R&D Strategies for New Automotive Technologies:

Insights from Fuel Cells

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Several companies have changed names or were acquired by another company throughout the period studied in this report. The names of the companies mentioned in the text corresponds whenever possible to the time period referred to in the text, for example Daimler-Benz until May 1998, and DaimlerChrysler thereafter.

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ABSTRACT

This study analyzes how the automobile industry is pursuing the development of fuel cells as a new propulsion technology for automobiles. Fuel cells represent a fundamentally different powertrain technology that competes technically with the internal combustion engine, which has traditionally been a core competence of automobile manufacturers. The emergence of fuel cells provides a threat to automakers' competence in internal combustion engines, but also presents an opportunity for establishing a competitive position and gaining competence in a new technology. The study gives insights into strategic issues that automakers face through fundamentally new technologies. The key questions analyzed in this study are how new technology such as fuel cells can be identified by automakers, how automakers develop and acquire competence in such a technology that has not been part of the traditional technology portfolio of automakers, and how automakers can keep control over this new technology and derive value as it moves closer to commercialization.

Fuel cells were historically first applied in the aerospace industry, and have only been developed for use in automobiles after a technological breakthrough resulted in significant increase of power density and cost reduction. Automakers with ties to the aerospace industry were among the first to recognize the potential of the breakthrough technology, and such early identification gave these companies a lead in R&D investment and patenting. This example of technology dynamics of fuel cells supports the importance of early identification of new technologies and links to related industries as a source of such technologies for the automobile industry.

The next phase of fuel cell developments is characterized by an attempt of automakers to acquire competence in fuel cells. Three different organizational approaches are observed among the automakers: internal development of fuel cells, collaborative research, and a wait-and-see approach that favors licensing of the technology. The design of collaborative research alliances, such as the partnership between DaimlerChrysler, Ford and Ballard, suggests that technology that is new to the automobile industry needs to be viewed from a systems perspective. While early research activity focused on the fuel cell only, the establishment of an alliance provided an effective way of combining technical competence on all components of a fuel cell powertrain system. The research alliance also broadens the coverage of intellectual property with patents, but this also limits the control of automakers over the technology.

The last part of the report discusses implications for automakers regarding the ability to control and derive value in the case the technology is successfully commercialized. It is argued that new suppliers are likely to participate in a future market for fuel cell powertrains, according to their technical competence and role as early participants in the development of fuel cell components. Automakers can keep control over the technology and participate in a potential market for fuel cells by becoming system integrators, and through continued development of key fuel cell components.

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INTRODUCTION

This study examines how the automobile industry is pursuing the development of fuel cells as a new propulsion technology for automobiles. The results provide insights into the dynamics of new technologies in a mature industry, and suggest typical response patterns of automobile firms trying to capture leadership in new technologies. In addition, the study provides answers to strategic questions that automakers face through fundamentally new technologies.

Fuel cells as a fundamentally new automotive propulsion technology

Today's largest automobile manufacturers started their commercial ascent at the beginning of the century with the sale of mass-produced automobiles powered by internal combustion engines. The internal combustion engine today still represents the predominant technology, and decades of intensive research and development efforts have transformed the automotive engine into a sophisticated, universal product engineered for a mass consumer market that demands maximum performance at lowest possible costs. Parallel to this development, automobile manufacturers have always investigated alternative technologies, but none of these efforts have yet resulted in a technology that would present a serious contender to the internal combustion engine.

In recent years, however, the automobile industry has witnessed an unprecedented surge in activities that target the development of alternatives to the internal combustion engine. Among the technologies pursued by almost all major vehicle manufacturers today are alternative fuel vehicles, electric vehicles, hybrid vehicles and more recently, fuel cell vehicles. Industry experts view fuel cells as a promising new technology, and several automakers have made significant investments into the development of fuel cell vehicles. DaimlerChrysler and Ford, for example, have together invested almost one billion dollars for the development of fuel cell vehicles, representing a sizeable part of the companies' R&D budget[1]. These and other efforts by the automobile industry have resulted in rapid progress of fuel cells in automobiles, and within the last few years, several prototype vehicles were manufactured. Nevertheless, widespread skepticism exists about the commercial viability of the technology.

