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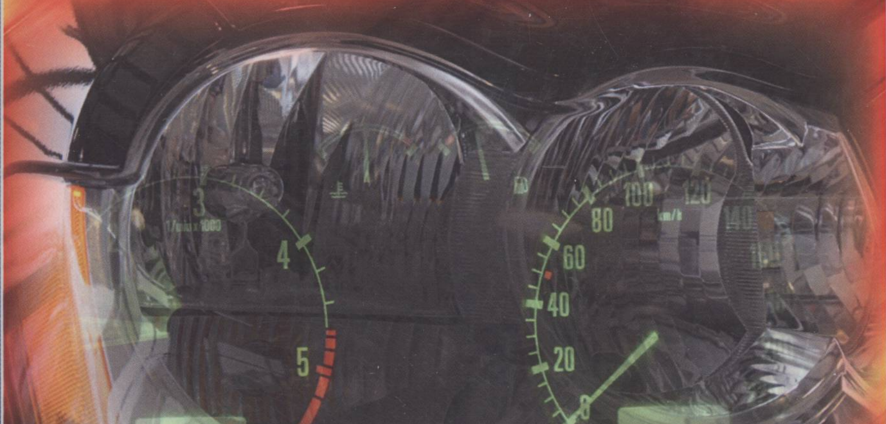

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FUEL CELL ENERGY SOURCE FOR ELECTRIC VEHICLE APPLICATIONS

PHATIPHAT THOUNTHONG

AND

BERNARD DAVAT

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Fuel Cell Energy Source for Electric Vehicle Applications

PREFACE

This book presents the utilization of a PEM fuel cell as a main power source in a distributed generation system, particularly for future electric vehicle applications. The fuel cell, known as a high specific energy source at the present time, is one of the well-known alternative sources of electric power generation when given consideration for decreasing oil consumption and hazardous CO_2 emissions.

Nevertheless, one of the main weak points of the fuel cell is its time constants dominated by temperature and fuel delivery system (pumps, valves, and in some cases, a hydrogen reformer). As a result, fast load demand will cause a high voltage drop in a short time, recognized as a fuel starvation phenomenon. One must limit the fuel cell current (or power) slope to prevent fuel starvation problems, to improve its performance and lifetime. Therefore, to employ a PEM fuel cell in dynamic applications, the electrical system must have at least an auxiliary power source to improve system performance when electrical loads at a DC bus demand high energy in a short time, as well.

The possibilities of using a supercapacitor or battery bank as an auxiliary source with a fuel cell main source are presented in detail. The very fast power response and high specific power of a supercapacitor or high specific energy of battery can complement the slower power output of the main source to produce the compatibility and performance characteristics needed in a load.

The studies of two hybrid power systems for vehicle applications: a fuel cell/battery hybrid powertrain and a fuel cell/supercapacitor hybrid powertrain are explained. First, the characteristics of fuel cell, battery, and supercapacitor as power sources are summarized. Then the configurations of the two types of hybrid power sources are presented. Finally, prototypes of hybrid power sources with small-scale devices are implemented in our laboratory (the GREEN laboratory, Nancy University, Nancy-Lorraine, France). Experimental results authenticate that energy storage devices can assist the fuel cell to meet the vehicle power demand and help achieve better performance.

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Chapter 1

INTRODUCTION

In this day and age, energy and environmental crises are fast becoming the biggest problems around the world; so, as a consequence, new renewable and clean energy power sources must be considered. One of the prevalent alternative sources of electric power is the fuel cell (FC), discovered by Sir William Grove in 1839 [1], [2]. A fuel cell utilizes the chemical energy of hydrogen and oxygen to generate electricity without pollution. The by-products are simply pure water and heat. A fuel cell is known as a high specific energy source at the present time. It is one of the prospected sources of electric power generation. There are many types of fuel cells characterized by their electrolytes. One of the most promising to be utilized in electric vehicle applications is the Polymer Electrolyte Membrane (or Proton Exchange Membrane) Fuel Cell (PEMFC), first used by the National Aeronautics and Space Administration (NASA) in the 1960's as part of the Gemini space program, because of its relatively small size, lightweight and ease to build [3], [4]. PEM fuel cell low-temperature operation lets it start quickly and increases its durability.

