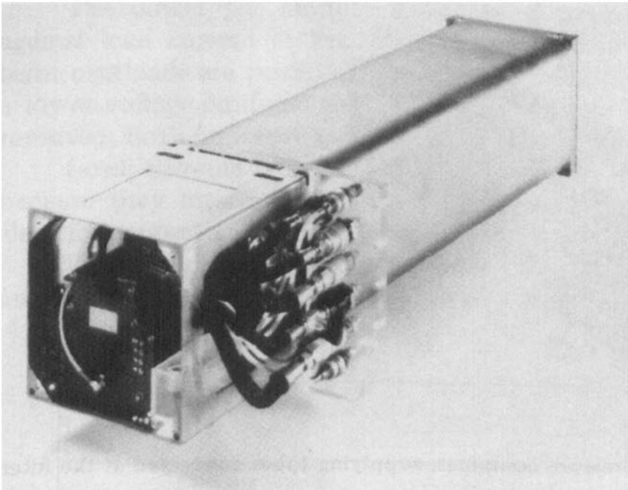


Fig. 15. FC module: 48 V, 125 A, 6 kW.

Controlling and monitoring device

Beside the four controlled functions

- Electrolyte temperature
- Electrolyte concentration
- H_2 inert gas removal
- O_2 inert gas removal

the following functions are monitored

- Module voltage
- H_2 pressure in the FC module
- Voltage of the H_2 reference cell
- Voltage of the O_2 reference cell
- Electrolyte temperature
- Electrolyte volume
- Electrolyte flow

The module is automatically shutdown when a monitoring circuit responds. Figure 15 shows a complete connected module.

The complete module with the pressure housing removed and the tubing also connected to the supply interface is shown in Fig. 16. For the FC stack in the background, which is the energy converter, only 15% of the total module volume is needed.

Operational behaviour and performance data

Static load behaviour

The operating behaviour at static or dynamic loading has been investigated for many FC modules. The measurements are related to more than

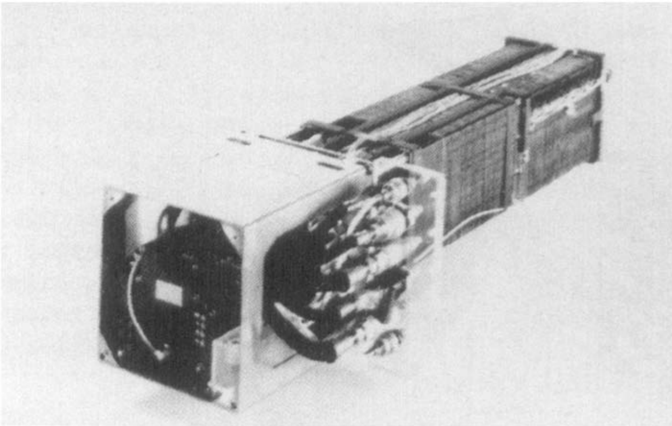


Fig. 16, FC module without pressure container, supplying tubes connected at the interface.

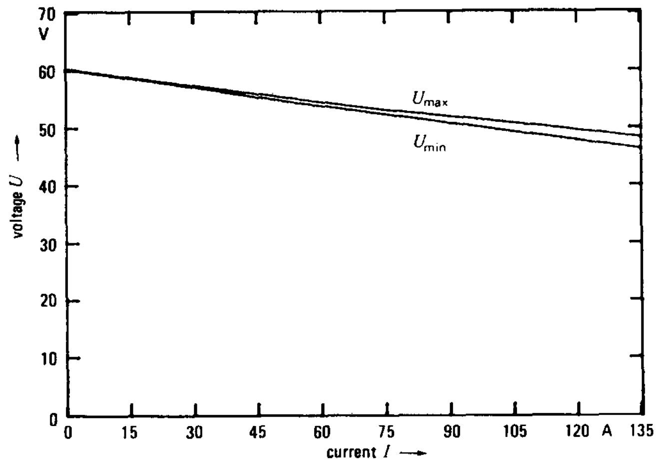


Fig. 17. Current/voltage characteristic at rated operating conditions after 100 h of operation in FC module BZA 4-2.