For most firms in the industry, these developments can prompt the critical question whether to ignore or aggressively pursue investments and leadership in new technologies.

[1] Daimler-Benz and Ford press statements on August 26, 1997 and April 7, 1998.

New technologies can provide a serious challenge to large, established firms, because these firms are largely focused on incremental improvements to conventional technology. The threat of new technologies is widely described in the literature as radical innovation (Abernathy and Utterback, 1978; Henderson and Clark, 1990), or disruptive innovation (Christensen, 1997). Such technologies not only provide a threat to established firms, but they may also have a profound impact on the way automobile companies develop these technologies. In a case study about the potential effect of electric vehicle developments on automotive companies, Christensen (1997) writes:

> "The mainstream organization is involved in taking sustaining technological innovations into existing markets populated by known customers with researchable needs. (…) The electric vehicle is not only a disruptive innovation, but it involves massive architectural reconfiguration as well, a reconfiguration that must occur not only within the product itself but across the entire value chain." Christensen (1997:201)

Technologies such as electric vehicles and fuel cells rely on technical know-how that is not the traditional competence of automobile manufacturers. The design of a fuel cell system requires detailed technological expertise in electrochemistry, electrocatalysis and chemical fuel processing, none of which are competencies that are part of the traditional technology portfolio of automobile manufacturers. Because the technology necessary to develop fuel cells for automobiles is not a core competence of automakers, these companies are facing strategic questions that may have wide-ranging implications for their future competitive position in a potential market where fuel cells compete with the internal combustion engine on price and performance. Even if fuel cells are never successfully commercialized, the results from this study can still provide useful insights into strategic issues that automakers are faced with by other new technologies.

Focus of the study

This report describes how the automobile industry pursues the development of fuel cells as a new propulsion technology for automobiles, and presents an analysis of strategic issues that automakers encounter during various phases of the technology evolution. The primary source of information for this study was a series of twenty-five semi-structured interviews with managers of the fuel cell projects at Daimler-Benz (now DaimlerChrysler), Ford and Ballard Power Systems in the period from October 1997 to May 1999. Additional sources of information includes corporate publications, business and technical literature, as well as quantitative statistics on public patent databases covering the last twenty years.

The content of the report is organized as follows. Section 1 introduces general aspects of research, development, and innovation in the automobile industry. Section 2 presents a simple description of fuel cells as the basis for discussion in the remaining sections, and Section 3 presents a summary of the history of fuel cell research. Strategic issues of fuel cells as a new automotive technology are discussed in Sections 4 to 7. Section 4 presents the framework for analysis of fuel cell developments. Three phases describe the development process, beginning with the identification of a technology, the technology development phase, and the exploitation and protection of technology as commercialization nears. Section 5 discusses the identification of fuel cells as a new automotive technology. Fuel cells existed long before they were considered applicable to automobiles, yet only few automakers realized the potential of fuel cell technology and decided to invest in further development of fuel cells for automobiles. Once a new and potentially marketable technology is identified, automakers have to decide whether and how acquire competence in such technology. Because fuel cells were not part of the traditional technology portfolio of automakers, certain automakers decided to develop the technology internally, while others gained access to fuel cell technology through research alliances with other companies. These different approaches are discussed in Section 6. Section 7 discusses how automakers can derive value from fuel cell technology and ensure control over their competitive position in the technology relative to other companies that have gained technical competence in fuel cells. Section 8 presents a summary and conclusions.

1. AUTOMOTIVE RESEARCH AND DEVELOPMENT

The following section describes conventional research and development (R&D) and technological innovation of automakers that provides a reference for the discussion in this study.

1.1. Corporate R&D of automobile manufacturers

An extensive literature describes the importance of product development in the automotive industry (Womack et al., 1990; Clark and Fujimoto, 1991; Scott, 1994, Cusumano and Nobeoka, 1998). Because most of the activity in product development focuses on the design and development of new automobile platforms and models, much less is known about the research organization within automotive firms, the laboratories and centers that are concerned with research of new technologies ranging from fundamental combustion science and materials research, for example, to the development of alternative propulsion systems. A few observations that are of particular interest for this study are briefly summarized here.