The first PEM fuel cell, designed by the General Electric (GE) Company under contract by McDonnell Aircraft Corporation, was employed by NASA for the Gemini Space Missions, as depicted in Figure 1. In that time, Manned Spacecraft Center completed an analysis of possible power sources for the Gemini spacecraft. Major competitors were fuel cells and solar cells. Even though any system selected would require much design, development, and testing effort, the PEM fuel cell designed appeared to offer decided advantages in simplicity, weight, and compatibility with Gemini requirements over solar cells or other fuel cells [3]. The first mission with the PEM fuel cell was Gemini 5, which flew August 21-29, 1965.

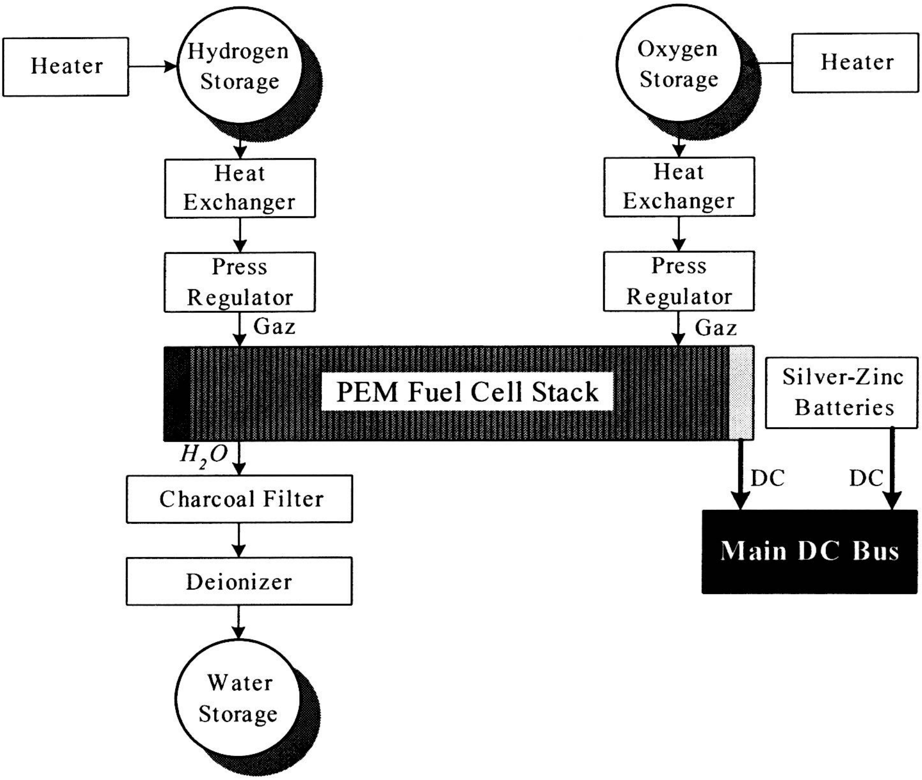

Figure 1. Simplified block diagram of the NASA Gemini fuel cell power generator [3].

Nowadays, electrical power for NASA's Space Shuttle Orbiter is still provided by fuel cell power plants designed, developed, and built by United Technologies Co. (UTC) Fuel Cells [5]. In the Orbiter, a complement of three-12 kW fuel cells produces all onboard electrical power; there are no backup batteries, and a single fuel cell is sufficient to insure safe vehicle return. In addition, the water produced by the electrochemical reaction is used for crew drinking and spacecraft cooling. Each fuel cell is capable of providing 12 kW continuously, and up to 16 kW for short periods.

M. W. Ellis *et al.* [1] and J. H. Hirschenhofer [6] have described that fuel cell power generation systems are expected to be used in a growing number of applications. For portable power, a fuel cell coupled with a fuel container can offer a higher energy storage density and more convenience than conventional battery systems [7], [8], [9]. In transportation applications, fuel cell vehicles (FCVs) have already proven much more efficient than similar internal combustion vehicles [10], [11]. Toyota and General Motor (GM) have also announced that their fuel cell prototypes running on hydrogen have twice the efficiency of their conventional gasoline vehicles. In stationary power applications, low emissions permit fuel cells to be located in high power density areas where they can supplement the existing electrical network. Moreover, fuel cell systems can be directly connected to a building to provide both power and heat with higher overall efficiencies [12].

