

# Solar Hydrogen Project at Neunburg vorm Wald, Germany

**SWB**  
A member of the  
Bayernwerk Group



## Field of Solar Hydrogen

Fuel Cell No. 6

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## Test operation of phosphoric acid fuel cell plants

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### Abstract

After overcoming major start-up problems [1], guarantee test runs were successfully completed in February 1993 on the phosphoric acid fuel cell plant (79 kW<sub>dc</sub>, 42 kW<sub>th</sub>) installed at the SWB solar hydrogen facility at Neunburg vorm Wald, Germany. The fuel cell plant comprises a fuel cell, a steam reformer with CO shift converter, and a pressure-swing adsorption unit. This article describes the fuel cell plant in detail. The most significant results of the guarantee test runs and specific knowledge derived from operation up to August 1994 are reported.

The fuel cell plant described in this article was set up for testing within a solar hydrogen demonstration facility. In designing the plant, efforts were undertaken to incorporate an extensive variety of operating capabilities. Accordingly, we are not concerned here with a commercial containerised production unit but with an experimental plant installed for test purposes.

### 1. Introduction

Solar-Wasserstoff-Bayern GmbH (SWB), a joint venture established in late 1986 by Bayernwerk AG (60 % of shares) together with BMW INTEC Beteiligungs GmbH, DASA, Linde AG and Siemens AG (each holding 10 % of shares), has built, currently operates and is now extending a demonstration facility at Neunburg vorm Wald in eastern Bavaria, Germany, for commercial-scale testing under industrial conditions of the interaction of major system components for energy supply based on hydrogen as an energy medium [2]. Most of the equipment installed at the facility is of a prototype nature. The project was created as a long-term scheme, split into several phases. Total budget of Phase 1 (1987 - 1991) was about DM 64 million (or US \$ 40 million); Phase 2 (1992 - 1996) is calculated to be worth another DM 69

million (or US \$ 43 million) expenditure. Grants of 35 and 15 %, respectively, were contributed by the German Federal Government and Bavarian State Government to the costs qualifying for public sponsorship.

Plant subsystems implemented in Phase 1 are:

- Solar generators employing monocrystalline and polycrystalline silicon technology (266.2 kW<sub>p</sub> in total)
- Electric power conditioning units (DC/DC converters, DC busbar, electrolysis power supplies, converters, AC busbar, hybrid system, DC/AC converters)
- Advanced low-pressure water electrolyzers, alkaline and membrane type, respectively (211 kW<sub>el</sub> in total)
- Hydrogen/oxygen gas systems
- Two gas-fired heating boilers using different fuel oxidisers alternatively oxygen and air (20 kW<sub>th</sub> each)
- Two fuel cell plants 6.5 kW<sub>el</sub> AFC, and 79 kW<sub>el</sub>, 42 kW<sub>th</sub> PAFC technology
- Filling station to fuel test cars with liquid hydrogen

In the actual Phase 2 the following systems are already installed and envisaged respectively:

- State-of-the-art solar generators employing different technologies, such as amorphous silicon, advanced monocrystalline structures and an improved polycrystalline structure (92.5 kW<sub>p</sub> in total). Associate electric power conditioning. Alternative module supports (guy rope system; manual adjustment of angle position)
- Alkaline pressurised electrolyser, 30 bar, 100 kW<sub>el</sub>.
- Fuel cell plant (PEMFC, polymer electrolyte membrane technology, 10 kW<sub>el</sub>) running on ambient air as oxidiser with scheduled mobile application in an electric fork lift truck
- Catalytic heater (10 kW<sub>th</sub>) burning natural gas and mixed natural gas/hydrogen with air as oxidiser
- Absorption-type refrigeration unit with catalytic burner (refrigeration capacity 16.6 kW<sub>th</sub>), hydrogen fuelled with air as oxidiser
- Optimisation of the existing LH<sub>2</sub> filling station to reduce vehicle fuel tank filling time; additional safety-related devices. Comparative testing of two clean-break coupling systems. Fueling of test vehicles.

## 2. Design and operation of the fuel cell plant

### 2.1 Fuel cell

This section briefly outlines the design of the fuel cell. Each single cell (Fig. 1) consists of a hydrogen electrode, a matrix holding the phosphoric acid electrolyte, an air electrode, and a separator between the air and hydrogen electrodes. Hydrogen and air pass through the grooves of the respective electrodes. H<sup>+</sup> ions formed at the anode (hydrogen side) migrate through the electrolyte to the cathode (air side). Simultaneously, electrons leave the anode and flow through a metallic lead to an external electrical load and then to the cathode. There the electrons react with the oxygen of the air and the H<sup>+</sup> ions to form water. The reaction takes place at a pressure close to atmospheric. The complete stack is made up of 192 single cells. Cooling plates are integrated between pairs of separators at set intervals. Deionised water used as the coolant flows through thin tubes inserted in the cooling plates and undergoes partial evaporation.