In the United States, General Motors, Ford and Chrysler have established different organizational approaches to R&D (Fine, Lafrance and Hildebrand, 1996). General Motors and Ford both have substantial corporate research laboratories employing several hundred scientists and engineers that support the scientific and technological needs of the operating divisions. During the last decade however, General Motors and Ford have significantly scaled back their corporate research laboratories in a transformation towards more product-oriented development and less involvement in basic research that seems to reflect a general trend of industrial research in the United States (Mowery, 1992 and 1998; Rosenbloom and Spencer, 1996). The reduction of corporate research among the largest automobile companies is viewed as the result of fierce market competition, the constant pressure for cost cutting and the need for improvements in product development and manufacturing operations. Nonetheless, General Motors and Ford are the two largest industrial R&D (research and development) spenders of all firms in the United States with current annual expenditures of $9 and $7 billion, respectively, or roughly 5% of revenues. The largest part of these R&D costs are by far development costs, while basic research only represents a very small fraction of this amount.

Chrysler's R&D organization emphasizes lean product development with high integration of suppliers, but only limited ability to perform research. Chrysler's Scientific Lab provides mainly technical expertise and services to the operating divisions, while a small division works on advanced development efforts, such as concept cars. In 1997 before its merger with Daimler-Benz, Chrysler spent about $1.7 billion, or 3% of sales, on R&D, almost all of which represents product development expenditure.

In Europe, Daimler-Benz (now DaimlerChrysler) has established a long tradition of technology leadership through investments in R&D. As a company with a strong emphasis on quality products, Daimler-Benz relies on differentiating its products through innovative technology. The company operates a central R&D organization, Research and Technology, which provides medium and long term research services to all of its business segments, including automotive, aerospace, and other subsidiaries. In 1997, Daimler-Benz invested about $5 billion, or 5% of annual revenues, in R&D.

Recent structural changes in the automobile industry have brought about two trends that have an impact on the automotive R&D organization: globalization and supplier cooperation in product development. Several automobile firms have established technical centers and satellite R&D divisions in the largest foreign markets, alongside with globalizing their manufacturing base. Studies of the supply chain point to an increasing role of suppliers in product development (Sako and Helper, 1998; Dyer et al., 1998; MacDuffie and Helper, 1997), as manufacturers become less vertically integrated. Chrysler in particular, and Japanese manufacturers have established the model of an *extended enterprise* with close cooperation of first tier suppliers. This results in increased responsibility for suppliers in technological developments, which may have consequences for manufacturer's reliance on suppliers for providing fundamental technological knowledge in the future. Dyer et al. (1998) illustrates how the supply chain of Japanese companies is structured according to the value content of automotive parts. Suppliers that are close associates of the *keiretsu* of automobile manufacturers produce higher-value components such as engine parts and transmissions, while more loosely associated suppliers tend to make commodity-type products such as tires, belts and spark plugs.

Within the more research-oriented part of R&D, the main research effort of automakers today is spent on technological development of the engine, drivetrain, electronic controls, materials and processing technologies. Engines are developed and manufactured by all major automobile manufacturers in-house, and engine design is viewed as a core competence of automakers (Fine and Whitney, 1996). Although internal combustion engines are at the core of automotive research, alternatives have been considered and, occasionally, developed. Alternative propulsion systems, such as electric, hybrid, fuel cell, and alternative fuel vehicles, are among the technologies that have been pursued by almost every automobile manufacturer. Certain automakers are investing significant portions of their R&D budget into alternative propulsion technologies. Some of the largest firms, among them General Motors, Ford, DaimlerChrysler and Toyota, today each spend up to a few hundred million dollars annually on alternative propulsion technology. Compared to R&D on conventional technology, this represents a sizeable investment. For comparison, the development cost for a new family of combustion engines typically amounts to one billion dollars at most. Being a leader in alternative propulsion technology may have a significant effect on the future competitiveness in global automobile markets, not least because these technologies provide a threat to the core competence of automakers in internal combustion engines.

