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Mobile fuel cell development at Siemens

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Abstract

Low temperature fuel cells with hydrogen and oxygen as the reactants are well-suited as a power source of an air-independent propulsion system in a submarine. Their higher energy density, noisless operation, absence of polluting gases and low waste heat as a consequence of the favourable efficiency are advantageous compared with convential systems. PEM fuel cells will be preferred for their overload capacity, low power degradation, long lifetime and the possibility to operate the fuel cell at different temperatures. Due to the fact that the PEM-FC can also be operated with CO_2-containing reactants and because of their considerable potential for increasing power, it is possible to construct energy storage systems with H_2/air fuel cells which can be used in electric cars or long-term storage facilities for regenerative energy systems. Depending on the storage capacity required, it is possible to obtain energy densities which clearly surpass those of high temperature electrochemical batteries like sodium/sulfur. Results of the current development will be reported and the application potential will be discussed.

Introduction

For many years, Siemens has been involved in the development of low-temperature fuel cells [1], particularly alkaline cells with mobile electrolyte and platinum-free electrodes (Fig. 1). The functionability of this system was demonstrated by the construction of a 100 kW system which was installed in submarine U1 of the German Federal Navy in 1987/88 and tested successfully by navy personnel between May 1988 and Feb. 1989. These activities were conducted by order of a consortium comprising German industrial firms. The experience gained with this system was of use for the construction of an electric vehicle by the Nuclear Power Center, Karlsruhe, in 1985, in which a hybrid power source with a lead/acid battery and a 17.5 kW alkaline FC system was installed, supplied with reactants from gas bottles. Alkaline fuel cell technology is now being used as the basis for the development of a fuel cell for the air-independent energy supply system of the European space shuttle Hermes which is scheduled to take its first flight in the second half of the nineties.

At the end of the seventies, the German Ministry of Defence had decided that in the event that the fuel cell has to be implemented as a power source for an air-independent propulsion system of a submarine, the PEM fuel cell would be preferred to the alkaline cell. Key factors in this decision were its high power availability and the absence of a corrosive liquid electrolyte. Other advantages which are well known and common to all fuel cell systems such as

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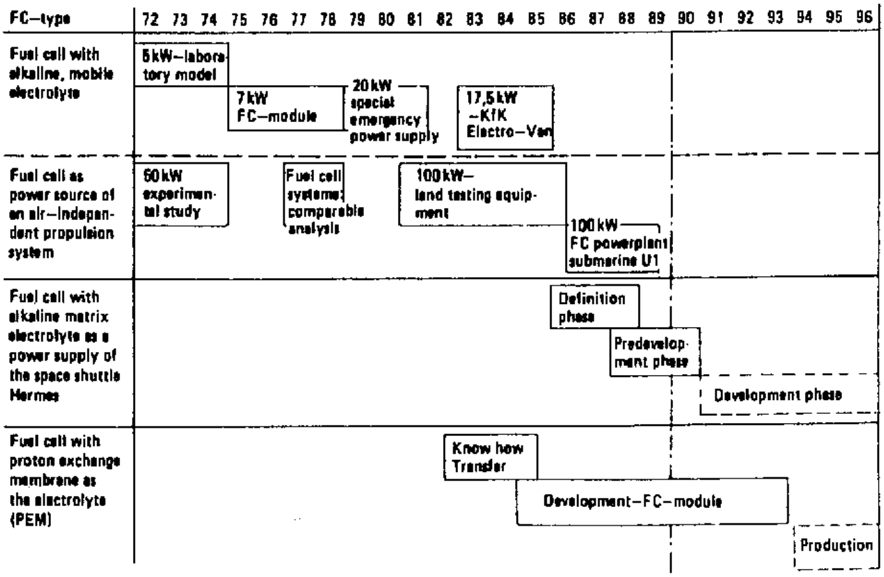

Fig. 1. Time schedule of Siemens fuel cell development.

- high conversion efficiency
- modular design which can be connected in series or parallel
- noisless reaction without polluting gases
- low maintenance

also apply to the PEM fuel cell. The fact that it is possible to operate the cell not only with technical grade hydrogen and oxygen, but also with hydrogen and air or reformer gas and air implies that there is a vast field of potential applications which would justify the high development costs.