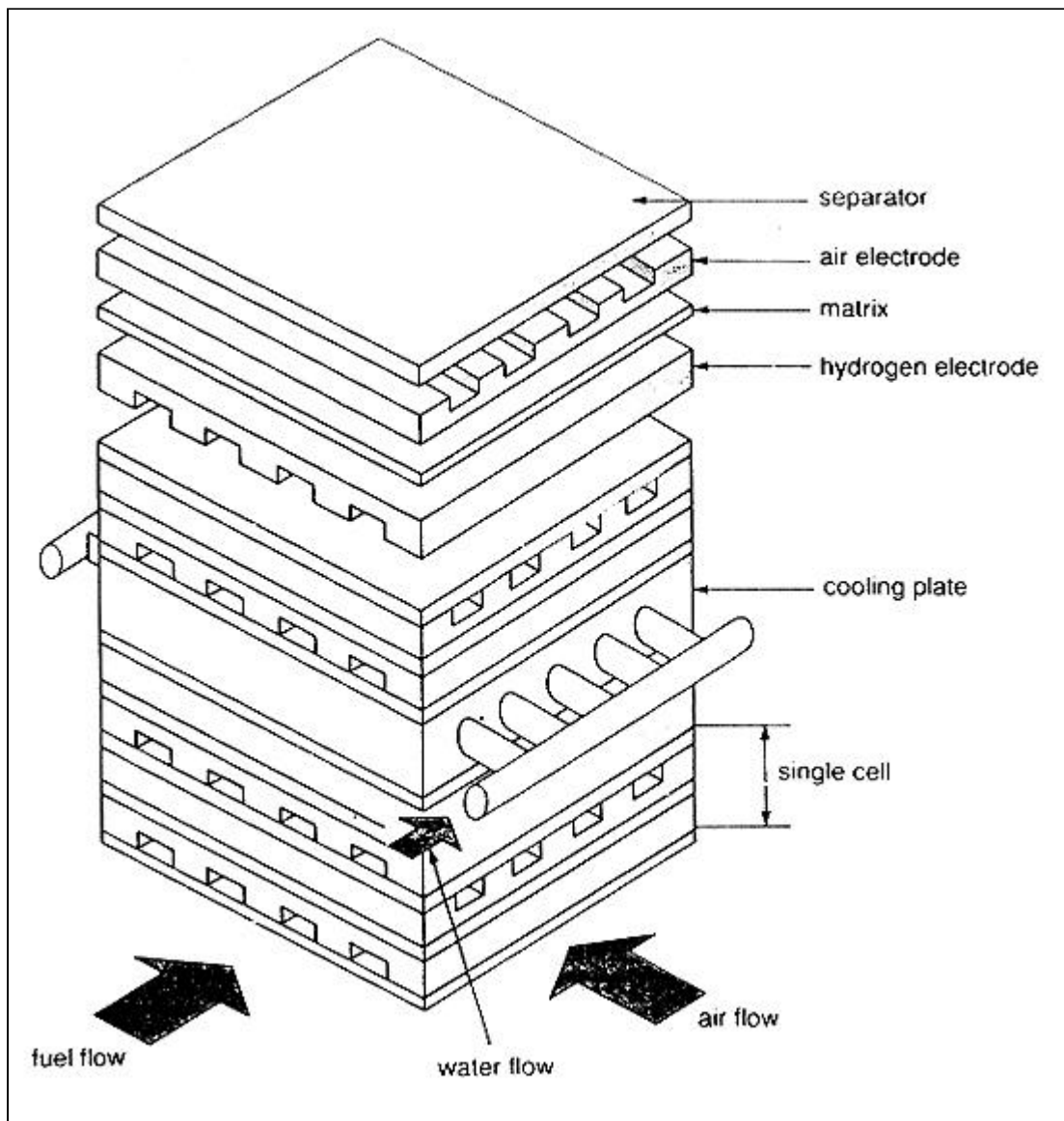


Fig. 1: Structure of stack [3]

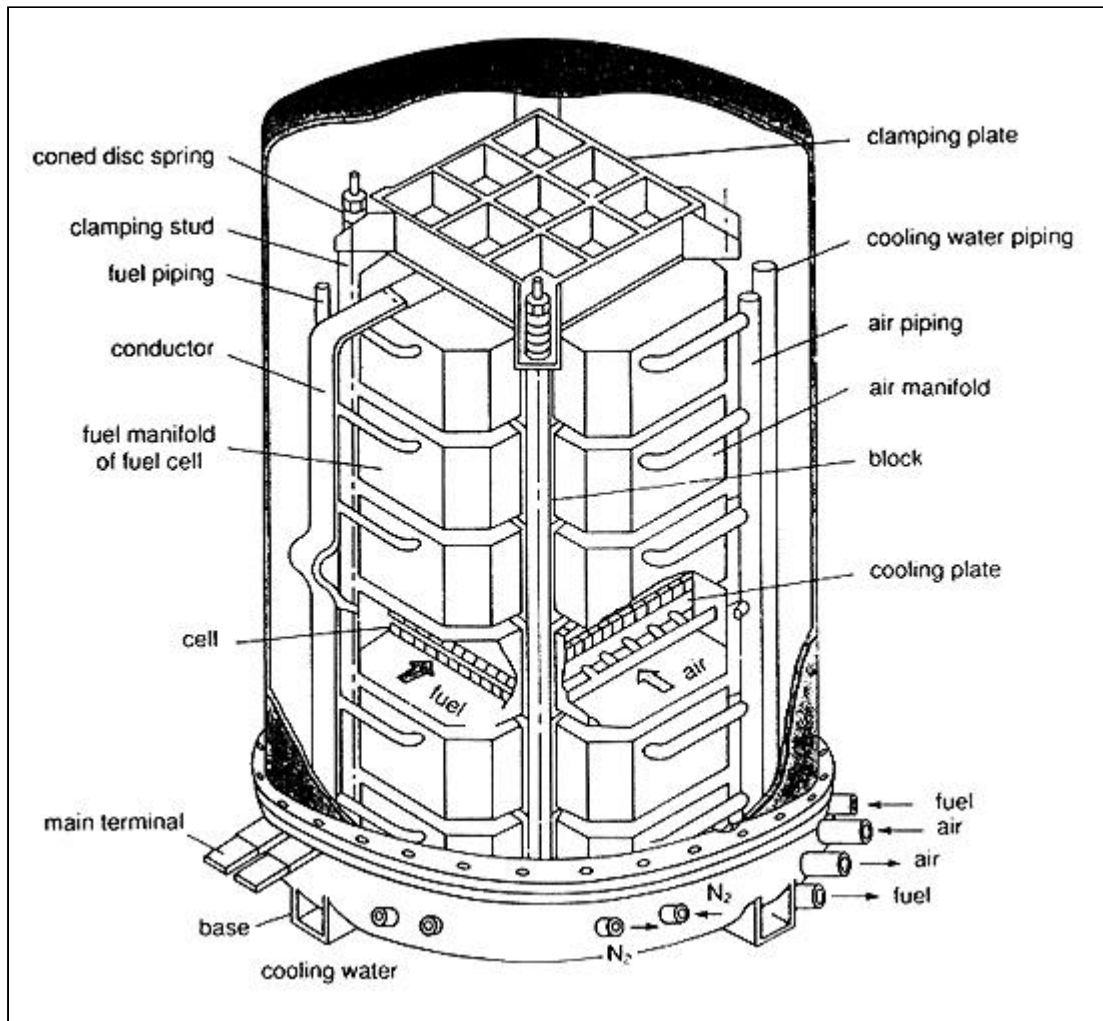


Fig. 2: Schematic structure of fuel cell [3]

In addition to the stack, the fuel cell mainly comprises the fuel, air and cooling water manifolds and piping and the electrical wiring which connects the electrodes in series together with the two main terminals (Fig. 2). The stack is secured in a clamping frame by springs. Principal design data for the fuel cell are summarised in Table 1.