1000 cells of the above-mentioned type. A typical current/voltage characteristic of the FC module is shown in Fig. 17. At rated current 46 - 48 V are attainable.

The spread in mean cell voltage as a result of variation in electrolyte temperature and as-manufactured deviations lies between the U_{max} and U_{min} curves and is equal to about ±15 mV at a rated current of 135 A. Figure 18 shows the voltage of the individual fuel cells at rated current. The voltage in the outermost cells is higher than in the other cells because connection in parallel involves lower loads (see Fig. 14).

The power per module under rated operating conditions is plotted against load current in Fig. 19 and amounts to 6 kW rated power. Short-term overloads are possible. The magnitude of the load current is limited by a lower voltage limit and the duration of the overload by the amount of heat removed. Both limits are monitored within the module.

Load currents below 20 A are allowable for only limited time periods because they interfere with the removal of water from the cells and with electrical potential. No problems are encountered for time periods of 5 min.

The module can be operated with 'technical pure' gases, 99.5% oxygen and 99.95% hydrogen. The impurities are separated by the installed inert

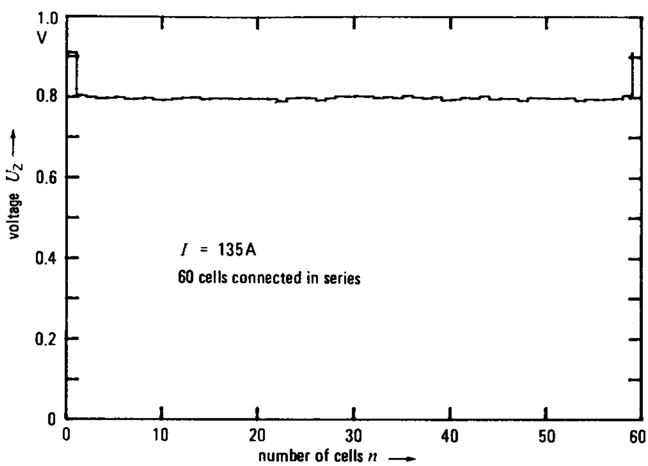


Fig. 18. Cell voltages at rated operating conditions in FC module BZA 4-2.

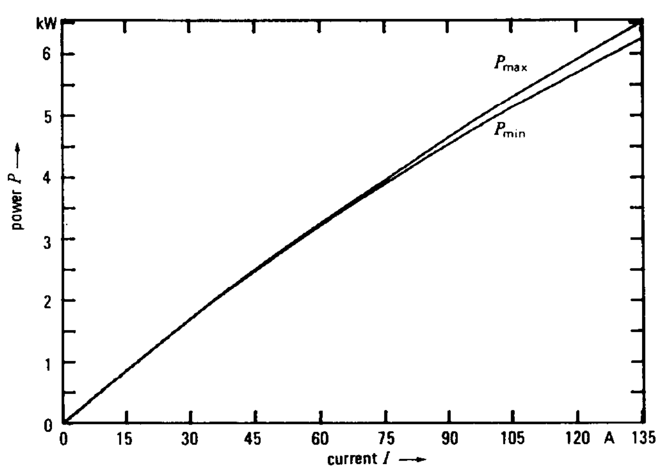


Fig. 19. Current/power diagram at rated operating conditions after 100 h of operation of FC module BZA 4-2.

removal system. About 80% of the rest gases are impurities of the reactants as shown in Fig. 20. This figure shows that this method is considerably more efficient than the others, especially when the attempt is made to get the largest possible amount of reactants to participate in the reaction and to have the smallest possible amount of residual gas left over. The curve of the overall efficiency, which corresponds to the static loading characteristic, is shown in Fig. 21. The efficiency is related to the lower heating value of the hydrogen. Only the power consumption of the coolant circulation has not been taken into account. The efficiency amounts to 61 - 63% at rated current and the maximum at part load to 71 - 72%. These numbers are nearly a factor of two higher than the efficiency of thermal engines.