1.2. Driving forces of technological innovation in the automotive industry

Technological innovation has become an increasingly important driver of competition in the automobile industry[2]. Technological change has reinforced the cycle for new products and is an important factor for product differentiation. In the automotive industry, technological change can be described as the result of three main factors (see Figure 1): changing consumer preferences, increasing product regulation and liability claims, and globalization of markets.

Increasingly stringent regulatory requirements are a major driver of technological innovation. Regulations for exhaust emissions, fuel economy, safety, and product liability require innovative technological solutions and raising research and product development expenditures. As a result of emission and fuel economy regulations, major investments are also made in alternative propulsion technologies.

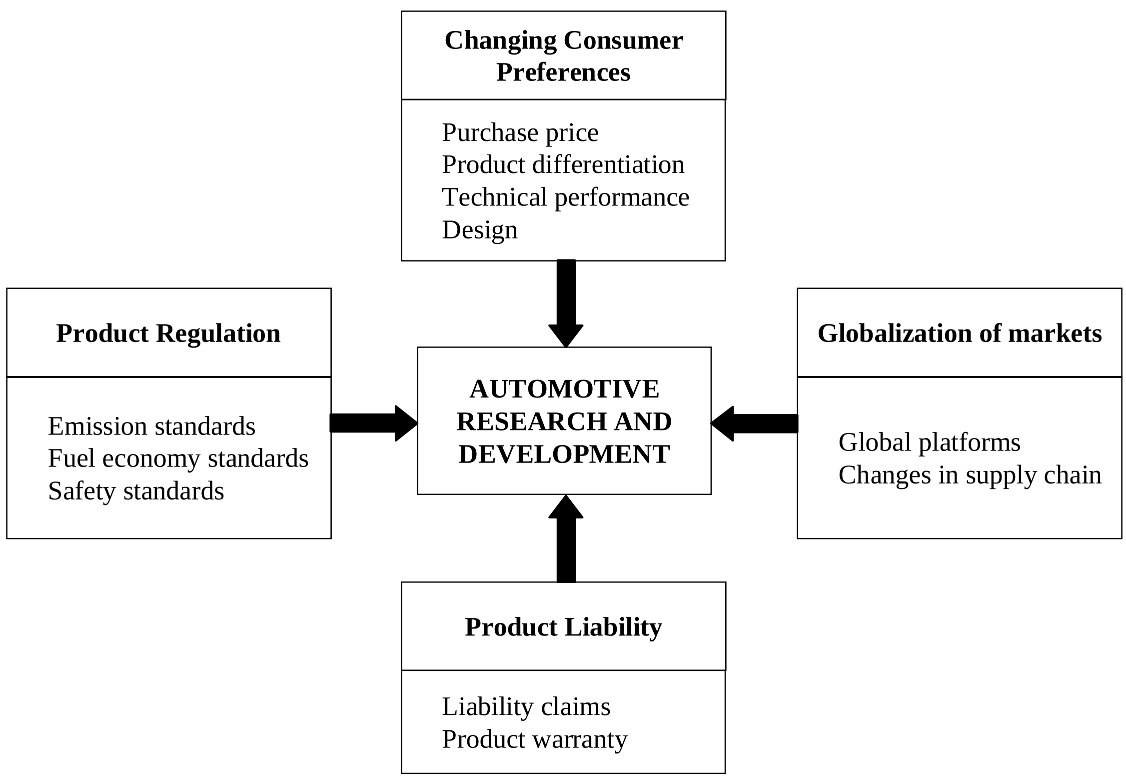

Figure 1. Drivers of technological innovation in the automobile industry.

[2] Innovation and product development in the automobile industry are described in more detail in Clark and Fujimoto (1991), and Altshuler et al. (1984:87ff).

With globalization, manufacturers are driven to reduce costs and enhance product differentiation on a global basis. This has been achieved with the deployment of common platforms and added flexibility of models based on the same platforms. This affects product development and technology through more product and process modularization and standardization. Cost pressure also increases the need to evaluate outsourcing of R&D functions, and to implement closer cooperation with suppliers in product development.