Siemens is currently concentrating its activities in the field of PEM technology on the H_2/O_2 system to develop a power source for an air-independent propulsion system. The H_2/air system, which will be preferred for terrestial transportation application — for example in an electric car — was also investigated but to a much lesser extent.

Design and performance data of the PEM cell

The basic principles of the cell design are shown in Fig. 2. The two essential cell components are

- the membrane/electrode unit
- the cooling unit

The membrane/electrode unit consists of the polymeric electrolyte, the platinum electrodes and the carbon paper sheets on both surfaces. It is less than 1 mm thick.

The cooling unit supplies reactants to the membrane/electrode unit, removes reaction products from the cell and seals off the various media against each other and the outside.

Figure 3 shows typical characteristics of the cell for H_2/O_2 operation and H_2/air operation. The long-term behaviour of a similar cell was tested at a constant power density of about 540 mA/cm^2 over a period of nearly 20 000 h. Long-term tests in

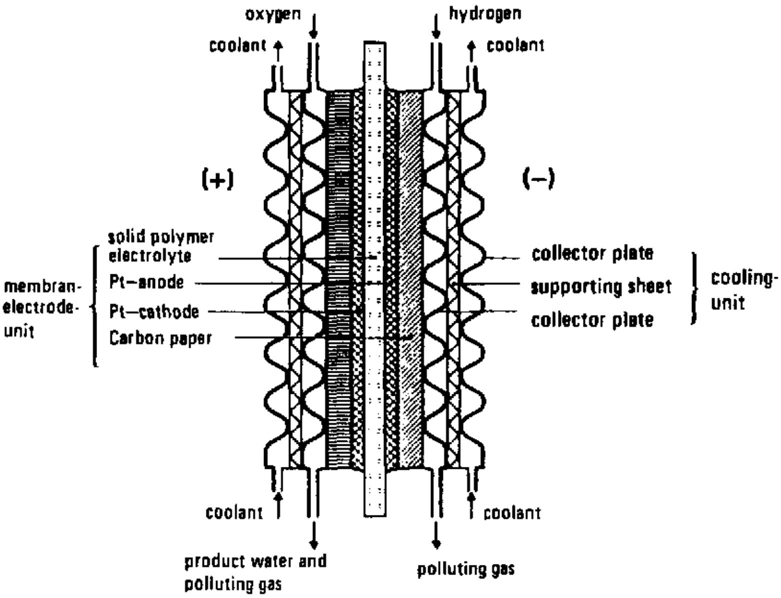

Fig. 2. Constructive features of PEM-FC.

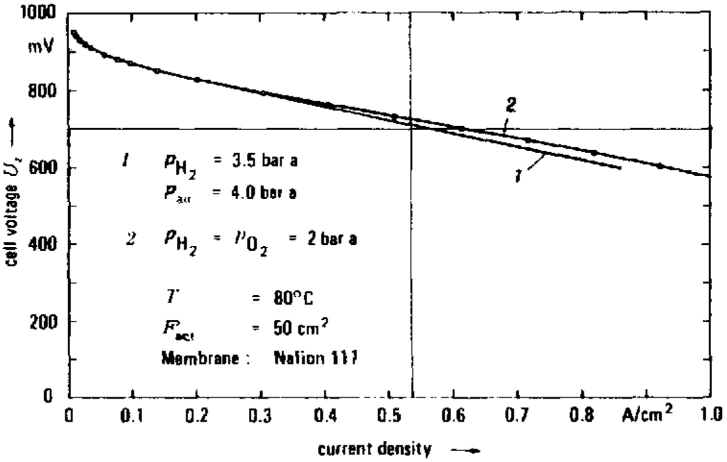

Fig. 3. Current/voltage characteristic of a test cell S III.1 (Standard).

the H_2/air mode have not yet been performed. In the O_2 mode, the characteristic is only slightly dependent on pressure whereas this dependency is considerably greater during air operation. No experience is available on cell operation using reformer gas. Due to the low polarisation of the anode it is expected that the impact on voltage will be insignificantly low. The well-known sensitivity of platinum electrodes to CO requires a high degree of gas purity or CO tolerant catalysts.