Table 1 Fuel cell design data	
Type	Phosphoric acid fuel cell
Manufacturer	Fuji Electric Co., Ltd.
Rated current $I_N$	610 A DC
Maximum voltage	154V DC
Rated power output	Electric power output at $I_N$ , dependent on $O_2$ content in the cathode air
Operating temperature	190°C
Operating pressure (gauge)	40 mbar
Electric power output range	25–100% rated power output
Number of cells	192
Effective electrode area per cell	0.3825m <sup>2</sup>
Current density at $I_N$	1.6 kA/m <sup>2</sup>
Electrolyte	Immobilised phosphoric acid
Electrodes (anode and cathode)	Graphite/platinum/polymer
Dimensions (l x w x h)	1.7 x 1.3 x 1.9 m

Table 1: Fuel cell design data

The fuel cell installed in the hall of the operating building at SWB requires supplementary air purging of the shell as a precaution against formation of explosive gas mixtures due to internal leakage.

## 2.2 Process description

The fuel cell plant was supplied by Kinetics Technology International B.V. In addition to the fuel cell, it contains the hydrogen generation unit and a pressure-swing adsorption unit (PSA) see Fig. 3.

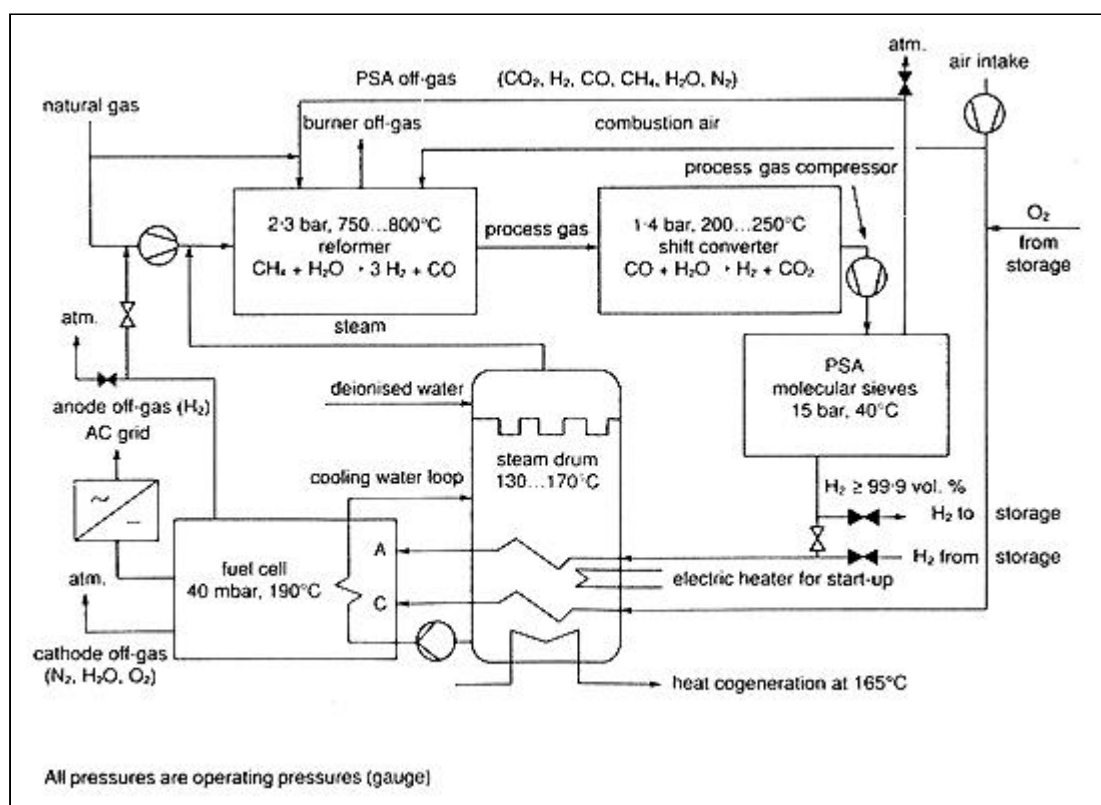


Fig. 3: Block diagram of fuel cell plant

Natural gas (Class H) supplied by the public utility is used as the reformer feed and fuel gas. After being desulphurised, the feed gas is converted with steam in the reformer to hydrogen and carbon monoxide, CO. In the low-temperature shift converter the CO reacts with residual water vapor to form more hydrogen and carbon dioxide. Nickel catalyst is employed in the reformer and copper catalyst in the shift converter. Steam is generated in the upper section of the steam drum utilising thermal power from the fuel cell. In the PSA installed downstream of the shift converter, the hydrogen is purified to at least 99.9 vol%.

Impurities contained in the crude hydrogen leaving the shift converter are adsorbed on molecular sieves at a pressure of 15 bar. During subsequent desorption at slight over-pressure, these impurities are rejected as part of the PSA off-gas, this being underfired in the reformer burner. Only small additional quantities of natural gas are needed to make up the total heat input required for the reformer and for start-up. The burner off-gas is utilised to preheat the feed gas and is vented to the atmosphere at about 200-300 °C via a separate stack. Pure hydrogen delivered by the PSA is either routed to the SWB on-site gas storage vessels or supplied directly to the fuel cell anodes.

Anode off-gas, which is mainly hydrogen not converted in the fuel cell, can be returned to the natural gas feed. Air supply to both the reformer burner and the fuel cell is provided by a blower which takes in ambient air. To increase fuel cell capacity, the cathode air can be enriched up to 50 vol% O<sub>2</sub> with pure oxygen from SWB's on-site gas storage. Cathode off-gas containing about 90 % of the reaction water generated, is released to the atmosphere.