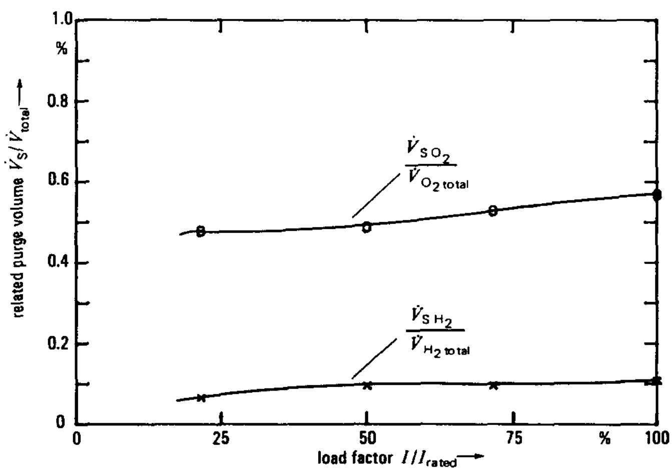


Fig. 20. Related purge volume as a function of the load factor of FC module BZA 4-2.

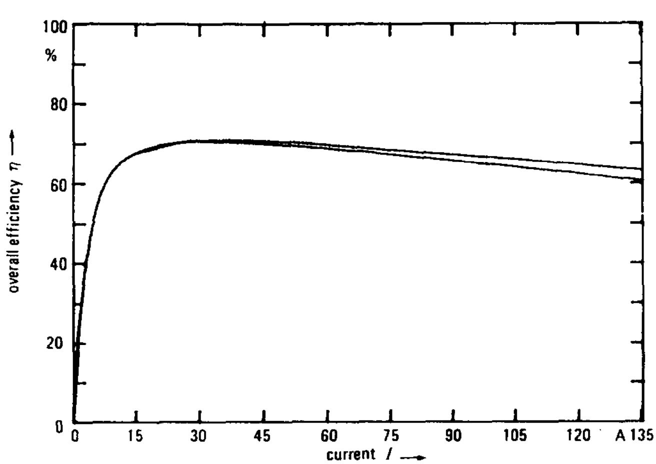


Fig. 21. Overall efficiencies after 100 h of operation of FC module BZA 4-2.

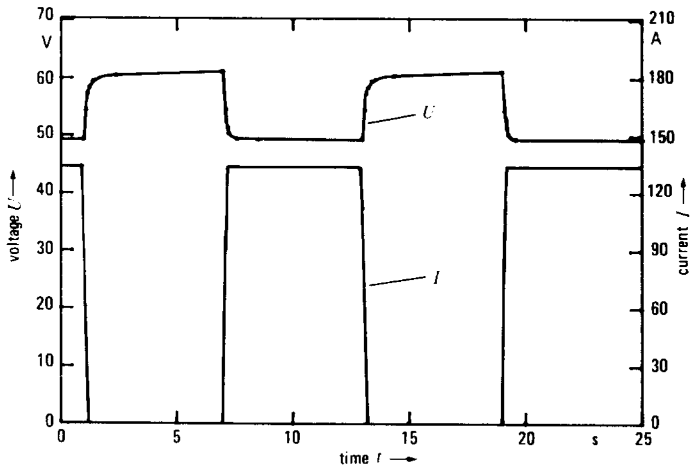


Fig. 22. Current and voltage behaviour under rated conditions of FC module BZA 4-2.

Dynamic load behaviour

As an energy converter out of operation the fuel cell module is without voltage. Regardless of the temperature of the module, it reaches the voltage dictated by the load current and electrolyte temperature within 5 s of being turned on. The increase in voltage is dependent only on the speed of gas exchange in the fuel cells. In principle, the fuel cell can be started up under load. During start-up time about 4 l of gas mixture (H_2/O_2) are blown into the residual gas system.

