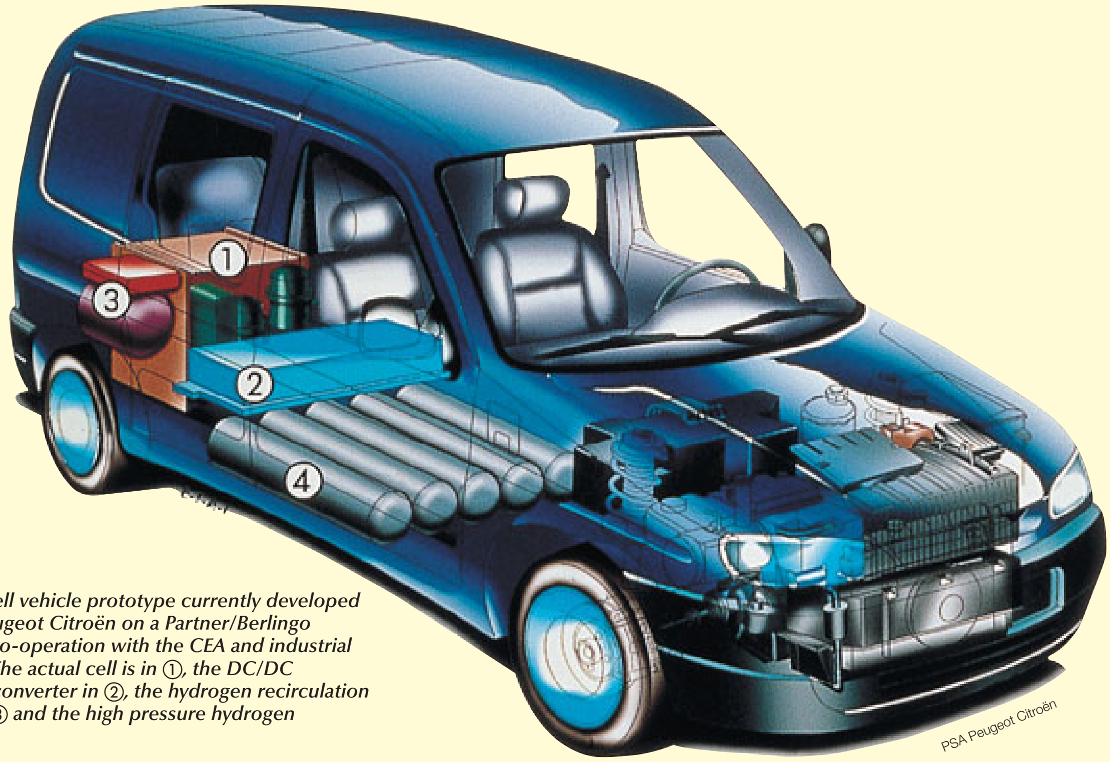
II. ENERGY CONVERTERS

fuel cells are shaping the future in many ways

Reducing emissions of carbon dioxide (CO_2), the most worrying of the greenhouse effect gases produced by combustion of hydrocarbon compounds, including the hydrocarbons (oil, natural gas) extensively used for production of electrical, thermal and mechanical energy, is a major objective. It can be pursued in two ways: by increasing the efficiency of energy converters using hydrocarbons or by using non-fossil fuels. In the latter case, there are two solutions: hydrogen and bio-fuels. "Clean" hydrogen can be synthesised by electrolysis from electricity produced without emission of CO_2 (wind, solar, hydraulic and nuclear power) or by gasification of biomass products (*see chapter I*). Fuels derived from the latter, such as diester, ethanol and bio-gas, are already on the market, while others are being studied such as dimethyl ether, methane and methanol. Work conducted on hydrogen and the fuel cells using it, to which the CEA has contributed, is based on these two approaches. To begin with, the hydrogen of these cells could be supplied through reforming (external or internal) of hydrocarbon compounds.