Storage system using H_2/O_2 and PEM technology

The H_2/O_2 fuel cell system is well suited as a power source of an air-independent propulsion system since it carries both the necessary hydrogen and oxygen. Thanks to its higher efficiency, the quantity of oxygen required for conversion in the fuel cell is only about half that required in combustion engines. Other advantages are the quiet operation and conversion of energy without changing the system weight. However, the power source does not only consist of electrochemical cells but constitutes a complex system with three main components

- fuel cell modules
- electrical system control and monitoring equipment
- fuel cell system peripherals

The interfaces between these three components can be precisely defined (Fig. 4). The fuel cell module can only be operated together with the other system components.

The fuel cell module (Fig. 5) consists of the fuel cell stack with a varying number of electrochemical cells, the humidifier, the separator for the removal of product water and the electrochemical and electronic control elements. The tasks of the auxiliary units are:

- H_2, O_2 and N_2 gas supply
- gas humidification
- removal of product water from the cells
- heat removal via a cooling system

Together with the auxiliary units, the fuel cell stack forms a module block which is installed in a pressurized container and operated in a protective gas atmosphere of 3.5 bar abs. Figure 6 shows a functional schematic of the module. A power source may comprise several of these modules which can be connected electrically either in series or in parallel as required. The control equipment must ensure that it is possible to maintain defined static pressures for all media at the inlet of the modules independent of load. If the monitoring system detects a fault and takes the faulted module out

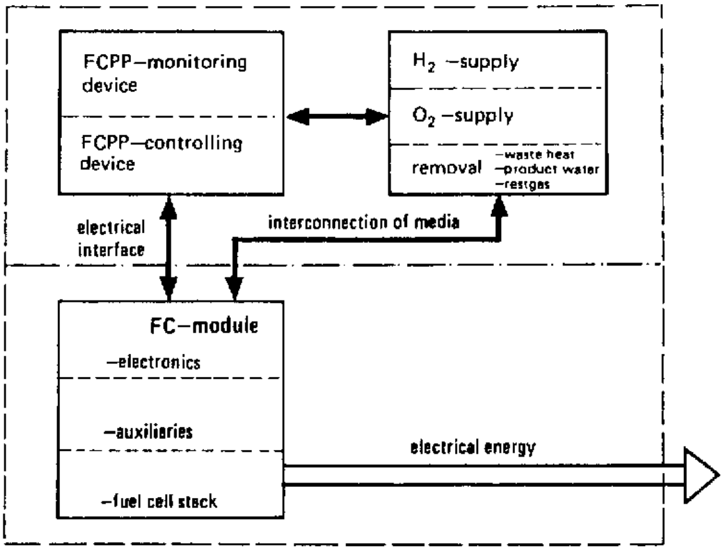

Fig. 4. Fuel cell power plant.

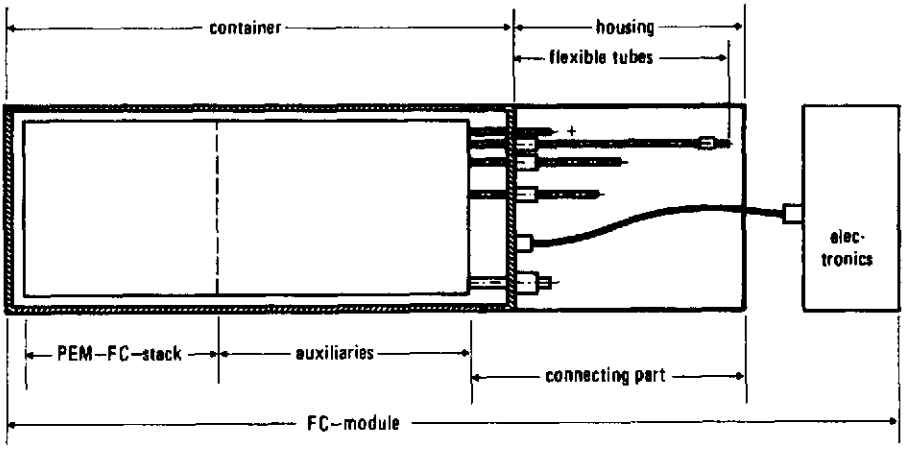

Fig. 5. Outline drawing of the fuel cell module.