The two-section steam drum serves as a process steam generator for the reformer and shift converter and as a central heat exchanger. During fuel cell operation thermal power is generated, which is utilised to

- heat the requisite gas flows to the desired temperature via the steam drum
- generate an adequate supply of process steam
- produce hot water for heat cogeneration.

Alternatively the fuel cell can be fuelled with pure hydrogen from SWB's on-site gas storage.

Operating modes available are:

1. Fuel cell operating on hydrogen manufactured from natural gas and ambient air.
2. As above but enriching the air with O<sub>2</sub> delivered from on-site gas storage.
3. Fuel cell operating on hydrogen delivered from on-site gas storage and ambient air.
4. As 3. above but enriching the air with O<sub>2</sub> delivered from on-site gas storage.
5. Generation of hydrogen for routing to on-site gas storage, fuel cell not operating.

The fuel cell at SWB is optimised for electric power output. Moreover heat can be cogenerated at a temperature level of 165 °C. In design of phosphoric acid fuel cells the ratio of electric power output to cogenerated heat is variable over a certain range. The fuel cell plant can be controlled over a range of 25 - 100 % of rated electric power output. Operation is automatic, supervised by visual display monitor with setpoint adjustment via the process control system in the central control room. Data acquired at the respective measuring locations are transmitted to the central archiving station.

### **2.3 Supplementary pressure-swing adsorption unit**

In principle the fuel cell could be fuelled either with pure hydrogen or with the shift converter product gas. Since the fuel cell anodes coated with platinum catalyst are subject to potential poisoning by CO, the CO concentration of the hydrogen fuel should be kept below 1 vol% to prevent permanent damage. This requirement is normally fulfilled by a reformer with downstream shift conversion. Supplementary use of the pressure-swing adsorption unit (PSA), which was delivered by Linde AG Process Engineering and Contracting Division, at SWB, reduces the CO concentration to below 1 vppm. Compared to commercial production units, this measure is intended to slow deterioration of the anode catalyst in the fuel cell. Product gas purity is checked prior to feeding the fuel cell.

Integration of the fuel cell plant in the overall concept of the Neunburg vorm Wald solar hydrogen facility was a factor in the decision to install the PSA. All hydrogen applications are supplied with pure hydrogen from SWB's on-site gas storage. Hydrogen delivered to the fuel cell by the PSA is of the same quality as the electrolytically generated hydrogen and thus can be tested within the solar hydrogen 'loop'. Apart from the advantages offered by a PSA, in part specific to SWB, consideration needs to be given to the increased electric utility consumption incurred by hydrogen compression and the additional capital outlay entailed.

### **2.4 Operation**

Following routine inspection, the fuel cell plant is started manually. Reformer, shift converter and PSA are put into service according to a start-up list. At the same time, the fuel cell is heated to the required starting temperature of 130 °C by circulating hot water from the lower steam drum.

Once the starting sequence has been initiated, the following procedures are performed successively and automatically: nitrogen purge of anodes and cathodes, air supply to cathodes, hydrogen supply to anodes, and switch-on of the starting resistors used as the electrical load. Finally the starting resistors are switched off when the DC/AC converter is cut in. The fuel cell plant can then be operated by setting values for current or electric power output.

From cold standby as defined below it takes about 4.3 hours for the fuel cell plant to attain rated power output. When fuelling with pure hydrogen from on-site gas storage, start-up time is reduced to about 1.8 hours (heating of fuel cell and starting sequence).

Shutdown of the fuel cell is made by an autostop sequence: rundown of electric power output to minimum load, switchover from DC/AC converter to electrical discharge resistors, cutting off hydrogen and air supply, nitrogen purge of anodes and cathodes, closing all gas valves on the fuel cell. The complete stop sequence takes an hour.

After the hydrogen supply has been cut, the PSA is shut down manually. Natural gas and steam supply to the reformer is turned off and the reformer and shift converter are purged with nitrogen. Provision is made for either fuel cell plant shutdown or hot standby. The latter shortens the start-up times stated above to about 2.5 hours (natural gas as fuel) or 1.1 hours (hydrogen as fuel). On hot standby the fuel cell is maintained at starting temperature of 130 °C via the cooling water circuit. The hydrogen generation unit is maintained under a circulating flow of nitrogen heated by the reformer burner and is ready to receive steam and natural gas feed. The PSA is pressurised and isolated.

The authorities involved, including the German Technical Inspection Authority TUEV, were consulted in due time before the fuel cell plant was purchased. The safety concept of the solar hydrogen facility was coordinated at an early date and a general operating permit was issued.

Siting of the fuel cell plant in an enclosed operating building was subject to a miscellany of provisions, which would need to be weighed against the respective drawbacks of outdoor siting when planning commercial plants. Indoor siting was chosen by SWB in the interests of optimum test conditions.

By contrast with space-optimised containerised plants, the good accessibility of the fuel cell plant at SWB, for instance at maintenance and repairs has proved valuable during commissioning and test operation.

Like practically all parts of the solar hydrogen facility, the fuel cell plant can be operated on double shifts every workday in summer and single shifts in winter for conducting the extensive test program scheduled. Continuous operation at base load was purposely excluded. 24-hour operation can be provided for limited periods of time to run special tests. While tests are in progress, special attention is paid to the behavior of the fuel cell plant with regard to unavoidable intermittent operating modes. Important knowledge relating to long-term stability, also under these difficult conditions, is expected to accrue from this.

## 2.5 Standby operation

When demand for electric power output from the fuel cell plant is temporarily absent, there is a fundamental choice among three different operating alternatives:

- Cold standby: Only electrical heating energy for the fuel cell is required to prevent crystallisation of the immobilised phosphoric acid. Start-up times from this state are relatively long. On restarting, temporary consumption of electrical energy and natural gas for heating the fuel cell plant are, however, high by comparison with restarting from hot standby.
- Hot standby: The reduced start-up procedure results in less labor, but compared to cold standby the instrumentation and control requirements are more extensive. Electrical energy is used continuously for the cooling water pump and heater as well as for the process gas compressor then used to circulate nitrogen and the combustion air blower. Natural gas is also consumed by continuous operation of the reformer burner.
- Operation at low electric power output: In this state, only the electric utility consumption is covered. The advantage of this is immediate readiness to be brought back on load, the disadvantage is continuous consumption of natural gas or hydrogen.

