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Environmental Impact of Fuel Cell Technology

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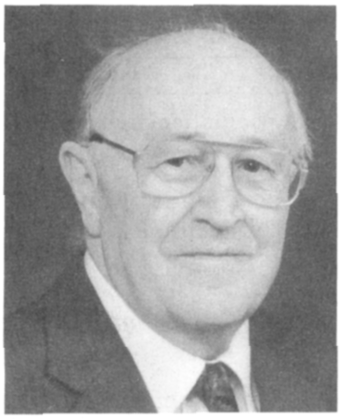

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Introduction

Fuel cell systems represent a new technological approach, which meets all requirements for a future sustainable conversion technology: high electrical efficiency, low emissions, good part-load characteristics, and possibility of cogeneration. Furthermore, all materials used in the fuel cells cause no environmental damage and can be produced without any problems. The main implementations of the fuel cell technology—beside the efforts in dispersed power plants and transportation applications—are on-site fuel cell plants. These so-called precommercial prototypes have already shown their reliability and availability in field tests in the United States, Canada, and Japan. Technological comparisons, which use new exergetic assessments, are also used as ecological and economic comparisons. Energy innovation steps without consideration of the environmental problems caused by transportation applications have to be rejected. Battery-driven electric vehicles have some disadvantages for the user. Consequently vehicles with internal combustion engines cannot be completely replaced by battery-driven vehicles. The ecological effects with new technologies

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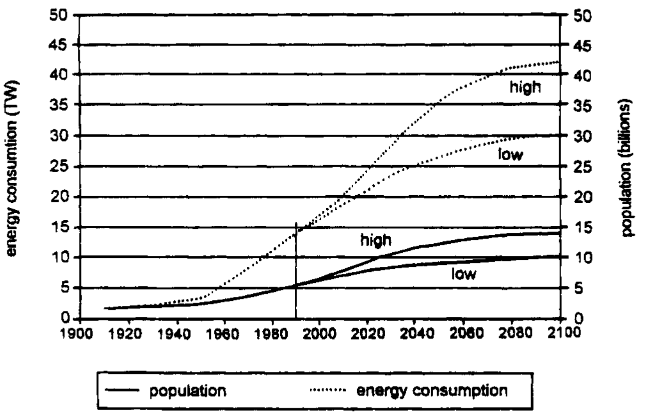

Figure 1. World population and energy consumption estimates.[43]

without these disadvantages would be significantly higher. The fuel cell technology represented in this field are the only real alternative for this problem.

1. Fuel Cell Development and Hydrogen Technology

The economic growth of modern industrialized society has been based on utilization of energy stored in fossil fuels—coal, petroleum, and natural gas. At present time, about 80% of the world energy demand is met by fossil fuels. Although they are concentrated in certain regions of the world, they are available worldwide in one form or another. Humans have learned to exploit them relatively efficiently to produce the energy services they need (see Figure 1). They are storable and portable, which make them excellent fuels for transportation.

However, consumption of fossil fuels has become a destructive force, locally because of emissions, spills, leaks, and strip mining; regionally because of pollutant dispersion; and now globally because of carbon dioxide accumulation and its threatening consequences—global warming, changing climate, and rising sea levels.

The need for higher efficiencies (in order to have more energy services with less energy) and concerns about the environment, together with diminishing reserves of fossil fuels, will make electricity and hydrogen logical choices for energy "currencies" in the 21st century. These two currencies complement each other. Electricity can be relatively efficiently produced from hydrogen through fuel cells, and in turn, hydrogen can be derived from electricity through the electrolysis of water (again, a very efficient process). This complementarity of hydrogen and electricity is further enhanced by the fact that hydrogen, unlike electricity, can be stored and easily transported over long distances. The storage feature allows hydrogen to fuel airplanes and vehicles presently entirely depending on fossil fuels.

The most important fact is that both electricity and hydrogen are independent of energy sources, i.e., they can be produced from any available (technically and economically feasible) primary energy source, such as fossil fuels, nuclear energy of fission or fusion (if or when available), geothermal energy, direct and indirect forms of solar energy, etc. If environmental concerns are taken into account, then this list is reduced to renewable energy sources. Both hydrogen and electricity efficiently complement the renewable energy sources and present them to the consumer in a convenient form and at the desired location and the desired time. With this fact in mind, a future energy system which would use hydrogen and electricity as the energy currencies can be designed as a permanent sustainable energy system.

2. Transition Strategies for a Sustainable Energy System

The application of fuel cell technology within the present energy system will result in a change in the way of supplying services to energy users; however, a decentralization of the energy system will be required.

Figure 2 shows how such an energy system may have to be set up and how the different levels of the specific innovation requirements would be defined. Special consideration is given to the energy supply via transmission lines, which will always be the responsibility of the large-scale energy producer. Indications are that a future trend to decentralization will happen in the private sector, in parts of city communities, and in local industry groups. A shift from the use of fossil fuels to renewable energy sources like solar energy (thermal and photovoltaic), biomass, wind energy, etc., will be emphasized. The reforming of fuel sources, the conversion and final production of energy will be adapted to the local situations. For the storage of any surplus energy, there will be suitable novel possibilities, rivaling the presently suggested return of the excess power into the central power grid. In connection with the fuel cell technology, the following areas are especially interesting: private and industrial sector, on-site plants (cogeneration); gas and electrical utilities, dispersed power plants and on-site plants (cogeneration); and transportation, fuel cells for electrical vehicles.

These areas have the potential capability to supply all the needed energy for the specific uses: mechanical work, process heat, room heating, warm water supply, vehicles, lighting, and electronic data transfer. The introduction of the fuel cell technology is also one of the short-term options of the IPCC response strategies of the intergovernmental panel on climate change.[1]

3. Fuels for the Fuel Cell Systems

Hydrogen is the only practically useful fuel for the present generation of fuel cells. The main reason is its high electrochemical reactivity compared with conventional fuels like natural gas, coal, naphtha, and alcohols, from which it is often produced. Hydrogen, derived from all kinds of renewable energies, is the only energy carrier which can be used without any environmental damage. The production from hydroenergy (energy from hydrogen) and solar energy and its conversion into electrical and thermal energy with a fuel cell presents a process cycle, which can be repeated without limits, producing no ecological harmful side products.

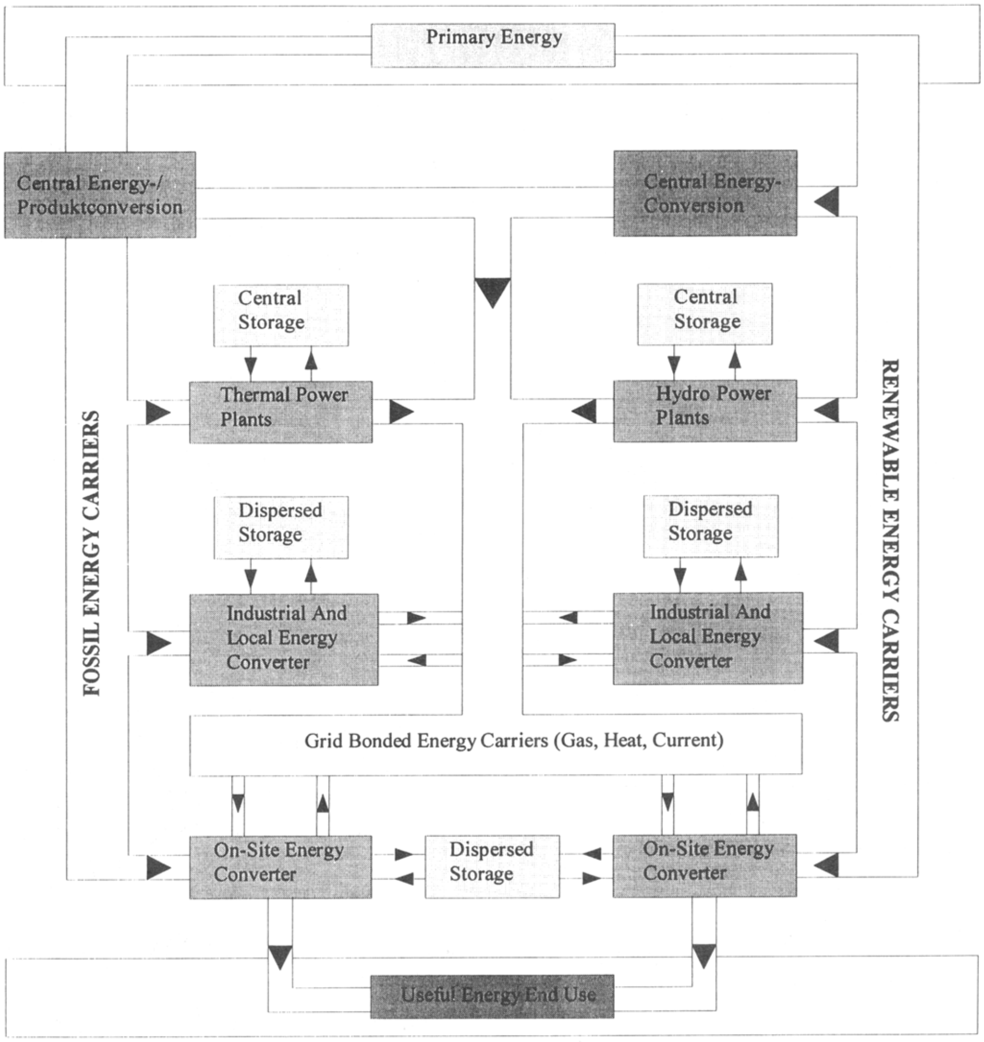

Figure 2. Transition strategies for a sustainable energy system.[37]

Hydrogen production technologies have been the object of considerable commercial research and development efforts and a series of well-known hydrogen production technologies (reforming, CO conversion, gasification methods, cracking processes, etc.) already exist. The different possibilities of manufacturing hydrogen are shown in Figure 3. Presently the costs of electrolytic hydrogen are four times higher than for fossil hydrogen. The consequence is that 96% of the hydrogen is now produced chemically.