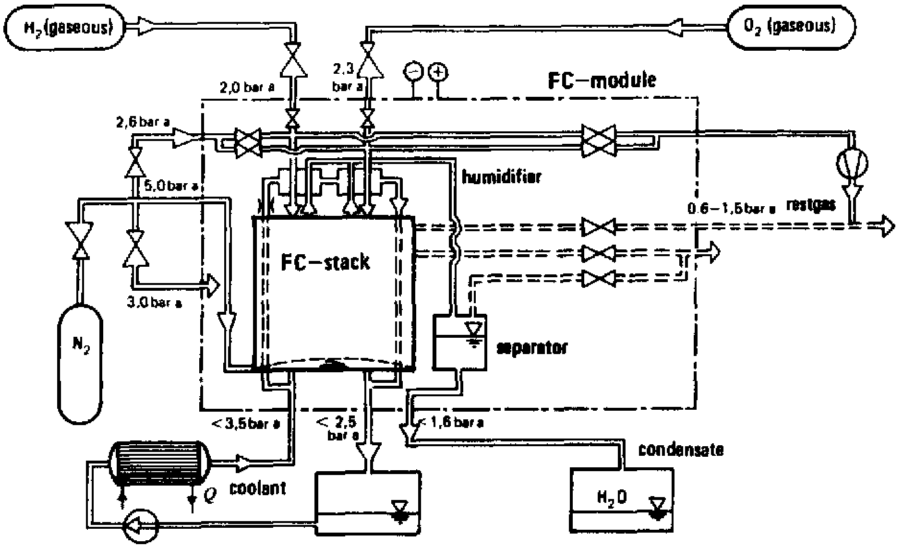

Fig. 6. Fuel cell module: functional schematic.

of operation, the current contained in it must be accepted by a free-wheeling diode (Fig. 7).

After laboratory tests of a large number of individual cells, fuel cell stacks comprising 4 cells and several fuel cell stacks comprising 10 to 20 cells [2, 3], during which an output of up to about 10 kW was reached, a fully integrated laboratory model was built as a further step. This PEM fuel cell module, the largest built to date, is now in the testing phase. Figure 8 shows the module block consisting of the 42-fuel cell stack, the humidifier, the separator, part of the electromechanical control elements and the media interface.

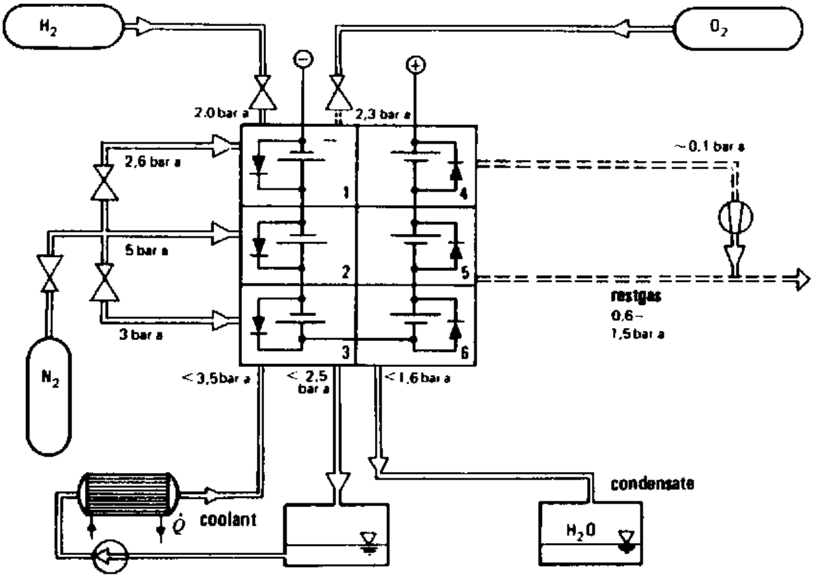

Fig. 7. Fuel cell power plant: functional schematic.