John T. S. Irvine [4] observed that much fuel cell technology has been introduced in recent years as a support of the future energy economy. There is currently a phenomenal commercial interest in fuel cell technology with new start-up companies being established and major players in the energy market turning their attention to this technology. In the long term they are an essential component of any hydrogen or similar clean energy economy, in the short-term they promise greatly enhanced conversion efficiencies of more conventional fuels and so large reductions in CO_2 emissions [13], [14].

In industry, UTC Fuel Cells (USA) is involved in fuel cell systems for space and defense applications. UTC fuel cells activity began in 1958 and led to the development of the first practical fuel cell application used to generate electrical power and potable water for the Apollo space missions. Since 1966, all of the more than 100 U.S. manned space flights, including the Space Shuttle, have operated with fuel cells supplied by UTC companies. In 1991, UTC Fuel Cells manufactured its first PureCell™ 200 power plant, the world's first and only commercial fuel cell power. The PureCell™ 200 fuel cell produces 200-kW of electricity and 700,000 BTUs of heat. The unit can be powered by natural gas, propane, butane, hydrogen, naphtha or gases from waste. Since their first flight in 1981, UTC Fuel Cells power plants have provided electric power for more than 100 shuttle missions. They shipped a 50-kW hydrogen-air PEM power plant to the U.S. Department of Energy and the Ford Motor Company. In 1998, UTC Fuel Cells delivered a 100-kW methanol power plant, with 40 percent efficiency, to Nova Bus for installation in a 40-foot, hybrid drive electric bus under a DOE/Georgetown University contract [5].

General Motors (USA) is involved in the development of PEM fuel cells for stationary power as well as the more obvious automotive markets. In February 2004, they began the first phase of installation operations in Texas at Dow's chemical manufacturing, the largest facility in the world. These fuel cell systems are used to generate 35-MW of electricity [15].

In 1983, Ballard Power Systems (Canada) developed intermittent-use and continuous use PEM fuel cell systems for a range of stationary and portable power products. Through the years the company's product development has covered fuel cells with various power outputs from 1-kW to 250-kW systems. Ballard completed field trials of a 250-kW stationary fuel cell in 2003. Now, however, Ballard is concentrating on the transportation and small stationary markets. For example, it developed a 1-kW Nexa fuel cell combined heat and power module in 2001 for the Japanese residential cogeneration market [16].

In Europe, Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW) (German) has developed and built a 10-kW PEM fuel cell system. This system is controlled by a standard Siemens programmable logic controller. The user interface has been programmed using the WinCC visualization environment allowing the user easy operation of the system according to the requirements of the application [17].

Axane (France) was created in 2001 and is working on PEM fuel cell technology. It is positioning itself in three markets that are likely to provide large commercial outlets in the short term [18]:

- Portable multi-application generators (0.5-kW to 10-kW),
- Stationary applications (more than 10-kW),
- Mobile applications for small hybrid vehicles (5-kW to 20-kW).

Its product range includes the RollerPac (a portable fuel cell powered 230-V, 2-kW AC electrical generator), Mobixane (under development), and the PolarPac (0.5-kW) currently working in the Polar Observer in the North Pole. The RollerPac has won a number of awards for its innovative design, most recently the Siemens Innovation Grand Prix. In 2004 Axane won a contract for the RollerPac to supply continuous power to a Bouygues Télécom pylon. Axane is also involved in a number of large EU research and development projects.

Various recent works in [19], [20], [21], [22], [23] have already highlighted the possibility of using the fuel cell in distributed power generation systems. Y. Kishinevsky *et al.* [12] reported that a stationary fuel cell at New York City, the US nation's largest state-owned electric utility, already installed 2.4 MW of UTC fuel cell capacity and operates 12-fuel cells at 8-sites in the early 1990s. Nine of the 12 fuel cells are powered by renewable biogas fuels. Most of these units supply both electricity and heat to the host facility with virtually no emissions.