The efficiency of most energy conversion systems is mediocre. However, this is not the case of electricity generators using fuel cells, whose efficiency, approximately 50%, is far greater than that (around 30%) of electro-diesel generators and turbines. Even for transportation and thus mechanical energy production, the efficiency of a fuel cell generator and that of a diesel engine are comparable (around 35%). However, the fuel cell is only just starting to be developed! Intended for applications beyond the electric vehicle, its restrictions are currently linked to cost. The aim is thus to considerably lower these and increase the reliability of systems – stationary or mobile – that can be built around this type of cell. The CEA is involved in all the different stages of this project, the benefits of which are keenly awaited by industrial firms. Today, the CEA has everything it needs (digital, experimental platform, knowledge of materials and reaction mechanisms, system approach) to accompany its industrial partners wishing to develop and market proton exchange membrane fuel cells (PEMFC) of several tens of kW.

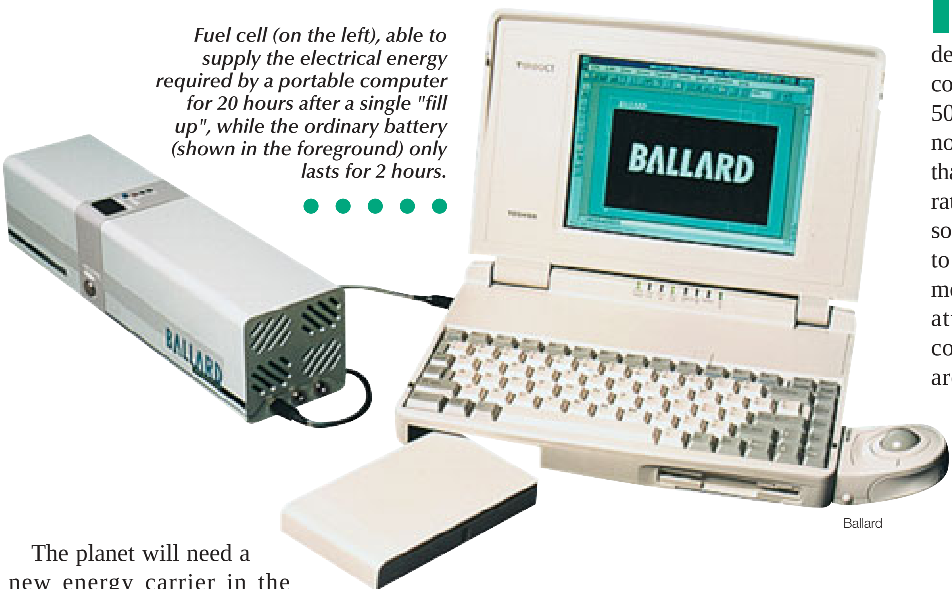


The fuel cell vehicle prototype currently developed by PSA Peugeot Citroën on a Partner/Berlingo model in co-operation with the CEA and industrial partners. The actual cell is in ①, the DC/DC electrical converter in ②, the hydrogen recirculation circuit in ③ and the high pressure hydrogen tank in ④.

The fuel cell: a solution for energy and environmental concerns

With its excellent capacity to convert hydrogen, the energy carrier of the future, into electricity, the fuel cell is on the road to fame and fortune. Initially limited to applications where cost was a secondary factor, this type of cell can henceforth aim at large-scale markets, starting with fixed installations for the production of electricity and heat. Furthermore, it has long been promised a glorious future as the power supply source of electric vehicles. Just beginning to get off the ground in the public transport sector, it will require more research and development if it is to be affordable in private vehicles. The general objective of the CEA and its industrial and research partners in the two most promising areas (PEMFC and SOFC fuel cells) is to lift certain scientific and technological barriers. Progress made means that this type of cell could also be used on the booming portable device market.

Fuel cell (on the left), able to supply the electrical energy required by a portable computer for 20 hours after a single "fill up", while the ordinary battery (shown in the foreground) only lasts for 2 hours.