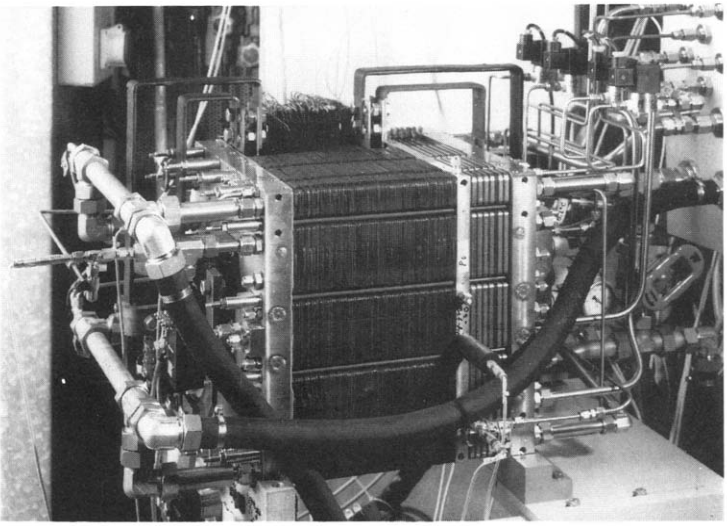

Fig. 8. 42-celled module block 20 kW-AV 1.3.

The current/voltage characteristic of an individual cell of this stack at rated operating conditions, i.e.

$p_{H_2} = 2.0 \pm 0.1$ bar abs.
$p_{O_2} = 2.3 \pm 0.1$ bar abs.
$T = 80$ °C
Membrane electrolyte: Nafion 117

about 100 h after initial start-up is shown in Fig. 9. At a rated load of 650 A, the cell reaches a voltage of 720 ± 10 mV. Figure 10 shows the performance of a 42-cell module block as a function of power current at a mean temperature of about 75 °C. The greater difference between the cooling water inlet and outlet temperature of the block which is due to the waste heat to be removed leads to a slight deviation of the curve from the curve given for 80 °C.

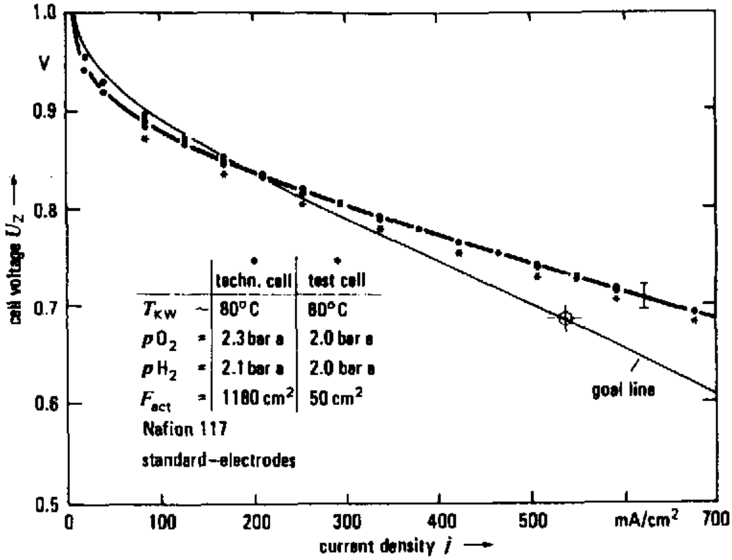

Fig. 9. PEM-FC: current/voltage characteristic.

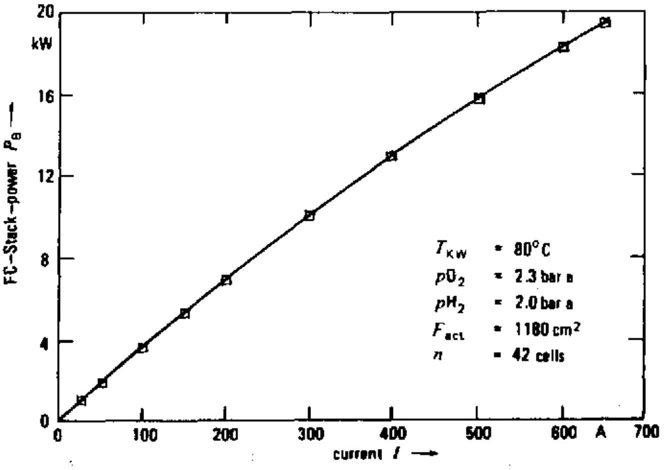

Fig. 10. Power as a function of the FC-stack–current (PEM-standard cell S II.4).