Using its own waste heat, it takes about 15 min at a constant module voltage of 48 V to heat up the module from room temperature to operating temperature of 80 °C. The lower the load, the longer the heating up phase. When the load current is altered, the module voltage follows the load spontaneously, *i.e.* in less than 100 ms (Fig. 22).

In the event of a short in the load circuit, the internal voltage monitoring function shuts down the module. Figure 23 shows a plot of current and voltage in the cell over time for this case. It can be seen from the plot that the maximum short circuit current is 1.300 A and the fade-out is about 1 s. The module can also be operated for up to 5 min when declined ±45° to the transverse or longitudinal axis. There is no time limit on operation when the module is tilted less than ±20°.

While switching off the module is disconnected from the load circuit, the O_2 supply interrupted and the energy stored in the fuel cells discharged across a 2 ohm resistor. Within about 25 s, the module is discharged to the point where the voltage remaining is less than 10% of the nominal. Upon shutdown about 10 l of gas mixture (H_2/O_2) are blown into the residual gas system.

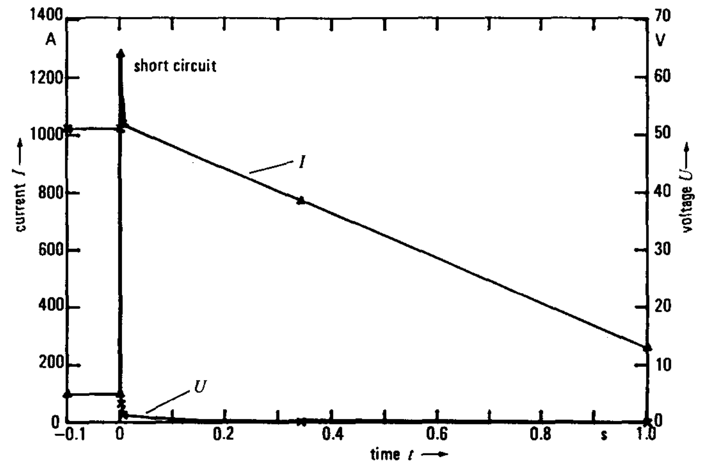


Fig. 23. Short circuit behaviour starting from 100 A at operating conditions of FC module BZA 4-2.

Demonstration of a FC system as a power source

To demonstrate and to investigate the function and the reliability of the FC system a power source was constructed, which consists of eight FC modules of the described 6 kW-type, mounted into a rack, the H_2 and O_2 supply and removal of the waste products and the central electrical installation. Total output of the power source is about 50 kW. Each set of four modules is connected in series, providing the required 192 V total voltage at about 250 A. The setup of the fuel cell power plant is shown in Fig. 24.

The modules are connected at the supply interface and are supplied in parallel. The overall electrical system controls and monitors the operation. Figure 25 shows the fuel cell power plant in test operation. The required data and the high system reliability were demonstrated during more than 20 000 h of accumulated module operation.

The time history of module voltage (Fig. 26) for 4 modules demonstrates how slowly the system deteriorates with operating time. Similar results were obtained in tests on cells over several thousand hours of operation.

The proper functioning and high reliability of the total power source of 100 kW was demonstrated during last year, when tests as a power source of an air independent propulsion system on a German submarine were carried out with very good results. The tests were finished in February of 1989.