Ballard

The planet will need a new energy carrier in the future. There are of course several candidates for the job but there is a general consensus today on hydrogen, although the time scales for its implementation have not yet been fixed. So, hydrogen it is. However, a good **converter** is then needed to convert this carrier into usable energy (mainly electricity and heat): this will be the role of the **fuel cell** that, thanks to its more attractive performance, should gradually replace traditional "thermal" conversion methods (engines and turbines). We know how it works (see box E) and that it can be applied in various cell types, according to the applications considered, which differ mainly by type of **electrolyte** (see table).

The various types of fuel cell

The various types of cells commonly developed normally operate around a point corresponding to a **gross efficiency** of about 50%. One of the key features of these technologies is the electrolyte. The table shows that, out of these five types of cell, three operate with a liquid electrolyte and two with a solid electrolyte. For reasons mainly relating to reliability and mass production requirements, the solid electrolyte concept is more attractive. Consequently, international consensus currently gives priority to two areas: **proton exchange membrane** fuel cells (PEMFC) and solid oxide fuel cells (SOFC). This corresponds to the choice made by the CEA in its R&D programmes.

Cell type	Electrolyte	Temperature (°C)	Area of use and power range
Alkaline (AFC)	potassium (liquid)	80	space - transportation 1 - 100 kW
Proton exchange membrane (PEMFC)	polymer (solid)	80	portable, transportation, stationary 1W - 10 MW
Phosphoric acid (PAFC)	phosphoric acid (liquid)	200	stationary, transportation 200 kW - 10 MW
Molten carbonate (MCFC)	molten salts	650	stationary 500 kW - 10 MW
Solid oxide (SOFC)	ceramic (solid)	700 to 1 000	stationary - transportation 100 kW - 10 MW

Table: different types of fuel cell.

E

How the fuel cell works

The Welsh scientist, William Grove, first demonstrated how the fuel cell worked in 1839. It is normally said to do the opposite of what happens in **electrolysis**. To be more precise, it consists of controlled electrochemical combustion of hydrogen and oxygen, with simultaneous production of electricity, water and heat, according to an universally known global chemical reaction:

$$H_2 + ½ O_2 ⇨ H_2O$$

This reaction takes place within a structure mainly consisting of two **electrodes** (the **anode** and the **cathode**) separated by an **electrolyte**. It can occur in a wide range of temperatures, from 70 to 1 000°C (figure). Although the intermediate chemical reactions involved vary according to temperature and the nature of the electrolyte and electrodes, the general principle remains the same. For the five major cell families (see table), the electrochemical reactions involved are as follows:

- alkaline fuel cell (AFC)

with the anode: $H_2 + 2 (OH)^- ⇨ 2 H_2O + 2 e^-$
with the cathode:
$½ O_2 + H_2O + 2 e^- ⇨ 2 (OH)^-$

- **proton exchange membrane** fuel cell (PEMFC)

with the anode: $H_2 ⇨ 2 H^+ + 2 e^-$
with the cathode:
$½ O_2 + 2 H^+ + 2 e^- ⇨ H_2O$

- phosphoric acid fuel cell (PAFC)

with the anode: $H_2 ⇨ 2 H^+ + 2 e^-$
with the cathode: $½ O_2 + 2 H^+ + 2 e^- ⇨ H_2O$

- molten carbonate fuel cell (MCFC)