Potential for development

Various results of the development work completed to date have revealed properties of PEM fuel cell technology which make it interesting for other applications as well. These properties include:

- insensitivity to reactants containing CO_2
- great potential for increasing power
- optimum temperature and load change behaviour
- standby operation
- reversible operation

Operating with gases containing CO_2

As mentioned above, the PEM fuel cell is relatively insensitive to carbon dioxide gas contained in the reactants. As a consequence of a higher content of CO the power output is reduced [4]. However, output will begin rising again as soon as the cell is supplied with pure gases only. During air operation, the required air flow is roughly 2.5 times the stoichiometric O_2 volume. The power required for air compression causes a reduction in efficiency and has to be supplied by a special turbocharger. Compared to that of the combustion engine, however, its efficiency is still competitive.

Increasing power by using other electrolytes

The possibility of increasing output was investigated by installing different membrane electrolytes in technical cells while cell design and the fabrication process remained unchanged. The membrane electrolytes used were

- Nafion 117 manufactured by Du Pont
- Nafion 115 manufactured by Du Pont
- XUS-13.204.10 manufactured by Dow Chemical

The current/voltage characteristics and the power characteristics were measured under rated operating conditions in the H_2/O_2 mode and the results obtained are shown in Fig. 11. Relative to a constant cell voltage of 0.7 V, the following load currents and cell power outputs were achieved

Nafion 117	750 A/525 W
Nafion 115	1100 A/770 W
XUS-13.204	1500 A/1050 W

This means that it is possible to double the output by using other electrolytes. Similar results may be also achieved at fuel cell operation using impure gases but different operating conditions.

Temperature and load changing behavior

The excellent load changing behaviour of the PEM fuel cell is well known. For its use in storage systems, periodic operation comprising heating and cooling phases is of particular interest. For this reason, several cells were subjected to a temperature cycle test during which the cells were operated for 3 h followed by a shutdown period of 3 h. During the shutdown period, the cells were cooled to about 30 °C. Operation began at full rated load which was held constant during the operational phases. The test results are shown in Fig. 12. Over a period of about 300 cycles, no impact on the functionability of the cells was detected.

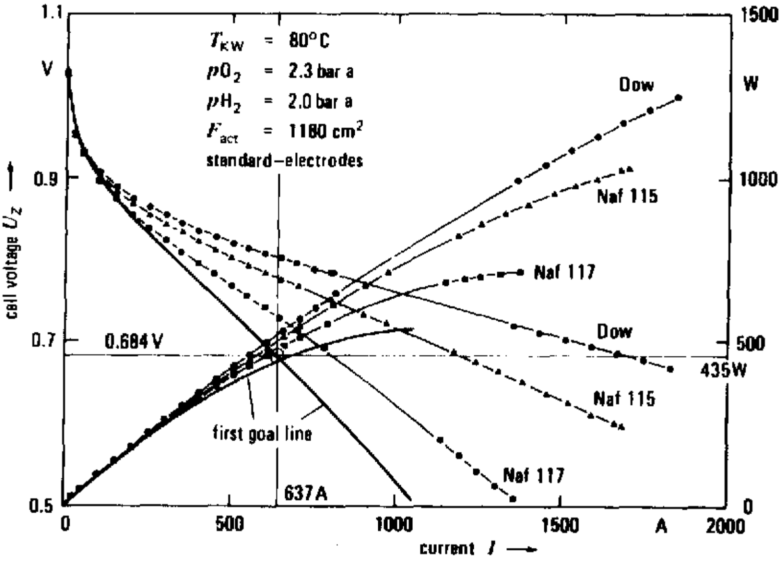

Fig. 11. Progress in increasing power of PEM-fuel cells by using different electrolytes.

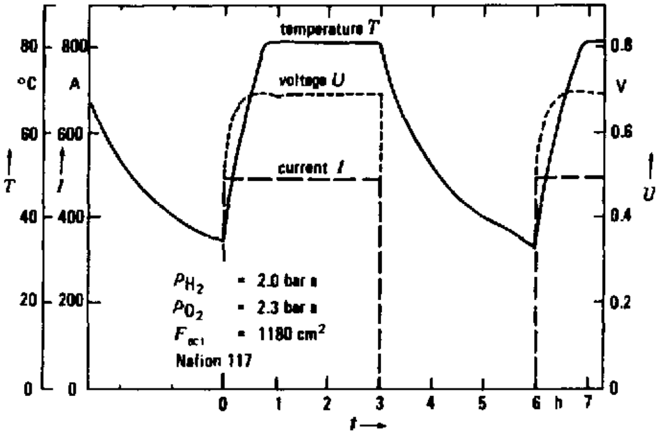

Fig. 12. Cell voltage, current and temperature as a function of operating time (temperature cycling).