Consumers are driving technological innovation through increasingly sophisticated demands. Today's consumer priorities concern purchase price, performance, safety features, comfort and accessories. These preferences constitute a substantial barrier for alternatives to the established internal combustion engine. For example, the failure of attempts to commercialize electric vehicles is attributed mainly to their limitation in providing adequate driving range at acceptable cost, a result of the limited energy storage capacity of even the most advanced batteries.

2. FUEL CELLS FOR AUTOMOTIVE PROPULSION

2.1. Operating principle of automotive fuel cells

A fuel cell is an electrochemical devices that converts fuel and air into electricity and water. Individual fuel cells, consisting of electrodes placed on an electrolyte membrane, are stacked up to form a fuel cell stack. The electricity from the fuel cell drives an electric motor connected to the wheels of the automobile. A high power device such as a battery or ultracapacitor may assist the fuel cell for peak power operation such as during acceleration. Auxiliary components are needed for overall control of the system, for water and thermal management, and for electric power conditioning. Figure 2 illustrates the basic components of a fuel cell powertrain system.

The most promising fuel cell technology for use in automobiles is the polymer electrolyte membrane (PEM) fuel cell[3]. The PEM uses hydrogen as fuel and provides a number of advantages over other types of fuel cells. It has no corrosive liquids in the cell, and today provides sufficient power density and lifetime for automotive application. However,

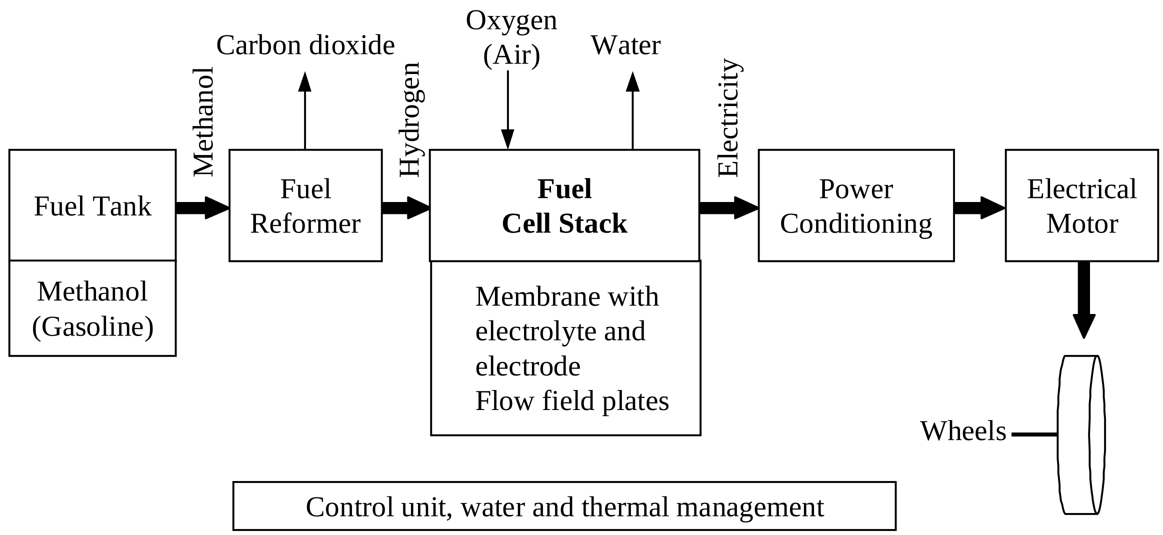

Figure 2. Basic components of a fuel cell powertrain.

initial concepts were very expensive due to the amount of platinum used as a catalyst on the surface of the polymer membrane. In addition, the PEM fuel cell is intolerant to carbon monoxide, which leaves hydrogen as the only fuel that can currently be used directly to supply the fuel cell. Hydrogen and methanol are currently the only practical fuels for automotive fuel cells, but hydrogen is not considered economically feasible as an automotive fuel. Hydrogen can be stored on-board or produced on-board in a chemical reformer.

Fuel reformers convert methanol or other hydrocarbons into a hydrogen-rich gas that supplies the PEM fuel cell. Currently, reforming technologies exist for on-board conversion of methanol into hydrogen. Future reformers may be able to use gasoline instead of methanol, but such concepts are in an early research phase.