4. Characteristics of the Fuel Cell Technology

4.1. General Aspects of the Fuel Cell Technology

A fuel cell is an electrochemical device which can continuously convert the chemical energy of a reducing agent and an oxidant fuel to electrical energy by a process involving an essentially invariant electrode–electrolyte system (see Figure 4). Fuel cells work at a high efficiency with an emission level far below of the strictest industrial standards.

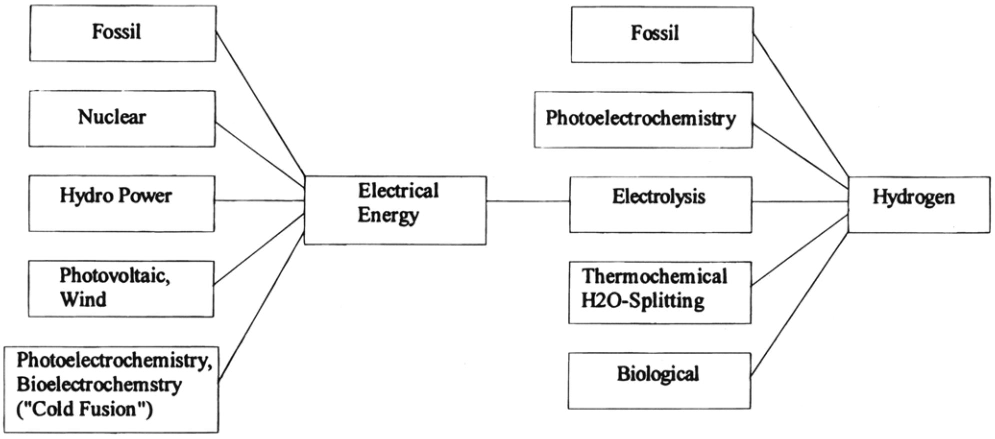

Figure 3. Schematic manufacturing of hydrogen.

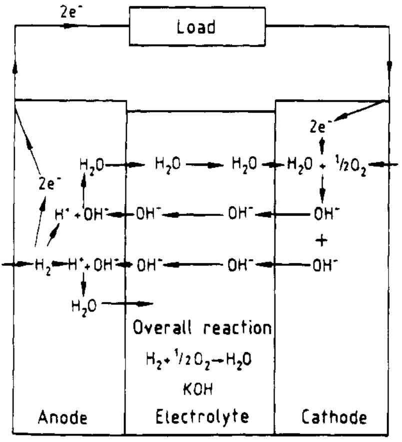

Figure 4. Principle of the alkaline hydrogen–oxygen cell.[44]

The operation of technical fuel cell batteries also requires control systems and components for supplying fuels and removing reaction products, heat exchangers, pumps, etc. Such electricity-producing aggregates, consisting of the fuel cell stacks and the accessories needed for their operation are often called "electrochemical power generators".

Despite their relatively long history and the progress attained in developments during the past 30 years, fuel cells have experienced very few applications up to now. The most important ones have been their use as main electrical energy sources for the manned spacecrafts of the Gemini, Apollo, and Space Shuttle programs of the National Aeronautics and Space Administration (NASA) of the United States. Attempts to develop systems on earth, to the mid to upper power range (200 kW to 11 MW), have been made in the 1980s and 1990s. They are aimed at applications such as load leveling for energy utilities, for remote power plants, cogeneration, industrial waste utilization, or emergency power supplies. In the lower power (1–10 kW) range studies are focused on the development of fuel cell systems for electric vehicle propulsion and military purposes.

4.2. Fuel Cell Systems

Fuel cell systems can be classified according to their working temperature, high-, medium-, and low- (ambient) temperature systems, or referring to the pressure of operation, high-, medium-, and low- (atmospheric) pressure systems. They may be further distinguished by the fuels and/or the oxidants they use: (1) gaseous reactants (such as hydrogen, ammonia, air, and oxygen), (2) liquid fuels (alcohols, hydrazine, and hydrocarbons), or (3) solid fuels (e.g., coal, metal hydride).

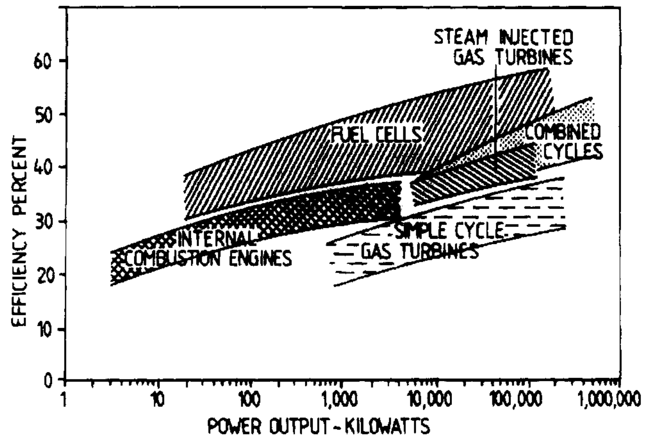

Figure 5. Comparison of fuel cell performance with other energy conversion systems (depending on design, materials, etc., a definite system will fall somewhere between the two curves shown).

For practical reasons fuel cell systems are simply distinguished by the type of electrolyte used and the following names and abbreviations are now frequently used in publications: alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and proton exchange membrane fuel cells (PEMFC). Their applications are listed in Table 1.

4.3. Advantages and Disadvantages of Fuel Cell Systems

The following listings summarize the most important features of fuel cells in comparison to other energy conversion devices:

Advantages

(1) Savings in fossil fuels due to the high efficiency of energy conversion (see Figure 5)

(2) Savings in fossil fuels due to the good part load characteristics

(3) Low pollution level, no noxious exhaust gases formed

(4) Production of water of drinking quality in hydrogen–oxygen systems

(5) Only a small number of moving parts (pumps, fans, blowers)

(6) Low noise level (replacing motorgenerators!)

(7) Low maintenance, exchangeable parts (mass-produced components)

Table 1. Applications for Technical Fuel Cell Systems[2]

type	electrolyte	temperature °C	issues	likely applications
alkaline fuel cells (AFC)	aqueous KOH solution	60–120	CO_2 troubles	electric vehicles, space, military
polymer membrane fuel cells (PEMFC)	polymer membrane	60–120	humidification of the reactant gases	electric vehicles, space, military
phosphoric acid fuel cells (PAFC)	concentrated phosphoric acid	160–220	CO sensitivity of the electrodes	cogeneration systems (<180 °C)
molten carbonate fuel cells (MCFC)	mixture of molten carbonates (Li_2CO_3/K_2CO_3)	600–650	CO_2 recycling necessary	dispersed and/or cogeneration systems (<600 °C)
solid oxide fuel cells (SOFC)	ceramic solid $ZrO_2(Y_2O_3)$	900–1000	ceramic cells	dispersed and/or cogeneration systems (<1000 °C)

(8) Fast start-up time of low-temperature systems
(9) The regenerative hydrogen–oxygen system, an energy storage system for space application
(10) Ability to use low-cost fuels with high-temperature systems
(11) Increased efficiency with the cogeneration of heat with high-temperature systems

Disadvantages (at the present state of technology)

(1) The high initial cost of the system (catalysts, membranes, accessories)
(2) Large weight and volume of gas–fuel storage systems
(3) Approximately 30% of the stored energy needed for liquefication of hydrogen
(4) High price of clean hydrogen (presently not competitive)
(5) Present lack of infrastructure to distribute hydrogen
(6) Estimated, but not accurately known, lifetimes of the cells (40000 hours for acidic, 10000 hours for alkaline cells?)
(7) Electrode degradation and the need of nearly complete carbon dioxide removal from the hydrogen fuels and the air in existing versions of the alkaline cells
(8) Pilot production of the direct oxidation of hydrocarbons just beginning after 30 years of research

It is expected that further research and development work will remove some of the disadvantages. Large progress has been made with cost reduction concerning catalysts by using smaller amounts at a high utilization rate. The production of fuel cell components will follow known mass-production techniques. The improvement of carbon materials as catalyst substrates and construction parts is one of the most promising ways of increasing life expectancy of low- and medium-temperature cells. New discoveries in metal hydride manufacturing and hydrogen liquefication methods have been made. Other developments which use sponge iron in a cyclic operation could make a breakthrough in the usage of synthesis gases for fuel cells.[36] Pressure cylinders have decreased in weight by 50% within the last 15 years. Alcohols and ammonia appear to be promising as hydrogen carriers; fuel reformer units are getting smaller and more efficient. The low-temperature direct hydrocarbon fuel cells need a breakthrough in catalyst technology in order to become a technical reality.

4.4. Alkaline Fuel Cells (AFC)

AFC systems were initially developed for space applications with essentially no cost limitations but presently lag about one decade behind phosphoric acid fuel cells for terrestrial applications, where cost and performance implications are critical. The best performance of these systems was achieved by the use of porous PTFE-bonded electrodes with high noble metal loadings. The mechanism is shown in Figure 4; the principle of an alkaline matrix fuel cell is shown in Figure 6.[3]

The AFC was used in the United States Apollo program to power life-support systems and has been used similarly in subsequent Space Shuttle programs. The Space Shuttle cells differ from the Apollo cells in the electrolyte supply structure, which is now based on immobilized 34–46% KOH electrolyte, absorbed in a thin layer of reconstituted asbestos separator.

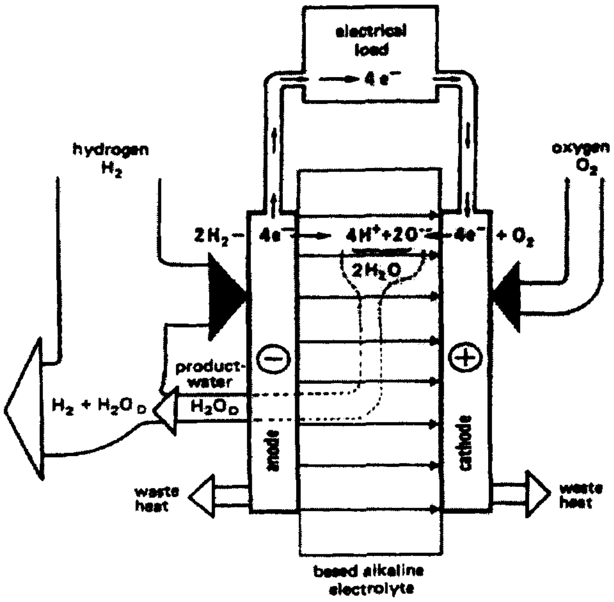

Figure 6. Principle of the alkaline matrix fuel cell.