Standby operation

Standby operation of the PEM fuel cell cannot be ruled out by certain limiting factors. Long-term tests without load have been performed during hundreds of hours. Tests have already been carried out over a relatively long period at about 3% rated load, however. This mode of operation is of particular importance for storage system applications in special emergency power supply systems or in a power source of an electric car. The relatively brief zero load periods in power sources for propulsion systems do not cause problems.

Reversible operation

If, for example, the hydrogen of a power source equipped with PEM fuel cells is supplied from metallic hydride storage, the possibility of recharging the system with current electrolyser is of particular interest.

If it were possible to operate the fuel cell also as an electrolysis cell, the electrolyser would no longer be necessary as a separate device. The problems encountered to date are primarily material problems for which, however, solutions might be found.

Possible applications (market potential)

As long as the application of the PEM fuel cell technology is restricted to air-independent operation in submarines or aerospace vehicles, cost reductions cannot be expected due to the small market volume. However, the technical characteristics of the PEM fuel cell as well as the increasing awareness of today's ecological problems are favorable prerequisites for a wider use, particularly as a

- power source for electric vehicles
- component of a long-term storage system in regenerative energy systems
- storage facility in special emergency power supply systems

The introduction and widespread use of electric vehicles adheres largely on the technical properties of the power source as well as on more stringent legal requirements imposed on conventional vehicles. As shown in Fig. 13, the energy density of a new PEM fuel cell power source with metal hydride storage and air operation is by all means comparable to a modern Na/S high-temperature battery. The latter's disadvantages such as thermal losses and high operating temperature are not relevant here. The larger the amount of energy stored, the more favorable the comparison becomes for the fuel cell [5].

Combining the PEM-electrolyser and the PEM-FC with a hydrogen storage tank as a long-term storage system opens up the possibility of refilling the vehicle tank and makes this solution interesting for users.

In consideration of the technical possibilities and the market potential, it would be more impressive and more convenient for comparison with conventional technologies, to demonstrate the behaviour of the new power source in an existing vehicle. For this

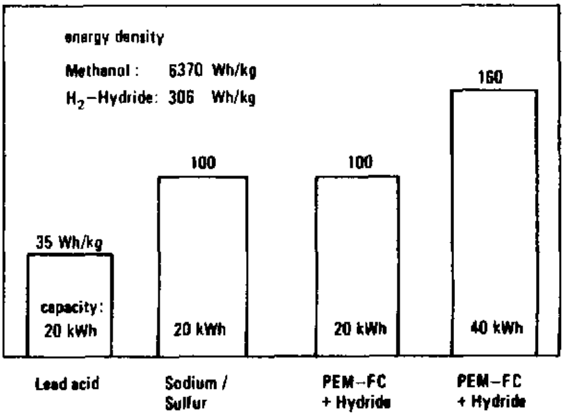

Fig. 13. Energy density of different storage systems.

TABLE 1

Advantages of the PEM-FC system as a power source of propulsion systems

High power density
High overloading capacity (no battery needed)
Water removal system independent of operating temperature
No energy losses during shutdown periods
Storage time unlimited
Low sensitivity to CO_2-containing gases
Operation with oxygen or air
Low maintenance
Long lifetime
Increasing efficiency at part load
Zero load possible
Waste heat for heating purposes

purpose Siemens has proposed a conceptual design of such a power source to Solar Wasserstoff Bayern, a Germany company, to demonstrate the PEM-FC in a forklift truck. The project will not start before the year 1994.

Without any doubt the application of the PEM-FC with hydride storage in an electric car would be more advantageous compared to other technologies, because of its characteristic behaviour, shown in Table 1.

An extensive market would have to be available for this technology to justify the considerably high development costs which will limit demonstration of this technology to pilot plants in the next decade. Due to its contribution to keeping our environment clean, however, this effort must be considered an investment for the future.

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