For another work, K. Chandler and B. L. Eudy [24] reported experimental results carried out on a Fuel Cell Transit Bus, known as hybrid Fuel Cell/Battery Vehicle, prepared for the U.S. Department of Energy (DOE). This bus has a rated power of 60-kW, and its energy source is composed of a UTC PEM fuel cell (60 kW, 160-250 V) as the main power source, and of 48 Panasonic lead-acid 12-V batteries associated in series as the auxiliary source. The bus has an approximate range of 200 miles with a fuel storage capacity of 25 kg of hydrogen at 248 bar (3,600 psi). In addition, Rodatz *et al.* [25] presented the field tests, in urban and highway sections, of a Fuel Cell/Supercapacitor-Powered Hybrid Vehicle with a PEM fuel cells (40 kW, 150 A), a supercapacitor module (5.67 F, 250 A, 360 V), and an AC motor (45 kW). This work also explained one of the key weak points of fuel cell, which is dynamic limitation. In fact, fuel cell voltage is highest when no current is flowing, and drops with increasing current because of activation over-voltage and ohmic resistance losses in the membrane. At high currents, the voltage drops drastically as the transport of reactant gases is not able to follow the amount used in the reaction. Consequently, reactant starvation occurs at the reaction side and the cell fails. Since a current is drawn through the stack, the failed cell may start to operate as an electrolytic cell and cause irreversible damage. Therefore, the current that can be supplied by the fuel cell needs to be limited. Moreover, a lag between fuel cell load current and response of the reactant supply system results in an under-supply of reactants to the fuel cell. This leads to a breakdown of the chemical reaction and to a rapid loss in voltage. This phenomenon may be avoided by restricting the dynamics of the load. Therefore, in P. Rodatz's tests, the dynamic of the fuel cell system was limited to a conservative 2.5 kW/s.

According to P. Thounthong *et al.* [26], [27] (who worked with a 500-W ZSW PEM fuel cell), M. E. Schenck *et al.* [28] (who worked with a 1.2-kW Ballard Power System PEM fuel cell), and A. Taniguchi *et al.* [29], it is widely accepted that one of the key weak points of a fuel cell systems is their dynamic limitation. In fact, many works have draw attention to slow fuel cell system dynamics: J. T. Pukrushpan *et al.* [30], [31], who attempted to improve fuel cell system dynamics by controlling fuel cell processor in order to avoid stack starvation and damage, when current is rapidly drawn from a fuel cell, and J. M. Corrêa *et al.* [32], [33], who worked with a 500-W Ballard and a 500-W Avista PEM fuel cell. The fuel cell system time constant, several hundredths of a millisecond, is dominated by temperature and fuel delivery system. As a result, fast load demand will cause a significant voltage drop in a short time, particularly due to air starvation.

It is therefore recommended, when utilizing a fuel cell, to employ a power loop or a current loop, in order to prevent overloads and fault conditions, and to associate it with, at least, a fast auxiliary power source to improve the dynamic performances of the whole system. Moreover, one can take advantage of this fast auxiliary power source to achieve an actual hybrid source, in order to disassociate mean power sizing from peak transient power sizing, the aim being a reduction in volume and weight, and in the case of fuel cells used as the main energy source, the possibility of regenerative braking.

Therefore, some kind of hybridization of fuel cells with other energy storage devices such as batteries and supercapacitors will remain advantageous for a long period of time. For example, the Toyota FCHV fuel cell vehicle uses a nickel-metal hydride battery pack as the secondary energy source, and the Honda FCX fuel cell vehicle uses supercapacitors as an energy buffer to achieve powerful, responsive driving. In hybrid electric vehicles, the fuel cell system provides the base power for constant speed driving while the other energy storage devices provide additional peak power during acceleration and high load operation and recover braking energy by regeneration. Hence, the fuel cell power rating and cost will be reduced; the vehicle transient performance will be improved; and energy efficiency will be increased. Additionally, fuel cells have slow dynamics by nature. If it is operated in nearly steady state condition in order to avoid speedy transition of fuel cell current or power, mechanical stresses are avoided, and lifetime of the fuel cell stack will increase.

The present book deals with the conception and the achievement of an energy management DC hybrid power source using a PEM fuel cell as the main energy source, and supercapacitors or batteries as an auxiliary power source, as proposed in Figure 2. Its interest is focused on a special, yet simple, control strategy. This, of course, enables management of transient power demand, power peaks, and regenerative braking with regard to main and secondary source constraints. The general structure of the studied system, the control principle of the hybrid source, the realization of the experimental bench, and experimental validation will be presented in the following chapters.