## 2.6 Control concept

The concept of the fuel cell plant is marked by a high level of automation throughout the entire sphere of process control. Operation within the electric power output range by adjusting setpoints for current or AC output necessitates extensive control capabilities. All gas flows to the fuel cell - hydrogen, air and oxygen where required - are corrected accordingly on adjusting setpoints. When doing so, the H<sub>2</sub>/O<sub>2</sub> ratio and the pressure differential between anodes and cathodes must be kept continuously within certain limits. Reformer feed (natural gas and steam) and PSA load are similarly adjusted. Slow thermal response of the reformer in particular is a critical time factor.

So as to attain rapid response to load changes and ensure constancy of power output, a supplementary product gas buffer vessel was installed on the outlet of the PSA.

This provides stable pressure and flow conditions in gas supply to the fuel cell anodes as a precondition for high constancy of electric power output. Control of reformer feed takes into consideration the actual pressure of the product gas buffer vessel.

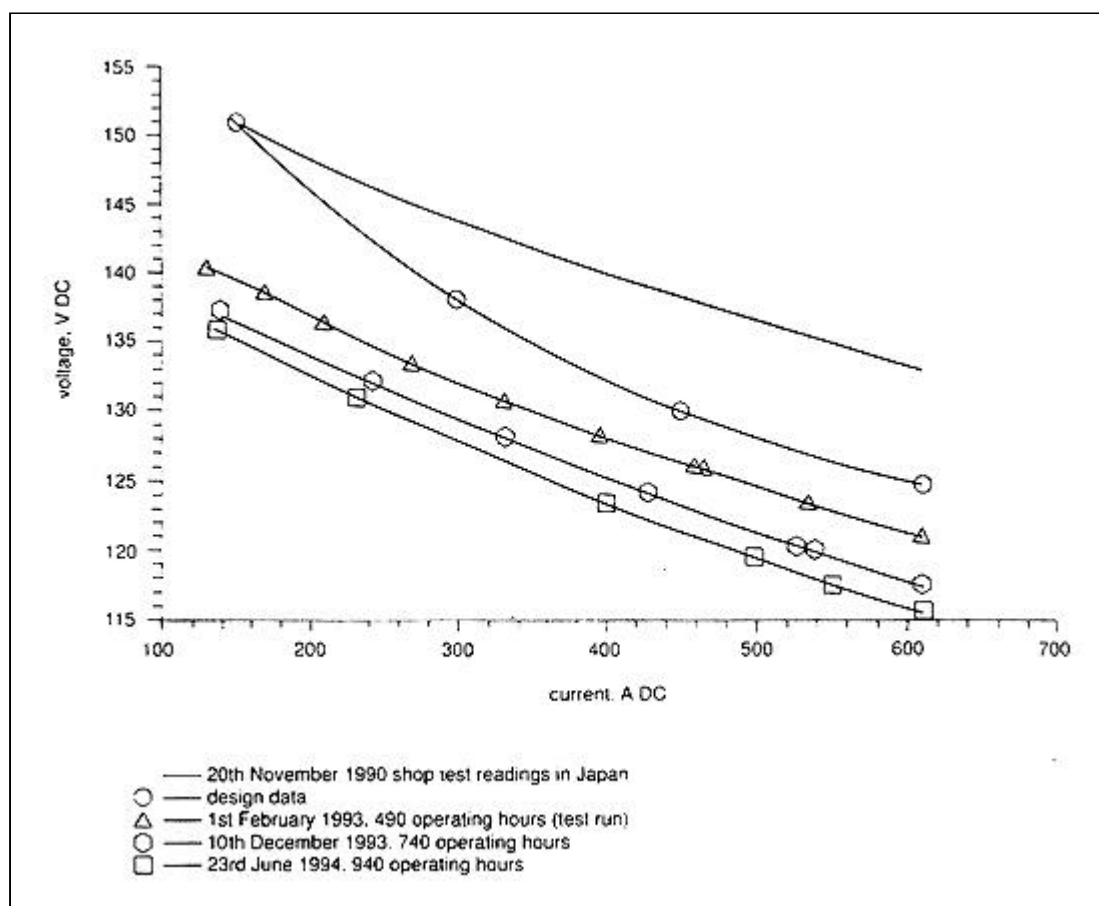
Extending the part load range of the test plant below 25 % of rated power output does not appear meaningful with a view to the test results reported below and the further augmentation

of instrumentation and control then required.

### 3. Test results

#### 3.1 Characteristic and voltage decrease of fuel cell

The voltage / current characteristic of the fuel cell was recorded during test runs performed in February 1993. Results in the mode operating with ambient air as oxidiser were compared with those recorded in November 1990 during successful shop test in Japan (*Fig. 4*).



*Fig. 4: Voltage-current characteristics in operation with ambient air*

Whereas a DC output of 81.1 kW<sub>el</sub> at 610 A was measured in Japan, the figure obtained at the end of the more than two-year period of commissioning with about 500 fuel cell operating hours was only 73.3 kW<sub>el</sub>. The resulting loss of electric power output amounts to approximately 10 %. Some 4 percentage points of this were measured after the fuel cell had been shipped from Japan to Neunburg vorm Wald and the remaining deterioration was observed in the course of commissioning. A further decrease of output was recorded during test operation subsequent to the fuel cell plant successfully completing guarantee test runs in February 1993, DC output measured on the 23rd June 1994 was 70.5 kW<sub>el</sub> at 610 A. Deterioration is presumably caused by the frequent starting and stopping sequences previously mentioned and the electrical voltage peaks occurring on the fuel cell electrodes at such times.