2.2. Benefits and drawbacks of fuel cells

Fuel cells are often seen as a solution to energy and environmental problems, and because fuel cells can be supplied with liquid fuel such as methanol, they are not subject to severe range limitations like battery electric vehicles. Fuel cells are frequently mentioned as a means to reduce carbon dioxide greenhouse gases, because the energy conversion efficiency of fuel cells is higher than for internal combustion engines (Lemons, 1990;

[3] See also Kalhammer et al. (1998) for a detailed summary on the status of fuel cell technology, their environmental benefits, and major automotive fuel cell programs.

Noreikat, 1996; Walsh, 1990). This is true in particular at part-load operation. However, in an energy balance over the total system from fuel production to use in the automobile, it is less clear whether fuel cells based on methanol provide a less energy-intensive technology than the current internal combustion engine petroleum-based system (FFV, 1998; Thomas et al., 1998). Fuel cells are also seen as a propulsion technology with lower environmental emissions, because there are no air pollutants from the fuel cell itself. Fuel cells are therefore frequently promoted as a solution to reducing air pollution from automobiles (Lemons, 1990; Howard and Greenhill, 1993; Noreikat, 1996; Walsh, 1990). A fuel reformer may add minor emissions. Additional advantages of fuel cells concern low noise, low operating temperature, ease of maintenance, and the availability of excess electricity on-board, which may be used to supply additional consumer accessories.

The main disadvantages and uncertainties of fuel cells today mainly concern costs, the choice of fuel and corresponding fuel infrastructure issues, and the lack of manufacturing and practical operating experience. Current modern internal combustion engines cost around $15 per kW, and projections for mass-produced fuel cell systems show that this number is difficult to achieve. Costs for fuel cells are high mainly because of the manufacturing cost of fuel cells, and the overall complexity of a fuel cell system, including the fuel cell stack, fuel reformer, electronic equipment and auxiliary components.

2.3. Energy and environmental regulations

Regulatory developments in the United States have had a profound impact on the development of fuel cells for automotive applications worldwide. The California Air Resources Board adopted regulations in the year 1990 requiring that Zero-Emission Vehicles (ZEV) be offered for sale in California by year 1998 (CARB, 1994). However, in 1996, the California Air Resources Board modified its ZEV regulation and entered into an agreement with automobile companies to voluntarily introduce ZEVs in the period from 1998 to 2003. These regulatory developments have spurred an unprecedented boom in research and development of alternatives to the internal combustion engine, including electric vehicles and fuel cell vehicles. Currently, only electric vehicles are capable of meeting the ZEV standard, but the commercial success of electric vehicles has been very limited. Fuel cell vehicles are seen as the next promising technology that is capable of providing near-zero emissions.

At the Federal level, automobile manufacturers are required to comply with Corporate Average Fuel Economy (CAFE) standards, originally established by Congress in 1975. Fuel-efficient propulsion systems are therefore of interest to automakers who must comply with CAFE standards. In addition, the Energy Policy Act of 1992 and other legislation paved the way for the development of alternative propulsion systems and Federal support for R&D of energy technologies. The Partnership for a New Generation of Vehicles (PNGV) was founded in 1993 by the US government for developing alternative vehicle propulsion and lightweight materials in a cost-sharing program with industry. Although fuel cells are one of the options evaluated by PNGV, the level of funding for fuel cells by the government is much lower than the amount spent by industry[4].

The climate change debate and the Kyoto Protocol of 1997 have renewed interest in fuel cells as a way of reducing carbon dioxide emissions from automobiles. A range of political and institutional differences distinguishes the strategic responses of European, American and Japanese automobile manufacturers to climate change issues (Levy and Rothenberg, 1999). European automobile manufacturers seem to be less opposed to emission targets than their American counterparts, and have agreed to voluntary emission reduction targets.

3. HISTORY OF FUEL CELL RESEARCH

The following section contains a brief history of fuel cell research that provides useful information for subsequent sections. Fuel cell research for automotive applications dates back at least thirty years, when fuel cells were developed for aerospace applications in the United States and Europe. Aerospace fuel cells developed in the 1960s later received renewed interest for other commercial application, first in electrical power generation, and then for automotive propulsion.