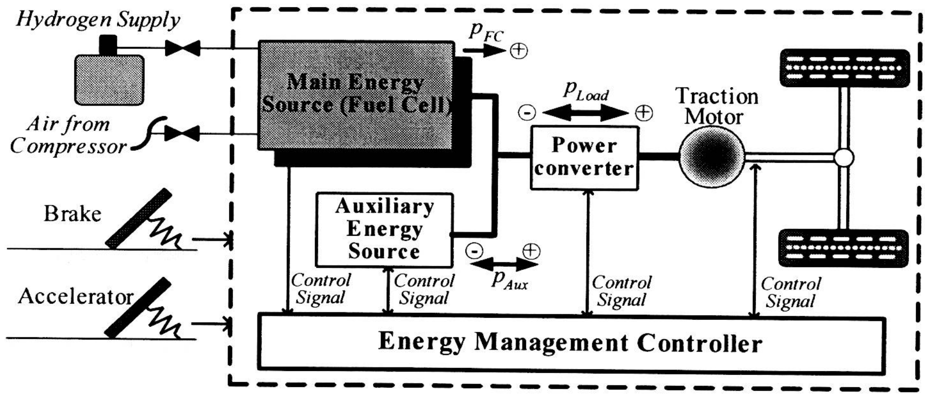

Figure 2. Concept of Fuel Cell Powered Vehicle.

Chapter 2

PEM FUEL CELL

A. BASIC PRINCIPLE

A fuel cell is an energy conversion device that converts the chemical energy of a fuel directly into electricity. Energy is released whenever a fuel (hydrogen) reacts chemically with the oxygen in air. The reaction occurs electrochemically, and the energy is released as a combination of low-voltage DC electrical energy and heat.

The structure of a single cell of the PEM fuel cell is represented in Figure 3 [34], [35], [36]. Flowing along the x direction, the gases come from channels designed in the bipolar plates (thickness 1-10 mm). Water vapor is added to gases to humidify the membrane. The diffusion layers (100-500 μm) ensure a good distribution of the gases to the reaction layers (5-50 μm). These layers constitute the electrodes of the cell, which is made of platinum particles. They play the important role of catalyst, deposited within a carbon support on the membrane.

Hydrogen oxidation and oxygen reduction are defined as follows:

$$H_2 \rightarrow 2H^+ + 2e^- \quad \text{:Anode} \qquad (1.1)$$

$$2H^+ + 2e^- + (1/2)O_2 \rightarrow H_2O \quad \text{:Cathode} \qquad (1.2)$$

They are separated by the membrane (20-200 μm) that carries protons (H^+) from the anode to the cathode and is impermeable to electrons. This flow of protons drags water molecules along the gradient of humidity, leading to a diffusion of water according to the local humidity of the membrane.