Kordesch equipped a passenger car with an AFC/lead–acid hybrid configuration in the early 1970s. The vehicle operated for 3 years and accumulated about 30000 km during its actual 1000 h of operation of the fuel cells. The 90 V fuel cell system and the 84 V lead–acid battery were connected in parallel and performed as a hybrid power plant.[4]

While AFCs offer the best prospect for the usage of non-noble metal catalysts (e.g. "Raney" nickel and/or "Raney" silver), particularly for terrestrial applications, carbonation of the electrolyte by carbon dioxide and poisoning of the catalyst by carbon dioxide and sulfur are the key drawbacks. Furthermore, high loadings of Raney nickel and/or Raney silver do not provide a cost advantage over platinum.

AFC work was "revitalized" in 1986 with the initiation of the Hermes manned space vehicle. In the meantime the discontinuation of this program caused a stepping down of efforts spent on that system. Newer developments have attempted to bring back the AFC system for electrical vehicles. The lifetime problem of the AFC could be overcome by a reduction of the active standing (calendar) time of the cells vs the real operation hours. Kordesch's vehicle has already shown this concept.[5]

4.5. Solid Polymer Electrolyte Fuel Cells (SPE, PEMFC, SPFC)

The first application of an ion exchange fuel cell was demonstrated by General Electric (GE) with a 1 kW unit in the Gemini space flights.

$$H_2 \rightarrow 2H^+ + 2e^- \qquad (1)$$

$${}^1\!/_2O_2 + 2H^+ + 2e^- \rightarrow H_2O \qquad (2)$$

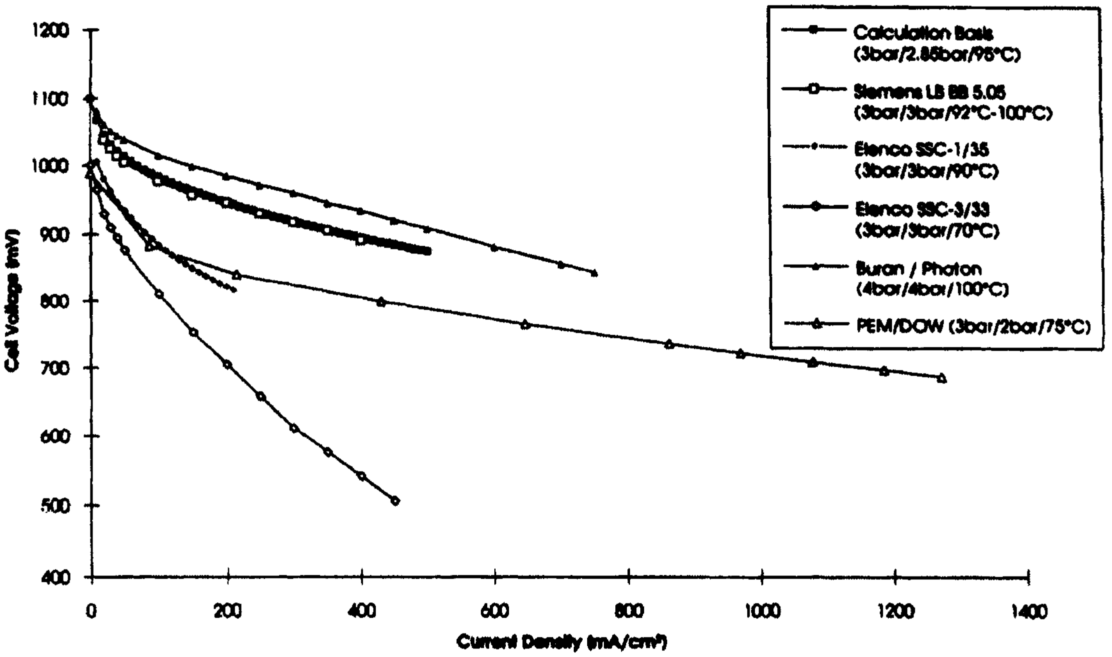

Figure 7. Comparative individual cell performance (at beginnning of life).[45]

Electrode reactions are those of an acid fuel cell system. The polymer membranes provide the barrier against gas cross-leaks between the electrodes, which can be extremely thin (50 μm) and thereby reduce ohmic losses in the electrolyte. The initial PS–sulfonate membrane was replaced by NAFION (DuPont), Dow membranes (Dow Chemical), and Aciplex membranes (Asahi Chemical Industry Co.). The water balance is still considered to be a main problem.[6] Figure 7 indicates the typical electrode characteristics of AFC and PEMFC.

Dehydration of the membrane is a problem; therefore, complicated cooling and transpiration systems have to be used in addition to humidification of the feed gases. Hydrocarbon reformates can be used, but CO, a catalyst poison, must be avoided.

Small and robust PEMFC modules can be readily manufactured and are probably the best candidates for light duty vehicle applications. Units up to 10 kW have so far been manufactured for the military, for underwater vehicles, and for aerospace applications.[7–9]

Although current loadings of Pt (used as an electrocatalyst) are very high (at around 4 mg/cm^2 Pt), reduced loadings (0.5 mg/cm^2) are anticipated. The latter loading, which would correspond to 4 g/kW, is still considered to be high for application in the transportation sector. Whether an additional reduction in Pt loading (to 0.1 or even 0.05 mg/cm^2) will be technically feasible remains to be seen.[10,11]

One concept for transport applications would use methanol as a fuel, which is subsequently externally reformed to hydrogen. A combined system based on an FC/ICE hybrid using methanol could be envisioned.

Ballard has recently exhibited a 5 kW system based on 35 active cells using the latest version of the Dow membrane (thickness 50 μm) and incorporating an integral gas humidification section. The active electrode area per cell is 235 cm^2 and the Pt loading is 4 mg/cm^2. The current density is ca. 1 A/cm^2 (i.e. 250 A) and the cell voltage amounts to 0.6 V (i.e. 21 V for the system).[12]

The near-term objective is to obtain a lifetime of 4000–5000 h with 0.5 mg Pt/cm^2 at a cost of U.S.$3000/kW. The long-term objective of reducing the Pt loading to 0.05 mg/cm^2 and a cost of U.S.$300/kW is rather ambitious technically, because it is unclear if the targeted lifetime can be obtained at such extremely low Pt loadings. The power obtained from a PEMFC system is believed to be sufficient to propel a vehicle even at peak load without an additional battery;[13] however, economy speaks against it.

Assuming that these long-term low Pt loading and membrane cost targets could be met, an ultimate capital investment cost of U.S.$50–100/kW would make PEMFC a viable alternative to ICE. Once the system is found to be commercially possible for vehicular applications, applications in stationary power generation are bound to follow. In this case a higher operating temperature might be sought.

4.6. Phosphoric Acid Fuel Cells (PAFC)

The PAFC is based on an immobilized phosphoric acid electrolyte. The cell is operated at 180–220 °C and uses air (O_2) as oxygen and hydrogen as fuel. PAFCs have an advantage over AFCs in that they tolerate up to 2% carbon monoxide and can be operated on reformed natural gas and naphtha. The technology has been developed for remote and/or combined heat and power (CHP) electricity generation.[14–16]

The PAFC systems utilize platinum (Pt) electrocatalysts incorporated into porous hydrophobic carbon electrodes. During the last 10 years binary and ternary Pt alloys which are claimed to be stable have been developed and tested in the United States.[17]

During the 1970s and 1980s many small units were tested in the United States and Japan for a multitude of applications. Between 1983 and 1985 a 4.5 MW

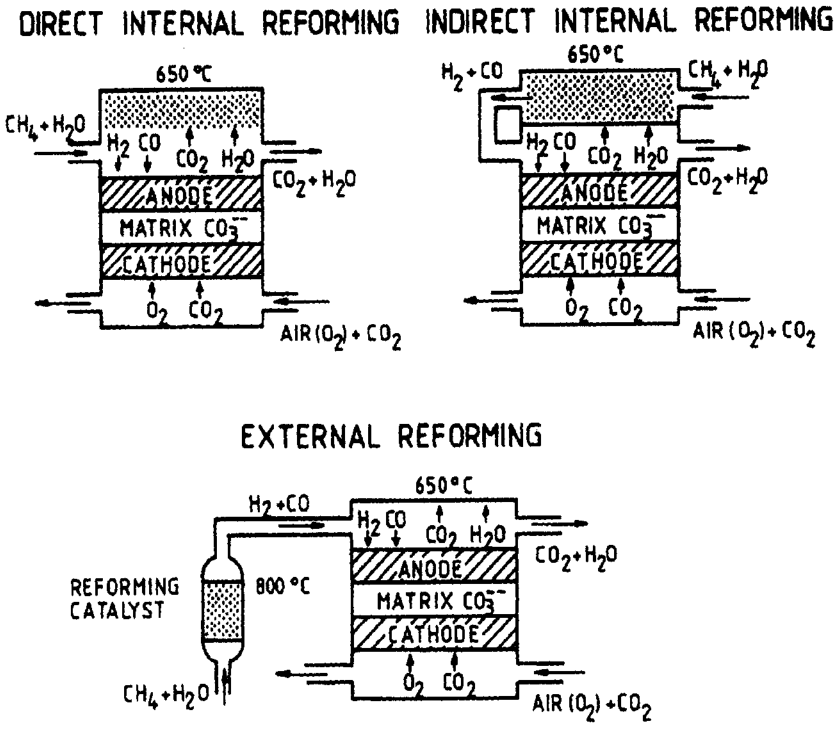

Figure 8. Different options for MCFC reforming.

plant was operated successfully in Tokyo and in 1992 its 11 MW successor was started (by far the largest fuel cell system ever tested). Stack lifetimes of 5 years (40000 h) are expected for IFCs (UTCs) 200 kW and 11 MW plants, with at least 30 years lifetime for the rest of the plant.[18] Developments are aimed at a 100000 h stack lifetime of a PAFC stack. PAFC technology appears to be ready for commercialization with both American and Japanese companies setting up production lines for 5–10 MW PAFC generators.