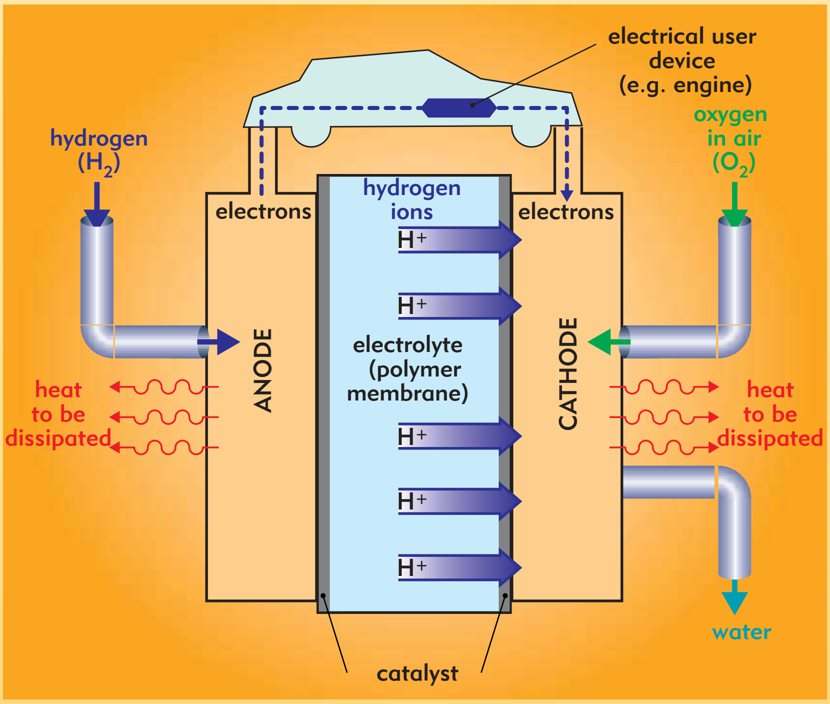
with the anode:
$H_2 + (CO_3)^{2-} ⇨ H_2O + CO_2 + 2 e^-$
with the cathode:
$½ O_2 + CO_2 + 2 e^- ⇨ (CO_3)^{2-}$

- **solid oxide** fuel cell (SOFC)

with the anode: $H_2 + O^{2-} ⇨ H_2O + 2 e^-$
with the cathode: $½ O_2 + 2 e^- ⇨ O^{2-}$

For more details:

Les piles à combustible: application au véhicule électrique, C. Lamy and J.M. Léger. Journal de Physique IV, Colloque C1, addition to the Journal de Physique III, volume 4, January 1994.
Fuel Cell Systems, Leo J.M.J. Blomen and Michael N. Mugerwa, Plenum Press.



Three main areas of application

Today's society offers many potential fuel cell markets. These are normally divided into three main categories of application: "portable equipment", "stationary equipment" and "transportation".

"Portable equipment" applications

This category mainly includes the mobile telephone (which consumes an average power of around 400 mW, 50 mW on standby and 1 W in conversation) and the portable computer (which consumes 10 W on average). Both applications are in a period of marked growth, but are increasingly handicapped by the life of their **battery**, even the most efficient such as the lithium-ion battery. The latter currently has a **specific energy** of around 160 Wh/kg, normally leaving a few days' battery life for a telephone and roughly 3 hours for a portable computer. Today, customers are currently asking for 3 to 5 times more, while the electrochemical battery has almost reached its limits. To give an idea of what exactly is at stake, just consider the "portable equipment" market: 300 million units sold for mobile telephones by the end of 1999 on world-wide scale and 640 million scheduled for 2005; 18 million portable computers sold in 1999 and 40 million scheduled in 2005.

The solution currently being researched in depth, mainly in the USA(1) is a fuel cell charging a small battery providing a better energy supply during transmission peaks (see *Miniature fuel cells*). Battery life will then only be limited by the size of the hydrogen or methanol tank. The user will recharge his portable just as he recharges a cigarette lighter or an ink pen, in a few seconds, and each recharge will give 3 to 5 times more battery life than present-day batteries. But the great thing is that they will take up the same amount of space! Enthusiasm for this sector is such(2) that today it is the sole subject on the agenda of many international congresses. Prototypes are available and the first commercial products should be on the market within the next three or four years. The technology used will be PEMFC owing to its low operating temperature and its "100% solid" technology supplied either directly with hydrogen or with **methanol** in the "direct methanol" version. In terms of cost, the reference is that of the best present-day battery (lithium-ion), i.e. 1 Euro/Wh.

The CEA has begun to analyse value on certain fuel cell projects. The first stage consists of helping to define the specification of the products or processes proposed by a functional needs analysis approach. This is followed by an estimation of the final cost price of the industrial product, based on laboratory work. It is then possible to position

(1) Motorola and Manhattan Scientifics Inc., in particular.
(2) "Mon téléphone carbure au méthanol", *Le Monde*, Wednesday 1 March 2000.