The fuel cell underwent about 220 starts during the test plant's first 1000 hours of operation roughly 140 of these starts taking place over the 500 operating hours logged within the two years of commissioning the test plant and the other 80 in subsequent test operation. The large number of starts is predominantly due to the manner in which the plant is run at SWB, this involving daily starting and stopping procedures in single- and dual-shift operation, and the automatic emergency trips, taking place mainly in the time, the test plant was being commissioned.

### 3.2 Load change response

Power output of the fuel cell is directly related to the hydrogen fuel supply rate. Therefore quick and exact control of the hydrogen flow is decisive with respect to speed of load change and constancy of electric power output for the overall fuel cell plant.

In all operating modes, time required for load change between minimum (25 % of rated power output) and full load in either direction is 1 minute to initially attain the new setpoint within a margin of 1 % (response time). 10 minutes after changing load, steady-state operation is regained with less than  $\pm 1$  % variation of AC output.

### 3.3 Efficiency

Measurements recorded in December 1993 for the various operating modes are listed in Table 2.

Due to the capability provided in the test plant of enriching the cathode air up to 50 vol% O<sub>2</sub>, DC output can be increased by 5 kW<sub>el</sub> compared to operation with ambient air.

At 46 - 49 %, the fuel cell efficiency is within the expected range for phosphoric acid fuel cells. In part load operation it rises to a maximum of 51 % (ambient air as oxidiser) or to 54 % when using cathode air enriched up to 50 vol% O<sub>2</sub>.

Operating mode	1	2	3	4
Fuel	18.8 Nm <sup>3</sup> /h natural gas		52.3 Nm <sup>3</sup> /h H <sub>2</sub>	
Oxidiser	Air	Air with 50 vol.% O <sub>2</sub>	Air	Air with 50 vol.% O <sub>2</sub>
DC output in kW <sub>el</sub>	72	77	72	77
AC output in kW <sub>el</sub>	67	72	67	72
Thermal power in kW <sub>m</sub>	21	21	45	45
Electric utility consumption in kW <sub>el</sub>	32	32	12	12
— for PSA only in kW <sub>el</sub>	16	16	—	—
Fuel cell efficiency in % (note 1)	46	49	46	49
Electrical efficiency in % (note 2)	19	21	35	38
Overall efficiency in % (note 3)	30	32	64	67

Note 1 DC output/(hydrogen flow rate × Lower Heating Value)  
 Note 2 According to VDEW<sup>4</sup> : (AC output – electric utility consumption) / (fuel gas flow rate × LHV)  
 Note 3 According to VDEW<sup>4</sup> : (AC output + thermal power – electric utility consumption) / (fuel gas flow rate × LHV)

Table 2: Measured performance of December 1993 fuel cell plant at rated power output ( $I_N = 610 A_{dc}$ )

The basis for calculating the electrical and thermal efficiencies indicated in Fig. 5 is the energy industry definitions issued by the Association of German Electric Power Stations (VDEW) [4].

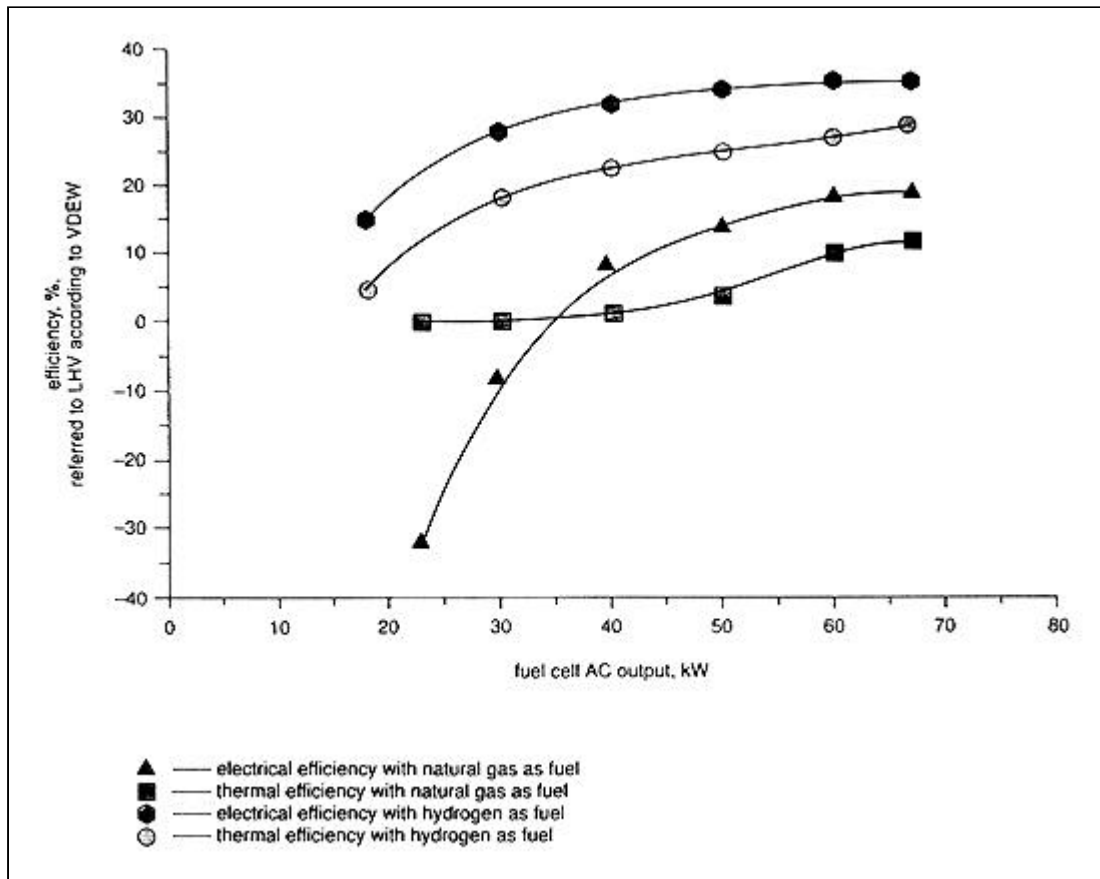


Fig. 5: Efficiency

When using natural gas as fuel, hydrogen must first be generated for the fuel cell by steam reforming. This process entails losses, resulting in efficiencies being distinctly lower with natural gas fuelling than when operating on hydrogen from on-site gas storage. Increased electrical efficiency at part load operation as usual for fuel cells cannot be verified in Fig. 5 due to the high electric utility consumption of this test plant.