4.7. Molten Carbonate Fuel Cells (MCFC)[19,20]

For the operation on coal-derived fuels the MCFC is considered to be preferable to PAFC. The MCFC operates at about 650 °C and has a higher cell efficiency than PAFC, which operates at an upper temperature of 210 °C. As a result, the polarization of the oxygen cathode is significantly reduced, which more than offsets the 0.2 V theoretical thermodynamic loss.

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \qquad (3)$$

$${}^1\!/_2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \qquad (4)$$

A well-designed MCFC is expected to operate at about 0.1 V higher than present PAFC designs (e.g. 250 mA/cm^2 for PAFC versus 160 mA/cm^2 for MCFC). This should raise the system efficiency by 14%.

The higher temperature of the MCFC permits its use in a combined cycle configuration to produce more electricity from its high-grade waste heat. MCFCs can use both a gas turbine as a topping device and a steam turbine as bottoming device in a combined cycle configuration to improve the overall electrical efficiency.

The system uses nickel-based electrocatalysts. Issues which need to be resolved include: electrode lifetime being too short, reduction of high temperature corrosion (this is required), and the need to scale up components.

Companies in the United States and Japan are pursuing this technology due to the inherent cost and efficiency advantages of the system.

Three options for reforming fuels for MCFC system exist (see Figure 8): external reforming, direct internal reforming (DIR—sometimes referred to as internal reforming (IR)), and indirect internal reforming (IIR—sometimes referred to as integrated reforming).

External reforming is conventional, with a separate reformer which produces a hydrogen-rich gas from hydrocarbons and steam. This technique is also used for PAFC systems.

In the internal reforming configuration the reforming catalyst is placed in the anode chamber of each cell. A direct heat transfer is feasible between the fuel cell reaction and the reforming reaction. The rate of methane conversion is also enhanced by hydrogen consumption at the anode. Additionally, the steam supply can be reduced because water is produced at the anode. Consequently a high efficiency of an MCFC system is expected when combined with internal reforming (65% in theory) whereby the waste heat from the fuel cell electrodes is utilized for reforming in situ.

The indirect internal reforming takes place in separate catalyst chambers that can be installed between some cells or adjacent to cell chambers. The objective is to transfer the heat of the electrochemical cell through the walls of the reformer for the reforming step. Controlling this heat transfer is technically challenging.

4.8. Solid Oxide Fuel Cells (SOFC)[21]

The high-temperature SOFC operation offers an important thermodynamic advantage because it can

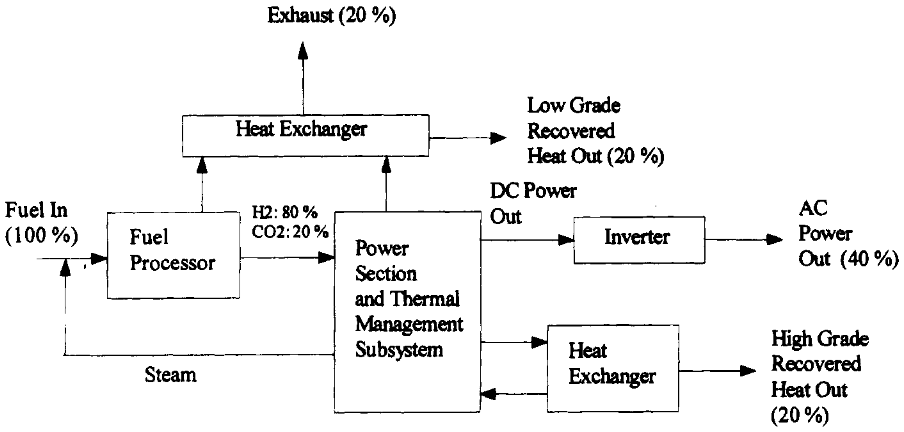

Figure 9. Power plant simplified block diagram.

be used as the topping device of a triple cycle, in combination with a gas and steam turbine. If operated in this mode, a SOFC generator would provide a higher efficiency than MCFC. Its long-term prospects in efficient power stations are therefore considered to be promising.

SOFCs do not suffer from the poisoning, leakage, or evaporation problems experienced by other fuel cell types. A thin ceramic electrolyte of modified zirconia is used. Zirconia is an insulator at room temperature but freely conducts oxygen ions above 900 °C. The electrolyte is coated with porous electrodes on both sides. The main manufacturing problems are brittleness, thermal expansion, and corrosion of the cell interconnection. The electrode reactions are given by eqs 5 and 6.

$$H_2 + O^{2-} \rightarrow H_2O \qquad (5)$$

$${}^1/_2O_2 + 2e^- \rightarrow O^{2-} \qquad (6)$$

Research is currently directed toward finding alternative materials to operate with comparable performance at lower temperature. Although operating at lower temperatures appears to be desirable, any measure which significantly reduces the oxide ion mobility would lead to an unacceptably high resistivity and thus to a poor performance. Alternative proton conductors, such as β-alumina, pose different problems.

SOFC systems seem to be further from commercialization than other systems but are currently being intensively researched in Europe, the United States, and Japan.[22,23]

5. On-Site Fuel Cell Power Plants for the Private and Industrial Sector

On-site power plants which cogenerate useful heating power are especially suited to provide electric power in an environmentally preferred way, contributing less to the potential climatic dangers of CO_2 production. Two aspects are important:

(1) Cogenerating on-site plants have a high overall efficiency because they produce electricity and usable heat (or steam). This combined (higher) efficiency in using the fuel materials is the reason why the relative amount of emissions released into the air is reduced.

Table 2. Specifications of the 50–1000 kW PAFC On-Site Plants

electrical efficiency	40% (LHV)
heat recovery	steam: 20–25% hot water: 20%
fuel	natural gas
start time	1.5–3.0 h
operation pressure	ambient pressure
form	container
footprint	installation area: 0.07–0.08 m^2/kW height: 3.2 m

(2) Using natural gas as fuel has the additional advantage that besides of the higher efficiency of the cogeneration, a relatively pure fuel gas is used. The flue gas after the combustion or reformation of natural gas is practically free of sulfur dioxide, dust particles, and heavy metal traces and is completely free of halogen compounds.

The development of phosphoric acid fuel cell power plants is now going in the direction of providing a part of the thermal energy in the form of steam with an efficiency up to 25%. Providing warm water yields an efficiency of 20% (see Figures 9 and 10). The present units of IFC/ONSI (USA) or Fuji Electric (Japan) provide only warm water at 40–80 °C. By comparing the new models with the older types (e.g. the PC 25, FE) it can be shown that the total exergetic efficiency is increased. The electrical energy efficiency stays the same. Table 2 gives a summary of the specifications of the future on-site PAFC plants. The life expectancy of the fuel cell stacks is estimated to be 40000 hours. This statement is made by all manufacturers. Ultimately the cost of the plants is projected to drop to $1.500 to $2.500 per installed kilowatt.

The following criteria have been used to compare fuel cell systems with conventional gas motors: efficiency, emissions, and cost.

5.1. Energetic and Exergetic Potential Estimation

In the past producer and user always discussed the total energy efficiency of a power plant. But the different forms of energy (electrical and thermal energy) and especially the different quality of the thermal energy have to be evaluated accordingly. Thermodynamics offers the model of the exergy.[24] Comparisons were made under special consideration of the Japanese developments.[25] The following phos-

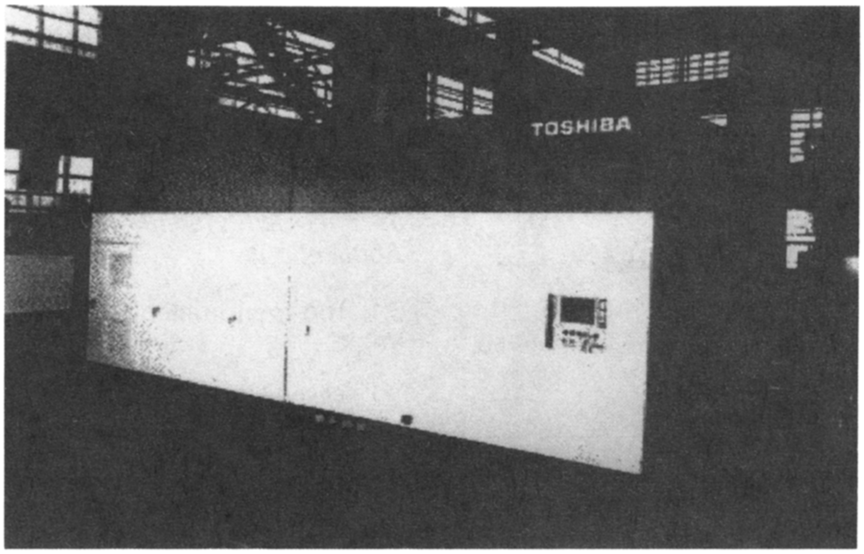

Figure 10. Figure of a 200 kW Toshiba fuel cell power plant.