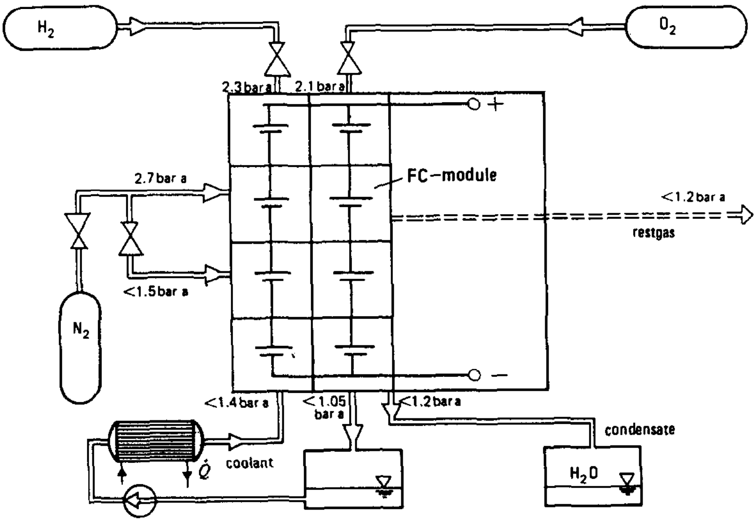


Fig. 24. Function schematic of FC system.

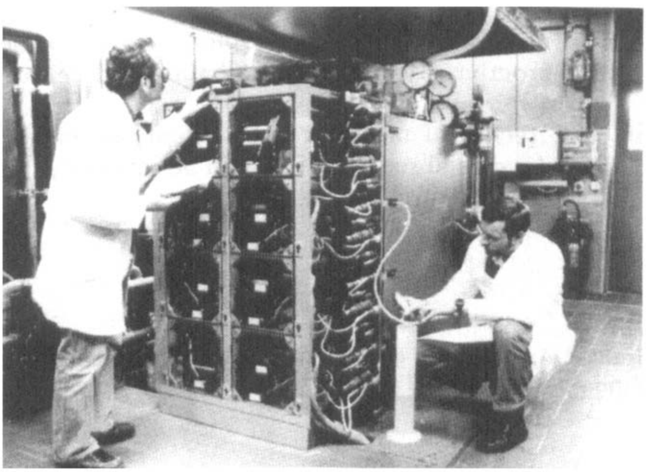


Fig. 25. FC unit consisting of 8 modules: 192 V, 250 A, 48 kW.

Conclusions

From the technical point of view alkaline fuel cells have proved satisfactory even with mobile and matrix electrolytes. The modular designed fuel cell system, as described by Siemens, made it possible to demonstrate its advantages in actual operation as the 100 kW power source for an air independent propulsion system. This may be the largest power source with alkaline fuel cells to date.

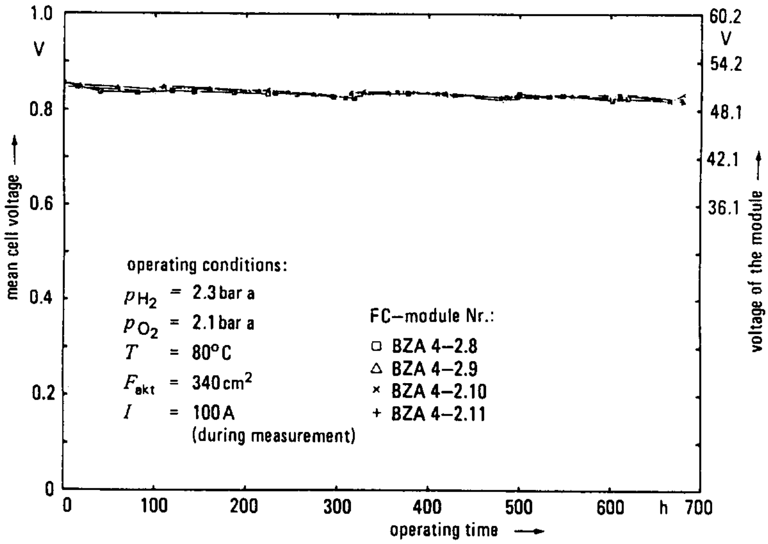


Fig. 26. Long term behaviour of FC module BZA 4-2.

On this basis, Siemens is now starting the development of a power source for the European space program. It will be an alkaline fuel cell of the matrix type.

The characteristics of cost, technical maturity and system advantages will permit broader application. As special requirements can be satisfied, the system may at first be applied in these special applications.

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