*Natural gas as fuel and ambient air as oxidizer:*

Electrical efficiency is 19 % at rated power output and declines strongly at part load. At an AC output of about 34 kW the electrical efficiency is zero, meaning that then just enough AC output is delivered by the fuel cell plant to cover the electric utility consumption required for operation. Between 23 and 34 kW AC output the electrical efficiency is negative due to the electric utility consumption exceeding the available AC output.

At an AC output between 23 and 40 kW, cogeneration of heat is no longer possible meaning that the thermal efficiency is zero in this range of part-load operation. The highest thermal efficiency of 11 % is attained at rated power output.

Low efficiencies of the fuel cell plant, even at rated power output, are essentially due to the high electric utility consumption of this comparatively small test plant. At an AC output of 67 kW the electric utility consumption amounts to 32 kW (i.e. 48 %). Full half of this is required by the process gas compressor upstream of the PSA. As already noted, a phosphoric acid fuel cell can also be fuelled direct with the product gas from the shift converter, this indeed being the normal process layout in commercially oriented plants. Without the PSA, the electric utility consumption of the test plant would be considerably lower and the electrical efficiency would improve, for instance being 8 percentage points higher at rated power output. This would also eliminate cooling and heating of the process gas at the PSA inlet and outlet, resulting in more thermal power available, associated with an increase in thermal efficiency.

*Hydrogen as fuel and ambient air as oxidiser:*

Electrical efficiency at rated power output is 35 %. Down to an AC output of about 35 kW the electrical efficiency remains above 30 %, then declining to 15 % at minimum load (18 kW AC output). Electric utility consumption is 12 kW at all operating points. This amounts to 67 % of AC output at minimum load and 18 % at rated power output.

*Transition to larger commercial plants:*

With larger fuel cell plants the rise in electric utility consumption is proportionally smaller while the power yield is higher. This is accompanied by an increase in electrical efficiency. Newer types of containerised phosphoric acid fuel cell plants of almost commercial design not including a pressure-swing adsorption unit attain electrical efficiencies up to 40 % at an AC output of 210 kW. The electric utility consumption of these plants is then no more than 5 % of the output. These plants are capable of additionally delivering up to 220 kW of thermal power with a thermal efficiency of 45 %. Overall efficiencies as high as 85 % are thus already realisable in these phosphoric acid fuel cell plants.

### 3.4 Energy balance

Figs 6 and 7 present the energy flow chart for the test plant in steady-state operation at rated power output when employing natural gas and hydrogen, respectively, as fuel. The reference point for the fuel gases is their lower heating value at 25 °C.

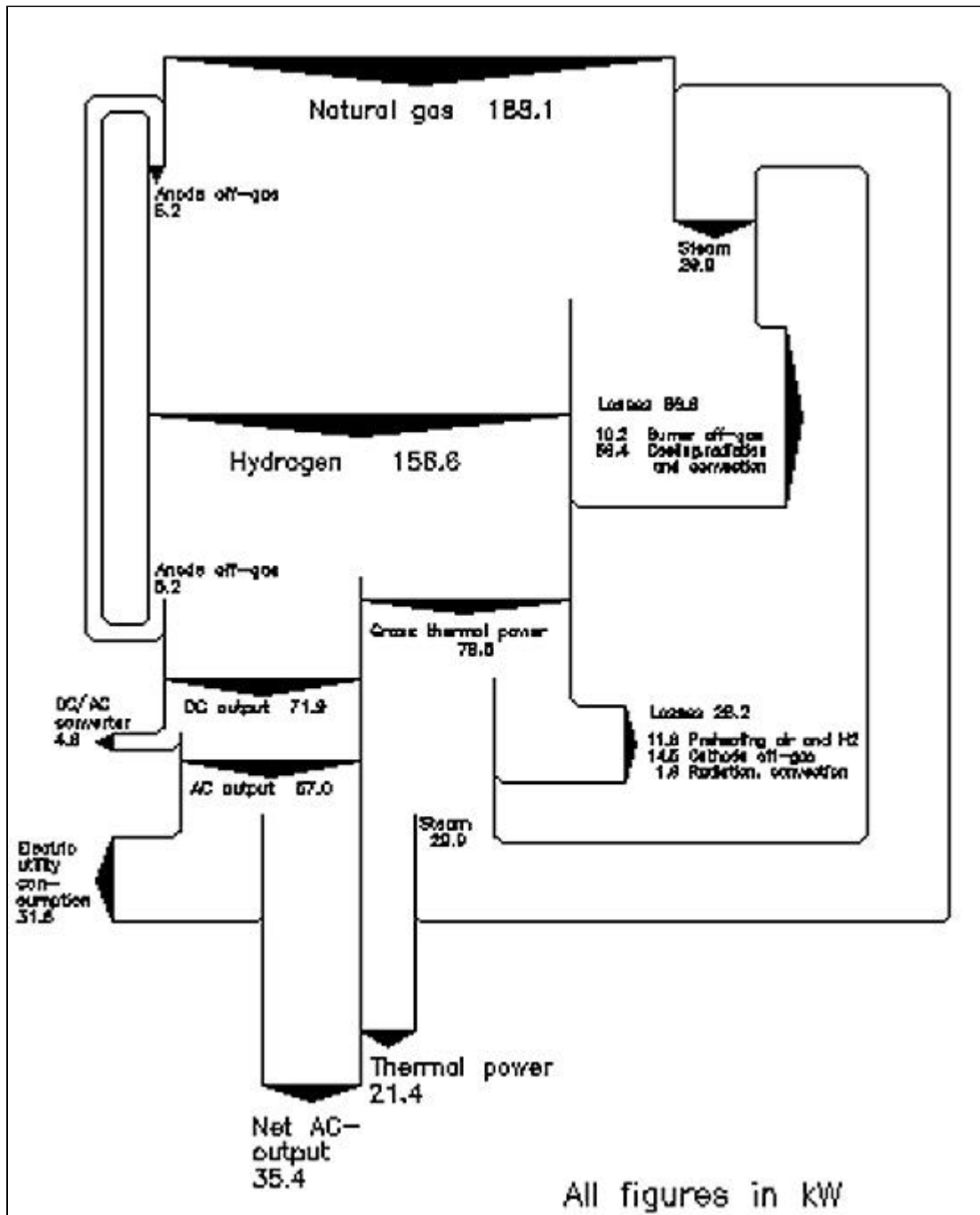


Fig. 6: Energy balance with natural gas as fuel and air as oxidiser at rated power output

Natural gas as fuel and ambient air as oxidizer:

As noted, the greatest savings potential for increasing net AC output lies in reducing the electric utility consumption.