Table 3. Energetic and Exergetic Potential Estimation

producer	IFC/ONSI	Toshiba	Mitsubishi	Fuji Electric			gas engine
electric power (kW)	200	200	200	50	100	500	350
energetic efficiency							
electric efficiency (%)	40.0	40.0	40.0	40.0	40.0	40.0	33.9
thermal efficiency (%)	44.0	40.0	45.0	40.0	43.0	45.0	51.2
steam		25.0	21.0		23.0	23.0	
hot water	44.0	15.0	24.0	40.0	20.0	22.0	51.2
energetic total efficiency (%)	84.0	80.0	85.0	80.0	83.0	85.0	85.1
exergetic efficiency							
electric efficiency (%)	40.0	40.0	40.0	40.0	40.0	40.0	33.9
thermal efficiency (%)	7.0	10.0	9.7	4.7	9.0	10.4	9.2
steam		8.2	6.9		7.2	7.5	
hot water	7.0	1.8	2.8	4.7	1.8	2.9	9.2
exergetic total efficiency (%)	47.0	50.0	49.7	44.7	49.0	50.4	43.1

phoric acid power plants were investigated: IFC/ONSI (PC25, 200 kW), Toshiba (TFC200, 200 kW), Mitsubishi (200 kW), Fuji Electric (50 kW, 100 kW, 500 kW), and a comparable gas-engine power plant (350 kW). The energetic and exergetic potential estimates are given in Table 3.

The comparable total energetic efficiency of the gas engine and the phosphoric acid fuel cell changes with regard to the total exergetic efficiency. The more recent phosphoric acid fuel cell plants (thermal energy in form of steam at 170 °C) have an exergetic efficiency between 49 and 50%. The comparable total exergetic efficiency of the gas engine is 43% (see Figure 11).

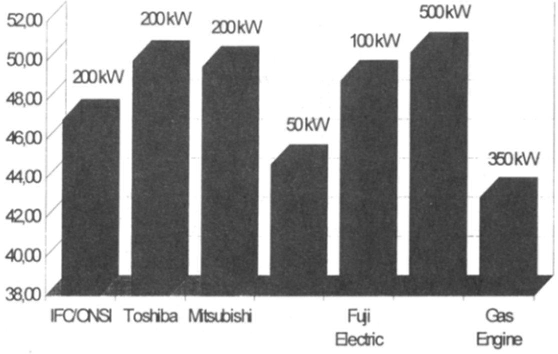

Figure 11. Total exergetic efficiency of the different power plants.

5.2. Ecological Comparison of the Pollutants

Among all fossil fuels, natural gas (CH_4) contributes the least to CO_2 emissions because of its high H/C ratio of 4. Figure 12 shows the calculated CO_2 emissions of the TFC-200 (200 kW, Toshiba) and the gas engine introduced in Table 3. The basis of the calculation is an energetic, exergetic, and electric consideration.

The emissions of classical pollutants NO_x, CO, and C_xH_y of the phosphoric acid fuel cell plants are negligible compared with the gas engine emissions. Therefore national and international laws represent no problems or restrictions for the introduction of the fuel cell technology. Table 4 shows the emissions from the PC25 (IFC/ONSI) and a comparable gas engine.

5.3. The Energy Costs for On-Site PAFC Plants

Gas and electrical utilities are mainly interested in the energy costs delivered by the power plants. For the following calculations the data from the PC25 of the Austrian Ferngas (Gas Utility), four data sets concerning gas engines from the STEWEAG (Austrian Electrical Utility) and two published records (BRD85, VKW) from German studies have been considered. Conventional gas engine on-site power plants are in operation only 3000 to 4000 hours per

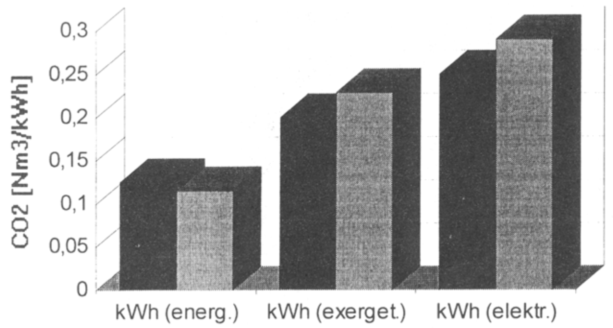

Figure 12. Comparison of the CO_2 emissions: darker shading, PAFC; lighter shading, gas engine.

Table 4. Comparison of Emissions

emissions[a]	PAFC on-site plant (mg/Nm^3)	gas engine (mg/Nm^3)	TA-luft[b] (mg/Nm^3)
NO_x	<10 (3.1)[c]	500	500 (250)
CO	<20 (5.7)[c]	650	650 (325)
C_xH_y	<15	150	150

[a] O_2: 5 vol %. [b] German emission standard. [c] PC25: after 1700 operation hours.

year. This is the reason why the different PC25 operating lifetimes have been used (Figure 13).

The thermal energy—cogeneration product—gives a calculated cost of 2.75 U.S.-cents/kWh. The electrical energy costs from the different gas engine power plants can be totaled in U.S.-cents as 11.53/kWh. The comparison shows that the PC25 ("precommercial pilot plant") has electrical energy costs similar to that of conventional on-site distributed power plants (calculation basis considering Austrian economic data sets, September 1994). This means that the fuel cell plant is already competitive with presently planned conventional gas engine power plants in Austria. After mass production of the fuel cell plants has started we can expect that also in future dispersed applications (for on-site power plants) fuel cells will have even more competitive advantages relative to gas engine plants. In summary the thermodynamic and ecological potential estimations confirm the statement that the phosphoric acid fuel cell technology represents an important approach for a sustainable future development. These evaluations pertain to dispersed fuel cell power plants in the range of 10–100 MW.

6. Fuel Cell Systems for Transportation Applications

6.1. The Environmental Benefits of Fuel Cell Vehicles

Fuel cell electrodes operate on hydrogen, no matter what the fuel supplied to the fuel cell system actually is. In direct fuel cells, pure hydrogen is fed to the electrodes. In indirect fuel cells the chemical which is the hydrogen carrier (methanol, ammonia, hydrazine, etc.), is first converted at a certain efficiency, producing side products (such as CO_2, as in the case of hydrocarbon conversion).

In any case, the use of a fuel cell system in a vehicle will lower the accountable pollution emissions due to its higher conversion efficiency. Compared with the heat engine it means that less carbon dioxide is produced per unit of energy which originally came from the fossil fuel. A highly efficient low-temperature fuel cell (like the alkaline system) is especially suited, for the case of a personal vehicle, where the waste heat is of little use, except perhaps in winter.

The advantages in reducing the overall CO_2 production (Figure 14) may also be true for the case where carbon, oil, or natural gas burning power stations produce electricity first and use it for electrolysis to make hydrogen. Of course, the specific circumstances must be carefully checked to arrive at valid comparisons. Only the energy values are indicative of the true efficiency of the whole chain of conversions. No CO_2 pollution problem seems to exist with the electric power production via water power, nuclear energy, wind, or solar installations.

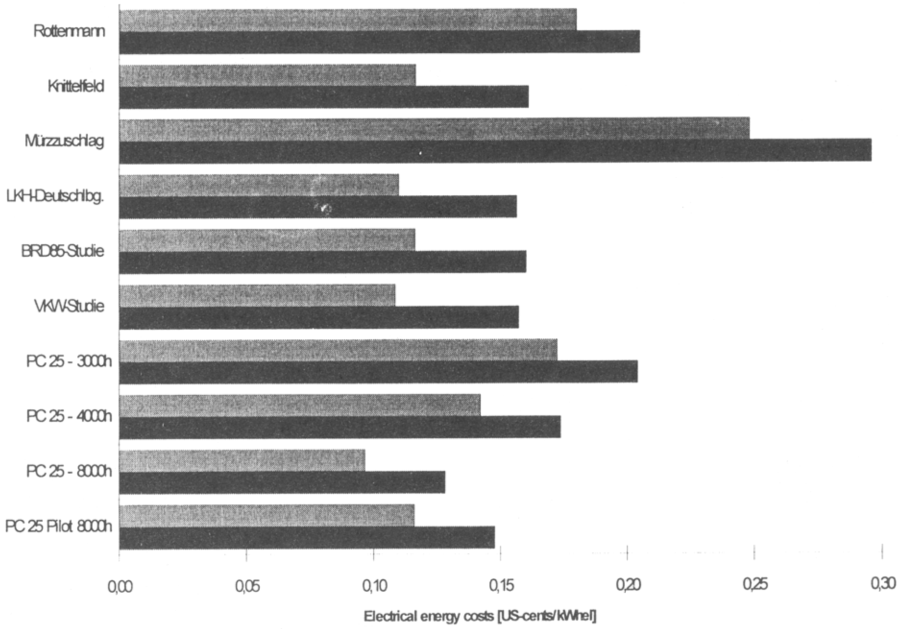

Figure 13. Electrical energy costs in U.S.-cents/kWh; with and without credit of the thermal energy of 2.75 U.S.-cents/kWh_{el}.[36] (Calculations basis considering Austrian economic data sets, Sept 1994).

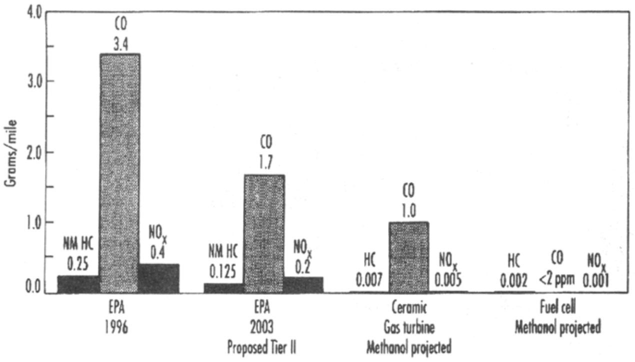

Figure 14. Future passenger car emissions.

Table 5. Presently (1993) Proposed Electric Vehicle Batteries[a]

systems	Pb/PbO_2	Ni/Cd	Na/S	Zn/Br	Ni/Fe	Ni/Zn	$Na/NiCl_2$
Wh/kg	35	50	120	70	60	80	100
W/kg	160	200	180	80	100	200	100
cycles	400	500	500	500	500	200 ?	400 ?
U.S.$/kWh	250	1500	1200	400 ?	800 ?	600 ?	1000 ?

[a] The Ag/Zn system is not considered due to its cost. The bipolar Pb/PbO_2 system is only in the prototype stages.

Table 6. Proposed/Achieved Performance of "Advanced" Batteries[a]

systems	Li/FeS_2	Li/polymer	Zn/MnO_2	Al/air	Zn/air
Wh/kg	180	200 ??	80 ?	200 ?	150 ?
W/kg	200	400 ??	100	100	100
cycles	1000 ?	300 ?	200 ?	Al	Zn
U.S.$/kg	500 ?	500 ?	250 ?	500 ?	500 ?