3.1. Fuel cells for aerospace applications: Discovery of the PEM fuel cell

After William Grove invented the fuel cell in 1839, over a century passed by without significant technological breakthroughs. Grove's fuel cell used hydrogen as fuel and

4 PNGV press statement on February 4, 1998.

oxygen to produce electricity. Hydrogen fuel cells were viewed as a particularly intriguing technology due to their high theoretical efficiency, clean emissions, and relatively simple, modular concept. Major advances in fuel cell research were provided by Francis Bacon of Cambridge University in England after 1933 (Appleby, 1990). Bacon's fuel cells built on the basic principle developed by Grove and incorporated research done over several decades. Bacon's research established the foundation for application of fuel cells in spacecrafts. For this application, fuel cells are superior to batteries because of their high energy density, and because costs are not a primary factor. Bacon's fuel cell concept was further modified by the Pratt and Whitney Division of United Aircraft Corporation (now United Technologies), where it was used for the Apollo lunar missions in the late 1960s.

Parallel to the events in the 1960s, DuPont had developed an electrolyte membrane called Nafion that was based on a Teflon-like material[5] (polytetrafluoroethylene). This membrane offered significantly extended operating lifetime, and was used by General Electric in its fuel cells for NASA's Gemini missions during the mid-1960s. Nafion was discovered in 1962 and developed for the chlor-alkali industry, where it is still used today in relatively small volumes by chemical engineering standards (Anand et al., 1996).

By 1964, General Electric had developed and patented its own fuel cell membrane based on materials similar to Teflon. General Electric's research was the basis for one of the early prototypes of the modern Solid Polymer Electrolyte (SPE)[6] fuel cell, also known as PEM fuel cell, that is now being developed for application in automobiles. In a critical decision, NASA decided to choose United Aircraft's alkaline fuel cell for electricity generation on the later Apollo missions, because it was believed that alkaline fuel cells could better meet the spacecraft's requirement for high power density (Prater, 1990). General Electric decided to discontinue research on the PEM fuel cell, and sold the technology to Siemens of Germany and Hamilton Standard Division of United Technologies in 1984 (Anand et al., 1996).

3.2. Fuel cells for stationary power generation

The global energy crisis of 1973 generated interest in fuel cells for high-efficiency electricity generation. Various types of fuel cells including alkaline, molten carbonate, solid oxide and phosphoric acid fuel cells were developed with government support by

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[5] Nafion and Teflon are trademarks of E.I. Du Pont de Nemours and Co.
[6] Solid Polymer Electrolyte is a trademark of Hamilton Standard.

various companies worldwide. In Japan, fuel cells were actively developed as an environmental technology offering low emissions and high efficiency in power generation. Companies active in fuel cell research received considerable support from electricity and gas utilities, and the Japanese Ministry of International Trade and Industry (MITI). By 1994, Japan had constructed 87 small power plants mainly using phosphoric acid fuel cells. All of the fuel cell plants in operation are manufactured by either Fuji, Mitsubishi, Toshiba, or United Technologies of the United States (Kordesch and Simader, 1996; Itoh, 1990).

Carbonated fuels, in particular natural gas, are the preferred type of fuel for use in fuel cells for stationary power generation. These fuel cells are impractical for automobiles because of high operation temperatures in excess of 500°C, relatively low specific power, and the use of corrosive liquids. On the reverse, PEM fuel cells that are today developed for automobiles, were not suited for electricity generation because PEM fuel cells depend on hydrogen fuel, and are intolerant to carbon monoxide, a major by-product in the conversion process of carbonated fuels.