Thierry Beghin/Libération

The first phosphoric acid fuel cell (PAFC) model to be installed in France, by EDF in early 2000, supplies a group of council flats in Chelles (Seine-et-Marne).

the end product with respect to the existing product, in terms of functions (in line with needs) and associated costs and to identify any factors generating additional costs. This work provides R&D with invaluable help in choosing between the various technical solutions available.

For "portable equipment" applications, economic criteria will probably be less important than for the other areas of application, insofar as the quality of the new service provided will justify – at least to begin with – a higher cost than the reference solution.

"Stationary equipment" applications

In view of the new deregulation laws in the electricity industry and the trend towards decentralisation of electrical power production, this sector is beginning to attract a large number of industrial companies, particularly in the USA. Activity is centred on two main areas of application: collective production (powers involved are in the 200 kW to several MW range) and individual or domestic production (powers involved are in the 2 to 7 kW range).

Many projects and demonstrations already exist in the first area. Thus it is that two industrial centres were set up around a subsidiary of the Canadian firm Ballard: a European centre with Alstom and an Asiatic centre with the Japanese firm Ebara. The objective of these centres was to distribute **cogenerators** (electrical-thermal) using the PEMFC cell (with an electrical power of 250 kW and a thermal power of 230 kW). A trial cogenerator is being tested at Treptow in the outskirts of Berlin, as part of a European project with EDF and four German partners: Bewag, HEW, Preussen Elektra and VEA.

The year 2000 also witnessed the creation of a 250 kWe prototype at Waziers (North of France) as part of a European PEMFC technology-based project, Thermie, involving Air Liquide, Schneider Electric and the CEA in France, and De Nora(3) in Italy. Meanwhile, the American firm, ONSI Corp., has been marketing the 200 kWe PAFC (PC 25) fuel cell (supplying 200 kWth in cogeneration) over the past few years, with some 200 units sold. A first model was built in France by EDF in early 2000 to supply a group of council flats in Chelles (Seine-et-Marne).

Other technologies are being tested but are not yet ready to be put on the market. The MCFC has already been put to the test: 1 MWe version by the German firm MTU, a 250 kWe version by the American firm M-C Power Generation and a 1 MWe version by the Japanese firm Hitachi. The 100 kWe SOFC has been tested by Siemens-Westinghouse.

Where individual production (in homes) is concerned, a number of projects are being conducted. The American company Plug Power LLC has joined up with General Electric (GE MicroGen) to release a 7 kW generator (HomeGen 7000). Tests are underway with ten or so prototypes in real life situations and commercialisation is scheduled for around 2002 at a forecast cost of 50-60 centimes/ kWh. Programmes of the same kind but on a lesser scale have been initiated with the American companies Northwest Power Systems (now Idatech) and Avista Labs. These devices, using PEMFC type technology, provide electricity and heat at 60°C (heating and hot water). They are supplied by conventional fuels: a **reformer** converts **hydrocarbon** fuel (normally **natural gas**) into hydrogen.

The potential international fuel cell market (for the "stationary equipment" application alone) is estimated at 45 billion Euro for 2030(4). As for target cost, it is around 1 000 Euro/ installed kW for the complete system. This is in line with the current level of development of this technology, and explains why the release times normally announced by the various manufacturers (mainly American up to now) already working on this market are

(3) De Nora is now Nuvera.
(4) According to a recent study by the *Fuel Cell Commercialisation Group*.

The PACo network gathers speed

Set up in June 1999 at the request of the French Department of Education, Research and Technology (MNRT), the fuel cell and renewable energies network aims to organise and harmonise R&D activities conducted in France on these technologies to ensure they are successfully industrialised. Initially, this structure has chosen to focus on the development of fuel cells: "PAC" in French, hence the network's name PACo. Jointly led by the CEA and Ademe (Authority for the environment and energy control), PACo consists of a steering committee of some twenty people, half from industrial firms and half from research institutes, and an office housing the funding organisations: the Department of Research, the Department of Industry, Ademe and Anvar (National agency for the promotion of research).