[a] Al/air and Zn/air cells exchange the anodes and electrolyte.

Some estimates speculate fuel cells will power 15–30% of the light duty vehicles by the year 2030. The savings expressed in barrels of oil saved as compared to 1990 are estimated to be enormous. The economic benefits from the methanol fuel cell scenario are said to be especially high. Even more can be saved by operating with hydrogen fuel. The amount of avoided pollution and air quality predictions can also be estimated. Detailed data were published by the U.S. Department of Energy, Office of Propulsion Systems and the U.S. Environmental Protection Agency within the Multiyear National Program Plan for fuel cells in transportation.[26]

6.2. Present Day Electric Vehicle Technology

The performance of electric vehicles, especially with lead–acid batteries, is generally poor if compared with that of gasoline or diesel engine powered automobiles. It must be recognized that this fact is mainly the result of the energy limitation of the battery, which determines the possible operational vehicle range. The power output is not the dominating problem. In order to be able to drive as far as possible, the weight of the batteries installed in some vehicles reaches nearly half of the total weight. In a vicious cycle this weight decreases the acceleration and grade climbing capability. The safety of some high-temperature batteries is also in question.[27] Tables 5 and 6 present data concerning the performance of presently proposed and so-called "advanced" batteries, respectively.

The double logarithmic diagram of Figure 15 presents a comparison between different electric vehicle propulsion battery systems. It is the specific energy content versus specific power density ("Ragone plot") for various battery systems, each weighing 300 kg (fuel cells have sufficient fuel in the tank, included in this weight). A vehicle weight of one ton is assumed. Such diagrams have been essentially unchanged for 15 years, indicating, to a certain extent, the lack of progress in the battery field as far as available systems are concerned.

The production qualities and lifetimes of batteries have changed, but not the application possibilities for vehicles competing with combustion engines. Gasoline (IC) engine data occupy the right upper corner of the diagram, the 500–600 km range at very high specific power values (over 400 W/kg). This indicates immediately that a Ni–Cd battery in parallel with a H_2–air fuel cell could match that performance in a hybrid configuration.

A serious disadvantage of the combustion engine is that low fuel consumption and low emissions peak

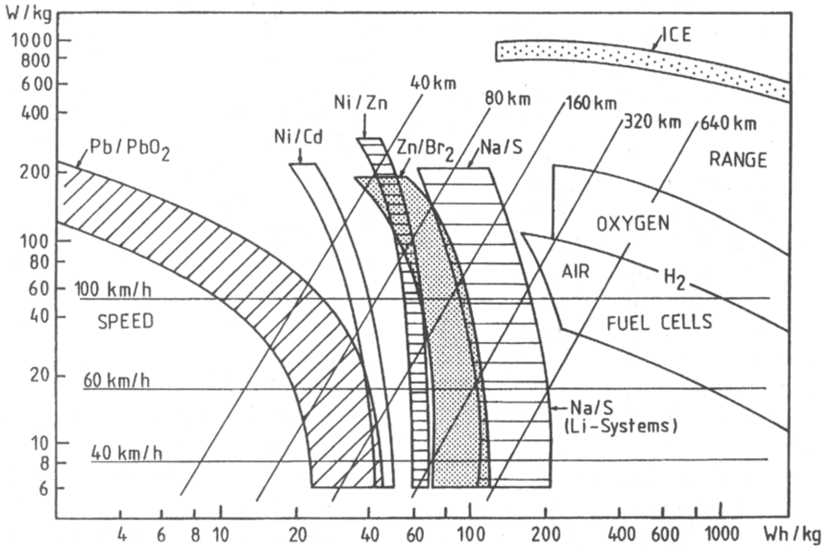

Figure 15. Working range of different battery systems (Ragone plot) showing the energy density as a function of the power density. Future bipolar batteries are not included.

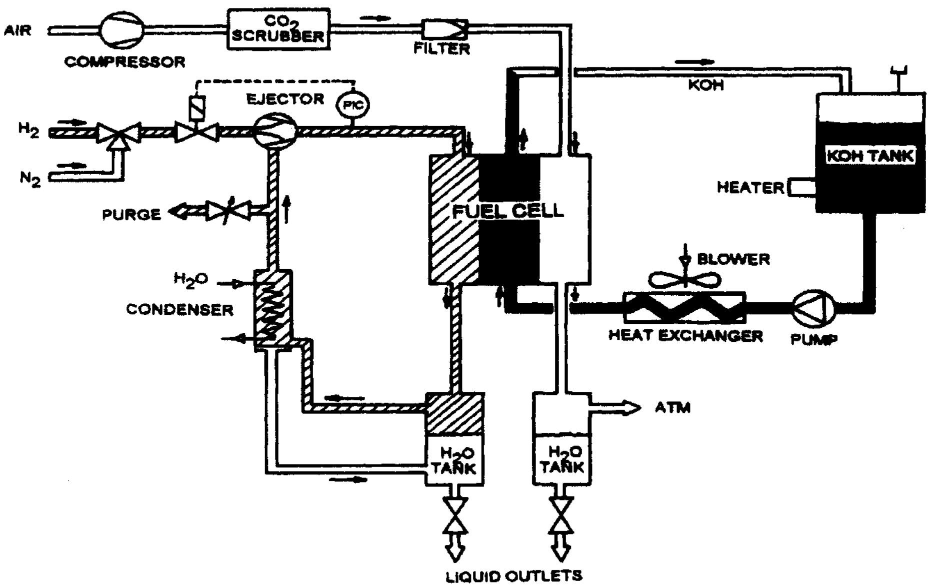

Figure 16. Flow sheet of the ELENCO H_2/air fuel cell system.

during continuous operation, while a fuel cell system is better on part-time duty. Also on high peak power the fuel cell hybrid system is superior, this on top of the principal 2-fold thermodynamic efficiency of the fuel cell over the heat engine. The lifetimes of combustion engines are in the 2000 operating hour range over a 10 year calendar life. Fuel cells can match that too, as will be shown later: calendar time can be very much prolonged if an intermittent use is considered. In this respect, fuel cells for vehicles can be of lower cost per kW and will be differently designed than fuel cell systems for power plants, which require at least 40000 hours of active operational life.

The 2000 operating hours correspond to approximately 200000 km of driving distance of an average automobile. Only buses reach millions of kilometers driving distances during their lifetime.

6.3. The Fuel Cell Vehicle Technology of the 1980s and 1990s.

6.3.1. Alkaline Fuel Cells for Electric Vehicles

The ELENCO Fuel Cell System. ELENCO has developed multilayer gas diffusion electrodes based on PTFE-bonded graphite and carbon layers backed by a nickel-plated screen and a porous PTFE layer on the gas side. The platinum content is about 0.3 mg/cm^3. The electrode thickness is less than 0.5 mm. In its automated manufacturing plant, the company can produce up 200000 electrodes annually. This is equivalent to 2000 kW of fuel cell power output. The electrodes are set into frames by injection molding, using ABS-type thermoplastic materials. The framed electrodes are friction-welded into 24 cell modules with an output of about 0.5 kW each. This is the smallest standard unit which can be built as an operational module. The modules can be connected in series and/or parallel configurations to form the stacks needed for specific applications. The largest fuel cell installation built by ELENCO contained 120 modules (52 kW), it was a mobile power supply for the Belgian Geological Service. It was laid out for 220 V and it was aimed at driving ground drilling machines.

The electrodes have a normal operational lifetime of 5000 h. The system uses pump-circulated KOH–electrolyte and a CO_2 scrubber in the air inlet stream. The water is condensed out in the hydrogen loop which contains a jet pump.[28,29]

ELENCO started in the electric vehicle field with a VW van powered by 32 modules (14 kW) of H_2–air fuel cells. The vehicle served as a "laboratory on wheels" and went through several modifications. The driving range with compressed hydrogen in steel cylinders was about 200 km. The first vehicle used a dc motor.

The EUREKA Bus Project. The project was initiated in 1989 by a study phase, and a cooperation agreement between the EUREKA partners was reached in May 1991. In October 1991 the bus construction started. A demonstration of the completed fuel cell operated vehicle was planned for late 1993, but has been postponed for 1994 (Figures 16 and 17).

The alkaline fuel cell system is the responsibility of ELENCO, N.V., Belgium. The additional Ni–Cd booster battery is to be supplied by SAFT, Industrial Battery Group, France (a subsiduary of Alcatel-Alsthom), the liquid hydrogen supply is provided by AIR PRODUCTS, Industrial Gas Division, Netherlands. The dc power converter system is constructed by ANSALDO Ricerche, S.r.l., Italy. The estimated final cost of the EUREKA project EU 201 is 4.25 million ECU (U.S.-\$3.43 million). The design parameters of the demonstration bus are listed in Table 7.

6.3.2. Phosphoric Acid Fuel Cells for Electric Vehicles

The DOE Program for Fuel Cells in Transportation. The program plan proposes a comprehensive cost-shared partnership between government and industry to accelerate the R&D of fuel cell technologies to enable their commercialization by the auto industry soon after the year 2000. This mission focused program expands upon the present DOE fuel cell

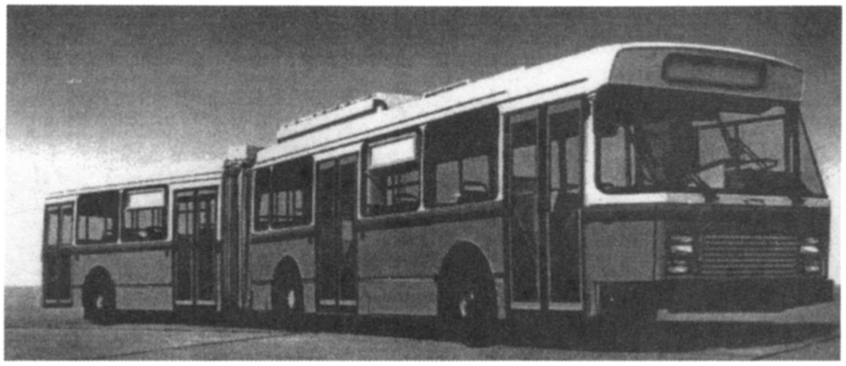

Figure 17. Picture of the EUREKA demonstration bus (1994).