Additional potential for savings is found on the thermal side, for instance in the off-gas losses. At a temperature of 305 °C approximately 10 kW<sub>th</sub> is lost with the burner off-gas vented through the reformer stack. This wasted heat could be utilised to supply about 5 kW<sub>th</sub> for steam generation in the steam drum and/or to contribute to preheating of air and hydrogen upstream of the fuel cell. The gross thermal power that is currently employed for these purposes could then be added to the available thermal power. Loss via the cathode off-gas from the fuel cell at rated power output is 14.5 kW<sub>th</sub> at a temperature level of 175 °C. This heat could be used for preheating the deionised water (6 kW<sub>th</sub>) and natural gas (1.4 kW<sub>th</sub>). Its utilisation for preheating air and hydrogen upstream of the fuel cell (12 kW<sub>th</sub>) would also be possible.

Generally the energy balance is subject to further improvement through optimizing heat exchange within the plant and reducing heat losses to the surroundings.

*Hydrogen as fuel and ambient air as oxidizer:*

Electrical and thermal yield is distinctly higher than with natural gas fuelling. Potential savings are nonetheless recognisable here too. As well as reducing the electric utility consumption, an available thermal option is to preheat the air and hydrogen with the cathode off-gas.

Comparing fuelling modes, running on hydrogen supplied from on-site gas storage results in the off-gas losses being higher by the energy content of the anode off-gas recycled in natural gas operation. This energy could be utilised by recycling the off-gas to the anode inlet.

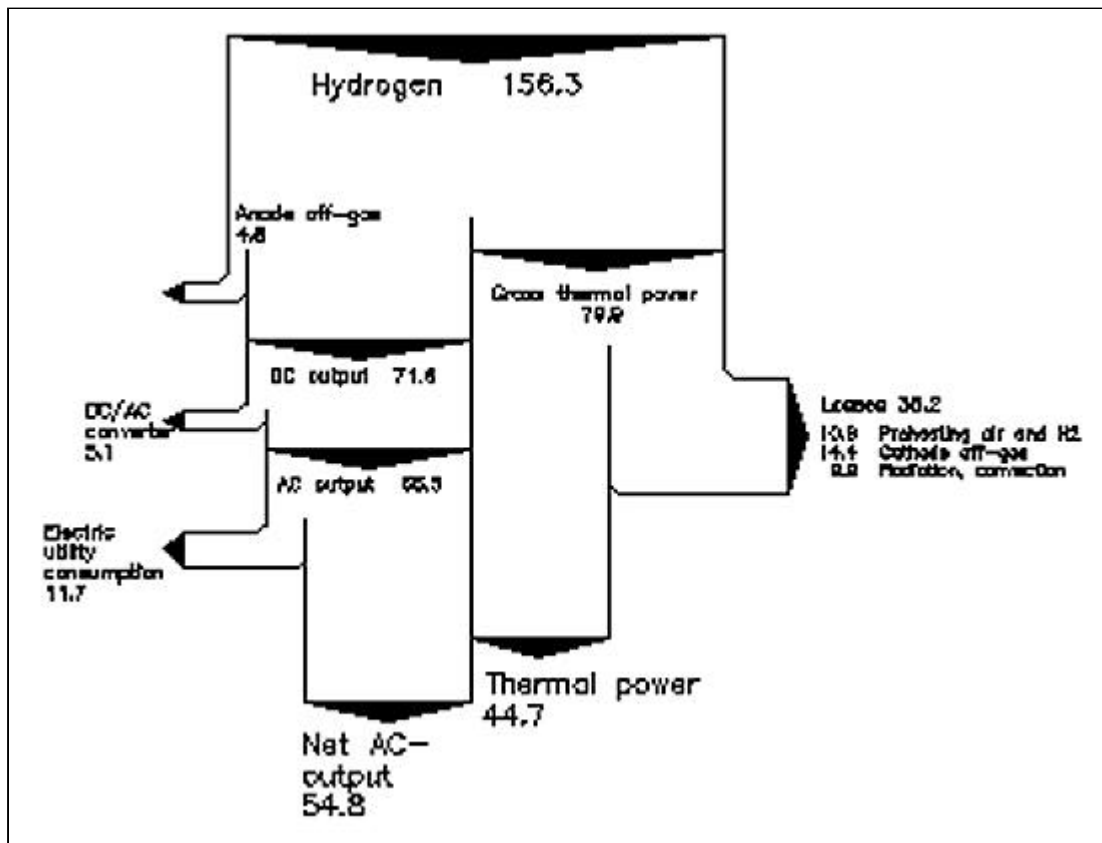


Fig. 7: Energy balance with hydrogen as fuel and air as oxidiser at rated power output.

#### 4. Outlook

More precise investigation into the starting and stopping behavior of the test plant commenced in the autumn of 1994. Following that, measurements are scheduled to check emissions from the plant.

Owing to the prototype nature of this test plant and the general lack of available operating experience with other plants, the SWB project may be expected to generate valuable knowledge relating to the optimisation and commercialisation of this technology.

Apart from the phosphoric acid fuel cell plant described in this article, SWB is operating an alkaline fuel cell plant using pure oxygen as the oxidiser for simulation of electric-powered

vehicles [1].

In addition operation of a PEM fuel cell plant to power an electric forklift truck equipped with hydrogen hydride storage is scheduled from 1996 on. This prototype is notable above all for running on ambient air instead of pure oxygen as the oxidiser.

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