Since its creation, PACo has approved more than twenty projects, half of which concern fuel cells (components and system) and a quarter fuels.

The other projects concern so-called "cross" actions such as technological watch, technical and economic studies and dependability. Moreover, since the aim of this structure, as the term "network" implies, is to create links between the French teams concerned by fuel cells, it is interesting to observe that, in all, roughly one hundred teams contribute to these projects, half hailing from industry and half from public research organisations.

Approximately 20 million Euro were provided to fund these projects during the period 1999-2000.

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DaimlerChrysler

The DaimlerChrysler prototype, Necar 4, running on liquid hydrogen, has now been followed up by a preproduction vehicle, Necar 5, equipped with an on-board reformer converting methanol into hydrogen.

so close (2002). This will probably be the first mass market to be occupied by "fuel cell" technology.

"Transportation" applications

Transport is the sector behind the fuel cell development of the early 1990s. In view of cost restrictions, particularly great in this sector, and owing to competition from traditional technology (heat engines), which is both mature and efficient, this category is divided into two sub-categories with relatively different specifications, one for heavy vehicles and the other for light vehicles. The requirement for light vehicles is approximately 3000 operating hours for a service life of ten years, while for heavy vehicles (for passengers and goods) the operating periods are multiplied one hundred fold. It is clear that technology and amortisation period – and thus acceptable costs – will be extremely different.

Light vehicles: a host of projects

A large number of prototypes have been created in this area since 1993. The German firm DaimlerChrysler, who buys its fuel cells from Ballard, has built four Necar prototypes, the most recent of which (*Necar* 4 running on liquid hydrogen), was brought out in 1999 and is built on a *Class A* basis. *Necar 5*, a preproduction model equipped with a methanol-supplied reformer, was built in November 2000.

The Americans have also put forward prototypes. General Motors has built a vehicle based on the Opel and christened the *Zafira*, equipped with a 75 kW Ballard fuel cell, along with the *Precept*, equipped with a 75 kW "proprietary" fuel cell. Ford has created several *Think FC5*. Not to be outdone, the Japanese have also designed prototypes: Toyota with its two *RAV-4's*, Nissan with *R'nessa* and Mitsubishi, Honda, Daihatsu and Mazda with the *Demio FCEV*. In mid 1998, Renault brought out its *Laguna* prototype equipped with a 30 kW de Nora cell, which it designed in partnership with Air Liquide as part of the European Joule programme. Other prototypes have been announced, in particular a French prototype to be brought out by PSA in the first half of 2001. This was designed in co-operation with the CEA and based on the *Partner/Berlingo* and, again, the project falls within the framework of the Joule programme. All these manufacturers anticipate preproduction runs as from 2004-2005. Despite the existence of several prototypes with on-board hydrogen storage (in liquid or gaseous form or absorbed in a **hydride**), the fuel used initially will very probably – for reasons of dependability, regulations and distribution logistics – be a hydrogen fuel (methanol or natural gas) supplying a built-in reformer. Between 2005 and 2010, manufacturers will probably sell at a loss to open up the market and acquire experience, as Toyota is doing today with the thermal hybrid vehicle *Prius*. The technology will only begin to be cost-effective after 2010. In the 2005-2010 period, DaimlerChrysler plans to build between 50 000 and 100 000 fuel cell vehicles. As 2030 dawns, the international market will be the new target, with an annual production in excess of 50 million vehicles, i.e. 10% of the global market.

The technology used in these applications will essentially be based on the PEMFC, even if some experiments have been conducted using AFC (by the English company ZeTek) and PAFC (University of Georgetown, USA). The target cost of this industrial sector is 100 Euro/kW for the entire traction line, roughly a third of which will be allocated to the fuel cell alone.

An already viable solution for heavy vehicles

Since 1993, several bus prototypes have been built. The Canadian firm Ballard pioneered this sector with six buses (200 kW cell), which have now completed their trial period following regular operation in Vancouver and Chicago. Ballard has announced their commercialisation for 2002. The German firm DaimlerChrysler, using the same Ballard technology, brought out a bus prototype (*Nebus*) in 1997 and has announced the release of a preproduction run of 30 buses

DaimlerChrysler plans to build a limited series of an urban bus, Citaro, the heir to the fuel cell bus, Nebus, presented in 1997.