Table 7. Design Parameters of the EUREKA Demonstration Bus

configuration	articulated design
turning radius	10.9 m
weight, empty	20600 kg
fuel	liquid hydrogen (LH_2)
fuel consumption	15 kg LH_2 per 100 km
operating range	300 km
exhaust (emission)	air, water vapor
passengers	80
total fuel cell power	80 kW
Ni–Cd buffer battery	775 V, 80 Ah
traction system (ac)	800 V
nominal power of the hybrid system	180 kW

program. The goal is to establish fuel cell vehicles (FCV) as a cost-effective replacement for internal combustion engine (ICE) vehicles as rapidly as possible.[30]

The objectives are as follows: (1) complete the demonstration of fuel cell urban transit buses by the year 1995; (2) establish the feasibility of multiple vehicle concepts to fabricate prototypes by 1998; (3) establish commercial viability of FCVs in small fleets (50–200 vehicles) by 2000; (4) the first generation of commercial FCVs is provided by 2005; and (5) begin sales of FCVs by 2011.

The technical plan for fuel cells in transportation includes (Figure 18): (1) phosphoric acid fuel cell (PAFC) system designs for buses, locomotives, and trucks; and (2) proton exchange membrane fuel cell (PEM) development for automobiles.

The PAFC City Bus Program. This program is a multiphase effort to develop and demonstrate a methanol-fueled PAFC propulsion system for urban transit buses. The reasons for selecting such an application for the development phases are many: (1) a first generation FC system needs a large vehicle to accomodate test instrumentation; (2) the regularity of a city transit route permits testing under better controlled conditions; (3) the environmental benefits are the largest in a city environment; and (4) the cost comparison is made with methanol-fueled (converted diesel) urban buses.

The PAFC system with a reformer (and in a battery hybrid configuration) was chosen because this FC system was considered (in 1990) to be at a high prototype development stage. The PAFC should provide the average power, and the secondary batteries, the peak power (see Figure 19).

At the start of phase I (1987) one of the industrial FC contractors was Energy Research Corp. (ERC) and Bus Manufacturing, USA, Inc. (BMI), with technical advice provided by Los Alamos National Laboratory (LANL) and management by Georgetown University personnel. ERC had experience in building PAFC systems for small vehicles (lift trucks). As the secondary battery the plastic bonded Ni–Cd system was considered, used in a load leveling (shunt) mode (without electric power converter) to accomodate the hybrid setup. Half-sized brassboard systems were built and evaluated.

The 240-cell stack performance was shown to be 150 V, 240 A (36 kW). The methanol reformer used a commercial Cu–Zn catalyst for reforming and shift reactions, its weight was ca. 100 kg and could provide

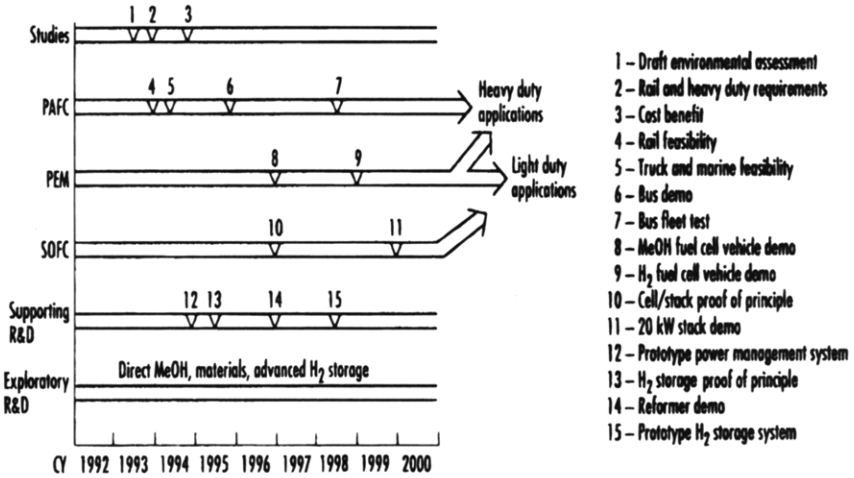

Figure 18. Activities schedule for fuel cells in transportation.

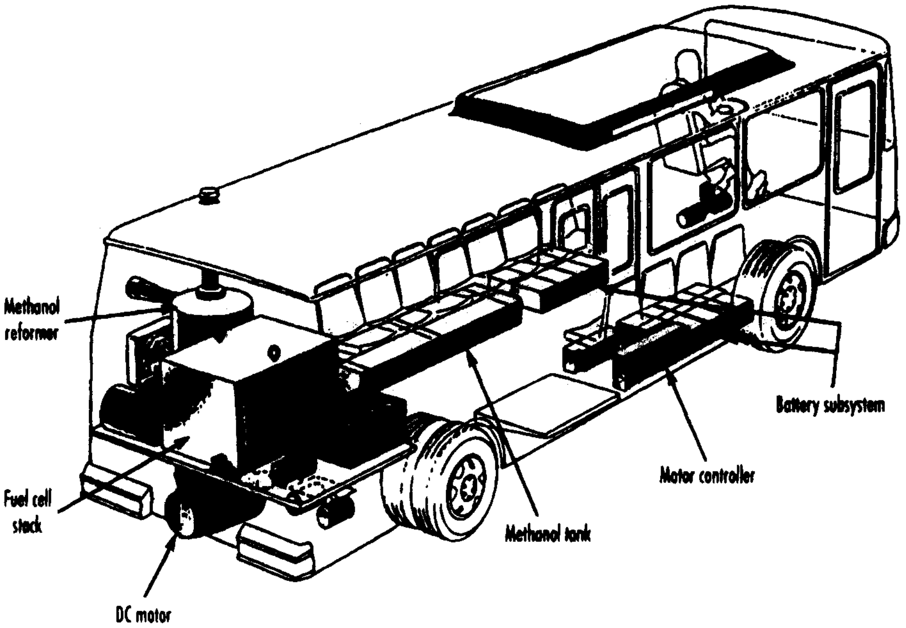

Figure 19. Layout of the fuel cell-powered urban bus for 25 passengers, sponsored jointly by the DOE and the California South Coast Air Quality Management District.

a hydrogen flow corresponding to a full 60 kW fuel cell output. The surge power (nonsintered) Ni–Cd battery had 110 cells of 100 Ah capacity (5 h rate). Fuel cost estimates based on improved brassboard performance (with heat recovery) revealed that the diesel engine bus costs could be fully matched ($1.57/mile in 1990).[31]

In phase II (April 1991) the PAFC system of FUJI was selected and a brassboard model of half the bus size underwent performance tests. The prime contractor was now H-Power Corporation. The program integration became the responsibility of Booz, Allen & Hamilton. BMI continued the design of the 40 ft city bus; SOLEC Corp. engineered the motor controller and power conditioner. As booster battery a lead–acid battery was chosen.[32] A status report was given late in 1992.[33] In phase II, the objective was to build three buses, to be delivered in 1993 and 1994, but the program was delayed, the full bus-size PAFC was not delivered. The first of the buses began operation in the spring of 1994 and is now undergoing testing. It seems now also possible that the PEM-fuel cell project may show better technical aspects which will result in a review of the PAFC vehicle project.

In May 1992 a program was started by DOE to investigate the best way to design methanol and hydrocarbon reformers for vehicle fuel cells. A 30 month, cost-shared contract was given to Arthur D. Little, Inc. of Cambridge, MA. The first phase is a feasibility study, the second phase is a fabrication and prototype testing effort. The best reformat requirements for PAFC and PEM fuel cells will be studied in the first part. A report on the reformer situation was given at the 1992 Fuel Cell Seminar.[34] Phase II is supposed to be finished at the end of 1994.

Methanol has the advantage of reacting with steam readily at about 200 °C on suitable, low-cost catalysts. Saturated hydrocarbons need far higher temperatures (700 °C), and it is not assured that they can be used in reformers suited for vehicles. Some processing difficulties can only be solved in stationary stations and therefore the view has been expressed that molten carbonate or solid oxide fuel cells may be a better choice because they do not need a separate reforming step. On the other hand, there is no question that these systems can only be used in large size mobile applications (e.g. locomotives) but not in street vehicles.

Other fuel storage possibilities like metal hydrides and liquid hydrogen are also being compared with the reforming methods. Hydrogen generators which used magnesium and sea water as reactants were considered for marine buoys, using SPE-fuel cells.[35] Iron sponge which reacts with water to produce hydrogen at high temperatures (over 700 °C) was suggested by H-Power Corporation as a low-cost hydrogen source. The basic idea is that iron sponge can be produced in large-scale reduction furnaces from iron ores and can be stored and transported in small containers or in truckloads alike. The thermal balances have not been clearly stated and therefore studies have been made at the Technical University Graz to establish the feasibility of this concept.[36]

6.3.3. The Proton Exchange Membrane Fuel Cells for Electric Vehicles

The DOE-PEM Fuel Cell Program. The Department of Energy's R&D Program sponsors basic and applied research on proton exchange membrane (PEM) fuel cells which are believed to have significant advantages over the PAFC system, once it is fully developed. These advantages would be reduced weight and size, due to high current density output; fast start up from room temperatures and operation at 80–100 °C; lower cost over a longer operational life span; operation on air (tolerating the CO_2) and simple reformates; and the easy of the stack (sealing) design due to the immobilized electrolyte.