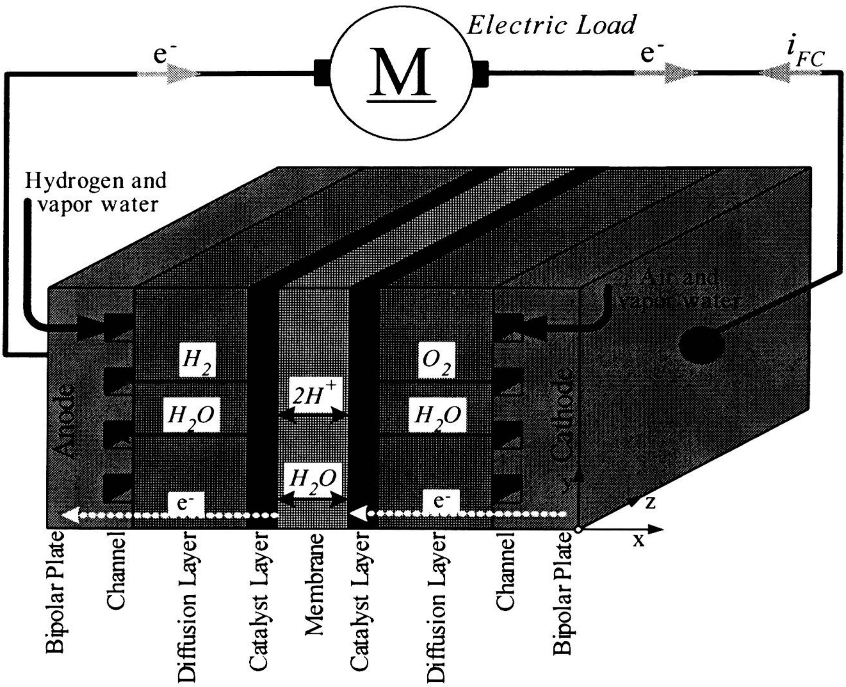

Figure 3. Different layers of an elementary cell of PEM fuel cell [36].

Water molecules can then go in both directions inside the membrane, according to the side where the gases are humidified and to the current density which is directly linked to the proton flow through the membrane, and to the water produced on the cathode side. Electrons (e^-), which appear on the anode side, cannot cross the membrane and are used in the external electric circuit (motor, lamp, etc.) before returning to the cathode.

Therefore, the overall reaction can be represented as:

$$H_2 + (1/2)O_2 \rightarrow H_2O + Heat + Electrical\ Energy \tag{2}$$

As developed earlier [35], [36], [37], and [38], the Nernst equation for the hydrogen/oxygen fuel cell, using literature values for the standard-state entropy change, can be written as:

$$E = 1.299 - 0.85 \times 10^{-3} \cdot (T - 298.15) + 4.3085 \times 10^{-5} T \cdot \left[\ln(p_{H2}) + \frac{1}{2}\ln(p_{O2}) \right] \tag{3}$$

where,

T is the cell temperature [K], and

p_{H2} and p_{O2} are the partial pressure of hydrogen and oxygen [bar], respectively.

B. PEM Fuel Cell Stack

The theoretical value of a single cell voltage of 1.23 V is never reached even at no-load. For the rated current, the voltage of an elementary cell is about 0.6 - 0.7 V; then, a fuel cell is always an assembly of elementary cells that constitute a stack, as Figures 4 and 5 depict.

In particular, Figure 5 presents the PEM fuel cell stack developed by the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), Ulm, Germany. This stack is also used in the experiment, in which will be presented in next sections. Its serpentine flow field plate is also illustrated in Figure 5(b). In a single fuel cell, these two plates are the last of the components making up the cell, as portrayed in Figure 3.

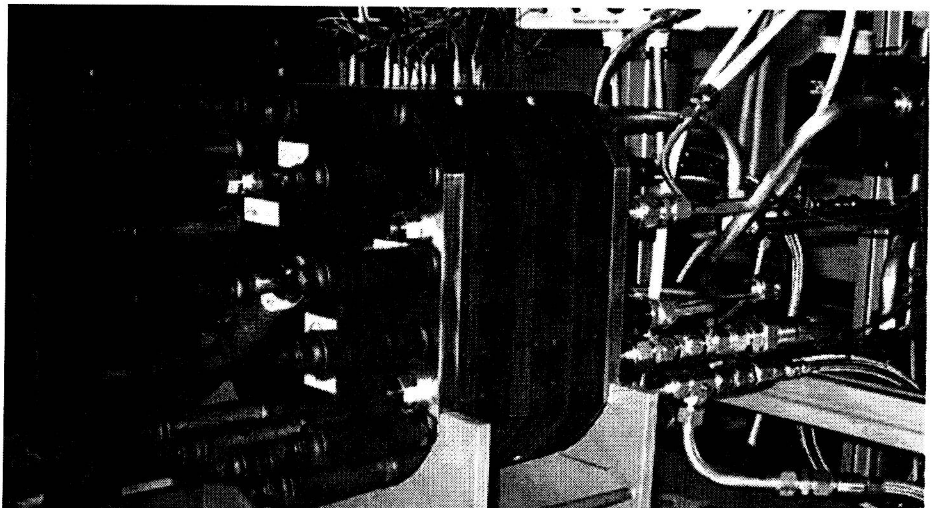

Figure 4. Prototype PEM fuel cell stack (2-kW, 300-A, 7-V) designed and developed by French Atomic Energy Centre (CEA) for submarine applications.