DaimlerChrysler

(*Citaro* project) in 2003, to be seen on the roads in several European cities. Given the service life expected, the economic situation of this application is the same as for the "stationary equipment" sector and thus commercially viable immediately, accounting for the optimistic attitude of the last two manufacturers mentioned.

Alongside these road applications, some manufacturers (in France, RVI and Iris-bus in particular) are examining the possibility of a "clean" tram without overhead contact line, using a fuel cell.

Last but not least, also worthy of note is the growing interest that shipbuilders are showing in the SOFC fuel cell, at MW level or more, to ensure cleaner, more efficient and discrete propulsion, particularly for military applications.

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Miniature fuel cells

The increasing power and battery lifetime requirements of portable equipment mean that new breakthroughs have to be made in miniature energy source performance. The fuel cell, which separates the energy storage and power conversion functions, is an attractive solution. However, research has still to find answers for several unavoidable restrictions.

Portable telephone using a miniature fuel cell brought out in October 2000 by the American firm Energy Related Devices; on the right, the removable methanol cartridge.

Energy Related Devices

Development of portable equipment, and in particular the cell phone, raises the crucial problem of energy supply. This point is not a major handicap today as the functions associated with the portable telephone are still limited. However, the foreseeable development of functions and applications of portable devices (access to Internet, new services, less intermittent use, etc.) and the introduction of new electronic components (flat, complex screens, etc.) will, in coming months, considerably alter the situation in terms of power consumption and battery lifetime. While today consumers put up with battery lifetime of a few days only and somewhat lengthy charging times, such annoying little things will very soon no longer be acceptable.

All parts manufacturers know this. Numerous research projects are being carried out, first to optimise circuit architectures and components so as to reduce consumption and, second, to develop miniature energy sources that are far more effective than the current storage **batteries** whose scope for progression is now relatively small. The **fuel cell** thus stands out as an attractive solution as it allows separation of electrical power supply and autonomy of use. This is because, in a storage battery, the volume of the **positive electrode**, which is an integral part of the component, determines the quantity of energy stored and thus the battery lifetime of the component. On the contrary, the fuel cell is divided into two separate parts: the fuel tank (hydrogen, **methanol**, etc.) and the cell core which will convert the electrochemical energy stored in the fuel into electrical energy. This type of cell thus offers additional freedom of operation, which could lead to battery lifetime being multiplied three or ten fold, while at the same time satisfying the instantaneous power needs of portable devices.

Three main restrictions

However, there is no cause for smug optimism as the miniaturisation that portable devices require results in technical restrictions in three areas, for which solutions are difficult to find.

First, it is necessary to manage calls with widely differing power demands whether in standby or operating mode. This involves considerable **fuel** flow rate variations, management of which may come up against problems of inertia and, in the case of portable devices, of availability of the miniature components allowing the necessary dynamic fuel supply of the cell core. A virtually continuous operating mode appears more reasonable in the current state of technology. However, this requires storage of the electrical energy supplied and thus use of a buffer element to regulate the necessary instantaneous electrical power.

Secondly, the products of the electrochemical reaction need to be managed. The core of a fuel cell must be supplied with oxygen and fuel (which will provide the hydrogen) for it to yield water. Although all the elements in the reaction are relatively easy to manage in traditional fuel cells, which are big, the same task will be trickier to handle in miniature portable devices.

The third restriction is linked to storage and supply of fuel in an acceptable form and a compact space, compatible with the battery lifetime required. Although the separation between the tank and the cell core provides additional freedom of operation, this freedom is far from being total as the entire system must occupy a specific maximum volume. This volume has to contain that of the cartridge, determined by battery lifetime requirements, and that of the cell core, determined by power requirements.