The principal difference to the alkaline system is that the proton (H^+) is the migrating species and the water is produced at the cathode (oxygen electrode). With the PAFC fuel cell it shares the possibility of

Table 8. Schedule of the PEM Fuel Cell R&D Program of the DOE

phase I	testing of the state of the art: study of several 5 kW PEM systems of Ballard Power Systems; new Stack fabrication also by Ballard prime contractor: Allison Corp.[39] Reformer development and fuel cell testing: Los Alamos National Laboratory membranes: Dow Chemical Comp. catalysts: General Motors Corp. vehicle System: General Motors Advanced Engineering overall management: Argonne National Laboratory
phase II	starting in 1993: Feasibility up to 25 kW systems
phase III	starting in 1995; Scale up to 50 kW
phase IV	starting in 1996; vehicle testing

using CO_2-containing hydrogen as fuel gas. However, there are also serious disadvantages which may not be easily eliminated: a high sensitivity to a few ppm CO in the fuel, requiring extreme cleaning efforts; the high cost of the platinum, which is presently used at the 4 mg/cm^2 level; the high cost of the membrane, in spite of great efforts to lower the price; the system must be pressurized, which leads to inefficiencies on the air side; and the water content of the fuel gas must be kept high to prevent dehydration of the membrane and an increase in resistance.

One point has been solved recently at the Los Alamos National Laboratory: in experimental cells the Pt level has been lowered to 0.1 mg/cm^2 with a tolerable loss in cell performance.[37] The other points have been the subjects of development efforts: an oxidizer must be added to the fuel to eliminate the CO. Presently air is added to the fuel to reduce the CO from about 0.5% to a few ppm. A turbocompressor pressurizes the air to at least 3 bar. An additional water removal system must be designed, because extra water is added to the gas entering the stacks for keeping the humidity above 400 mm H_2O.[38]

The very high current densities which can be drawn from the PEM electrodes led to suggestions operating without a booster battery (Ballard). However, there is a trade-off between power output, need for expensive accessories, size, and above all, *cost*. Heat management is also an important point. Therefore, the DOE proposal of a hybrid system is really justified.

The PEM-Program of DOE is divided in four phases as described in Table 8.

It should be recognized that the idea to use an organic ion exchange membrane as solid electrolyte and separator in an electrochemical cell was first described in the early 1960s by W. T. Grubb of General Electric Co. and that it took nearly 40 years until the first practical applications were found. The use in vehicles was always contemplated, research into membrane cells for space applications was a continuous project for General Electric Co. and NASA space efforts, but the key question was the reliability and the absence of "pinholes" in the membranes. The situation changed when DuPont Co. introduced the NAFION membranes. Further progress after the introduction of new membranes by Dow led to the general decision that electric vehicles should use PEM fuel cells.[40] The company which was most active in the field and practically assured a coverage of the field was Ballard in Vancouver, BC, Canada.

The Ballard Bus System. Ballard in conjunction with the Province of British Columbia and the Government of Canada has begun a program to develop a commercial transit bus powered by Ballard's PEM fuel cells. Phase I began in November 1990. The bus was designed to operate solely on the fuel cell system (later with a secondary battery only to be used for the storage of energy from regenerative braking). The goal is to demonstrate the same performance capability as the corresponding commercial diesel bus. The hydrogen is supplied from six steel cylinders stored under the bus floor.[41] Optimization is planned in phase II of the program. The bus demonstration was successfully made in mid-1994 (Figure 20).

6.4. Technological Outlook and Conclusion

The feasibility of electric vehicles to operate on fuel cell power plants is a fact. The choice of the type of

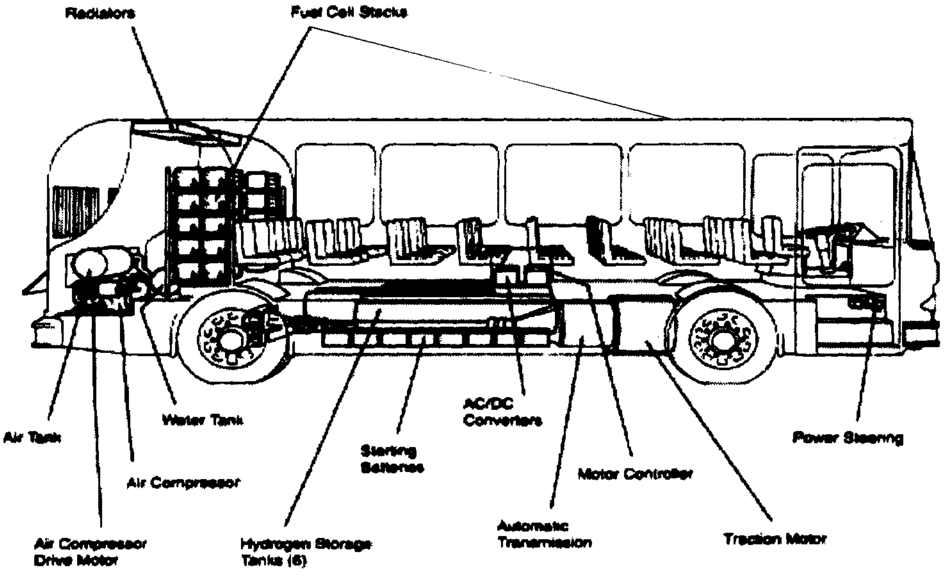

Figure 20. Picture of the Ballard PEM-fuel cell operated bus for 32 passengers.

fuel cells is still open but has been narrowed to the low- and medium-temperature fuel cell systems. The idea of oxidizing hydrocarbon fuels directly in high-temperature systems, preferentially in solid oxide fuel cells is at least at the present time speculative. It should not be forgotten that the electrochemical conversion is most efficient at low temperature and that it is not very practical to use the waste-heat of such "dispersed power generation systems" as automobile propulsion systems. This is, of course, different with stationary power plants.

It appears that the type of fuel cell to be used in street vehicles will ultimately be decided by economic questions and answers. Such an investigation has recently been made by Olle Lindström.[42]

Applying the teachings of the historical developments to predictions about electric vehicle fuel cell developments, the AFC may even have a better chance than the PEM systems. This statement may appear prejudiced and colored by personal experiences, but it can stand to be challenged. Even simple "hindsight" (which is usually right) can come to similar conclusions. However, there are also hard facts:

The best performing fuel cells are the alkaline "space vehicle systems". Since 1970 they are performing reliably on oxygen and hydrogen at high current densities (1 A/cm^2, at 0.75 V). The Russian PHOTON (Figure 7) needed 40 mg Pt/cm^2, NASA shuttle units can do it at low Pt loadings. Catalyzed carbon substrates have been successfully used in air electrodes, which since 1960 deliver current densities between 100 and 150 mA/cm^2 at 0.75 V. Only PEM electrodes can do better now, but at a tremendous increase in cost and complexity of the system.

Practically all systems have arrived at the thin electrode and/or bipolar construction of the battery stacks. The alkaline "OXY" was an excellent prototype system, which was already geared for mass production before the company went out of business. The ELENCO alkaline system is still the only publicly demonstrated fuel cell which looks economically affordable. In this connection it should also be mentioned that no large funding has gone into the development of alkaline systems for street vehicles during the last 15 or 20 years.

The lifetime question is always brought up with the goal set at 40000 hours. This is only a requirement for power stations. It is questionable if fuel cells which should operate in the field and not under strictly controlled conditions will be able to approach such time periods without the possibilities of replacement of components (electrode stacks, electrolytes, or accessories).

The automobiles of the 1960s may prove to be a good comparison: oil changes were frequent, lubrication needs were apparent, and the exchange of components (pumps, fans) was regularly anticipated. Still, today in the 1990s we do not expect a gasoline engine to operate for more than 2000 h without an overhaul. Why should a street vehicle fuel cell stack be required to do much better, especially if it is built mainly from essentially low-cost materials (like carbon) and a small amount of catalysts, which can be easily recovered.

The key wording is therefore: *hours of "operation"*. In this matter the city car of Kordesch has already shown proof of concept and its reliability details. The most significant difference, if compared with all previously and later built and driven fuel cell vehicles was the possibility to shut down completely between operational periods, like a combustion engine usually does. The "unavoidable" consequences were the electrolyte could be exchanged when visibly "dirty" or partially carbonated (pH-change!); the gas manifolds could be washed when clogged; and the well-known process of "regeneration of catalysts" by exposing the electrodes occasionally to the opposite gas (which meant polarization in the other direction) was performed at each shutdown. This method was patented by other researchers later. The layout as a hybrid fuel cell system was of great importance: the parallel connected (shunted) lead–acid battery prevented damaging parasitic currents and high-load electrode polarization into the voltage range where Pt or Pd solubility increased; and the parallel secondary battery eliminated all operational waiting periods and driving delays. Last, but not least, the circulating KOH system was self-regulating in its concentration range, and cooling problems or gas cross-leakage possibilities did not exist. The fact that the water was produced at the anode made the elimination easy by simple H_2 recirculation.

The design of both electrodes as hydrophobic porous carbon sheets with a gas permeable repellent backing was standard with Union Carbide electrode made in the 1970s. The electrodes were wetproofed in steps (by multiple spraying-with increasingly repellent catalyzed active carbons). This procedure was probably responsible for the reestablishing of properly functioning interfaces, each time the stacks were refilled with KOH after a shutdown. It should be noted that the carbonate formation was also minimal because the electrodes did not wet deeply, as is e.g. the case with Pt-catalyzed graphite/carbon PTFE layers. Surface wetting was also partly "reversible" and not "permanently established", like in cells with microporous asbestos layers or other separator-type immobilized KOH electrolytes.

Experience and post-mortem studies of the stacks showed that the failure mode of the cells was mainly leakage at the frames, especially where the polysulfone sheets and metal terminals met. A nonuniformity of the electrode interfaces related to gas and KOH manifolding was also noticeable. This was not surprising because the whole system was hand built. In 3 years only two 6 V H_2–air modules (out of 15) had to be exchanged for sudden loss of performance.

Unfortunately, the shutdown of electrode production and fuel cell testing at Union Carbide Corp. in the mid-1970s prevented a more detailed analysis and more experimentation with batteries and stacks in the intermittent operational mode of an electric automobile. At other companies the efforts were directed to immobilized electrolytes and finally to PAFC systems.

Conclusion. It may pay to reinvestigate alkaline fuel cells with circulating electrolyte from the view points of actual combustion engine duty cycles.

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