The 3 to 10 times increase in battery lifetime mentioned above is technically feasible in the case of cell phones, but requires further research and development to become reality and satisfy needs. It also assumes control, in miniature form, of the auxiliary components ensuring management and supply of fuel and of the fluids associated with reactions.

In view of all the factors to be considered, it appears that pure and simple replacement of storage batteries by fuel cells is doubtless not a solution that can be directly used today. On the other hand, the fuel cell / battery (or another buffer energy storage element) combination seems to overcome most of the problems mentioned, while also getting round the cold start-up difficulties of the device.

Although the results of the first prototypes using methanol as fuel are encouraging, basic physical studies are still necessary for a better understanding of catalysis mechanisms, adaptation and optimisation of electrolytes with miniature structure and running on high methanol concentrations. This last point is undoubtedly one of the barriers to be overcome. In view of all these constraints, in 2000 the CEA set up a team of ten persons to work on key issues and hopes, over the next two to three years, to provide an answer to the main queries and come up with a credible demonstrator.

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Prospects for Fuel Cells in Europe

The European Union's framework programme has supported the research, technological development and demonstration of fuel cells since 1988. Its efforts in this area have been stepped up since fuel cells represent an innovative technology that could contribute significantly to the sustainable development of the European Union and to other key objectives of the European energy, transport and environmental policies in the short and long terms. The budget spent by the European Union was increased from 8 million Euro between 1988 and 1992 to approximately 54 millions Euro in the Fourth Framework Programme (FP4) (1994-1998). Since the Fifth Framework Programme (FP5) (1999-2002) started, the EU's support of fuel cell systems development is already in excess of 30 millions Euro (figure for end of 2000). In addition, several Member States of the European Union are also running national programmes connected with the development and application of this new emerging technology.

Co-operation between the European Member States and the European Union in this field was already underway in 1995 with the setting up of a 10-year R&D fuel cell strategy for Europe, reviewed and revised in 1998. It aims at improving co-ordination of complementarity between national programmes and European programmes in order to make research in Europe more efficient. The implementation of this strategy under the Framework Programme has certainly contributed to improving and optimising research, development and demonstration activities in Europe, but has by no means reached all the expected results. Today, national research policies and Union policy in this field still lack harmonisation.

The growing industrial interest, supported by research centres and academia, in fuel cell RTD has encouraged the European Commission to select this field as a pilot experiment as part of promotion efforts to set up a European Research Area for fuel cells. This area has also been adopted by the European Council and supported by the European Parliament. Major strategies have already been put forward by the Commissioner for Research in a paper addressed to the Council, Parliament, Economic and Social Committee and Committee of the regions that may already be concerned by the current fifth Framework programme. These are:

- The *networking* of European *excellence* around the most critical themes that still represent important barriers to the commercialisation of fuel cells. These networks should contribute to making the European research effort more efficient by introducing and implementing a "critical mass" that will also make European research more competitive.
- The opening of national programmes to participation from European Member States and the support of large *integrated projects* with the participation of industries, research centres and universities.
- The strengthening of *co-operation with third countries* and particularly signatory countries of the scientific and technological co-operation agreements with Europe.

The result of a political incentive, these suggested actions will nevertheless be implemented on a voluntary basis.

Today, with the results obtained during the previous calls for proposals in the ENERGIE programme, a new approach and new priority areas have been suggested with the aim of implementing this programme during the last two years of the fifth framework programme. This new approach, called "Target Action", includes action geared towards technological research and development in the short, medium and long term relating to fuel cell systems and technologies linked to hydrogen use. The new priorities are naturally focused on stationary, mobile and portable equipment applications and include socio-economic and preliminary standard research activities linked to the development of rules concerning safety, standardisation and training. One of the major roles of this initiative is to encourage co-operation initiatives within national and international programmes and in particular the EUREKA programme. This type of action should help simplify the emergence of new technological solutions having an important, measurable and directly relevant impact on their contribution to European policy objectives.

Alongside this new approach, a limited number of important strategic priorities for the European Union will also be supported through a broad-ranging action covering the overall initial program part of the European Commission's ENERGIE work programme.

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