3.3. Rediscovery of the PEM fuel cell for automotive application

The PEM fuel cell has not received much attention until the mid 1980s. The PEM fuel cell had three crucial limitations that prevented it from being used commercially besides the application in spacecraft. Its membrane was prohibitively expensive because the electrodes required a high loading with platinum, it was intolerant to carbon monoxide, and it had low power density. The following statements about the PEM fuel cell powerfully reflect the sentiment against the PEM technology in the 1960s:

> *"Outstanding problems still concern cost, the use of cheap materials of construction, cheaper catalysts than the noble metals so far required and cheaper and more durable engineering components such as pumps, heat exchangers, condensors and so on. From information available to date it seems unlikely that production costs can be reduced to £100 per kW, which would seem to rule fuel cells out for commercial electric traction. " Barak (1967:496).*

> *"Expensive electrocatalysts continue to be a problem." Cairns and Shimotake (1969:392).*

However, a series of independent technical improvements during the 1980s opened the way for the PEM fuel cell to be considered in automotive propulsion. During the 1980s, researchers at Los Alamos National Laboratory (LANL) and Texas A&M University continued research on polymer electrolytes, and achieved a substantial reduction of platinum loading requirements by two orders of magnitude by 1988 (Lemons, 1990; Appleby, 1995; Anand et al., 1996). With this breakthrough, the cost of the platinum required for an automotive fuel cell was reduced from well over $50,000 to a few hundred dollars.

A second breakthrough was achieved by Ballard[7], a Canadian company founded by Geoffrey Ballard. Ballard received a contract in 1983 from the Canadian Department of National Defense (DND) to evaluate the potential of the PEM fuel cell for military applications (Prater, 1990) around the time when General Electric's early patents on its SPE fuel cell had expired. Ballard made a breakthrough in fuel cell performance and successfully developed a selective oxidation process that reduces carbon monoxide in reformates from carbon-based fuels. With this, Ballard demonstrated a first system consisting of a PEM fuel cell and a methanol reformer. Using a new polymer membrane from Dow Chemical in 1987, Ballard achieved an increase in power density to almost four times that of the previously available Nafion membrane from DuPont. This meant that fuel cells could eventually be made smaller, lighter and cheaper. One of the first Ballard fuel cell prototypes was the size of a small automobile engine and was able to deliver about 2 kW of power. However, this was still far below the power of an average automobile engine (60-80 kW). The UK Royal Navy first tested the Ballard fuel cells for use on submarines.

DuPont, Dow Chemical and Asahi Chemical Industry Co. of Japan were the only companies developing Teflon-like materials commercially for the chlor-alkali industry. Ballard therefore decided to develop its own membrane, and also started to collaborate with Johnson Matthey Ltd. of the UK to develop improved, low-platinum membrane catalysts. Johnson Matthey is a large international company active in materials technology, precious metals and specialty chemicals that has since acquired considerable experience in catalyst technology for fuel cells and methanol reforming.

The advances made by Ballard suddenly opened new potential markets for the PEM fuel cell. Previously unachievable power densities made the fuel cell a potential candidate for automotive propulsion, as well as a range of other applications. From initial research into the PEM fuel cell for aerospace application, over two decades passed before the technology was rediscovered and a breakthrough was achieved.

[7] Later renamed Ballard Power Systems Inc.

3.4. Early investments of automobile manufacturers: Daimler-Benz and Ford

Long before Ballard's research on PEM fuel cells, General Motors and Allis Chalmers developed fuel cell vehicle prototypes, but these designs were flawed because of an excessively heavy fuel cell system. In 1959, Allis Chalmers[8] was active in NASA's Apollo program, and built a tractor with a fuel cell weighing over 900 kg and providing only 15 kW of total power. In 1967, General Motors built a van powered by a Union Carbide fuel cell system that put the total weight of the car to 3400 kg, which ruled out any commercial application of the technology (Kordesch and Simader, 1996):

> *"The present state of fuel cell engineering can be appreciated by consulting the papers describing the design, development, and operation of the GM Electrovan which is powered by Union Carbide hydrogen-oxygen cells. This is a remarkable achievement, especially when one considers the relatively sophisticated control system and the high performance of the vehicle. The most notable disadvantage of this fuel-cell powered vehicle is the excessive weight of the fuel cells (3,380 lb.!) made necessary by the peak power requirement (160 kw.) of five times the nominal rating (32 kw.). … Despite the disadvantages, the Electrovan proves that fuel cell engineering has progressed to the point that vehicles can be powered by hydrogen fuel cells and can retain reasonable performance and range." Cairns and Shimotake (1969:396).*

Because early attempts failed to develop fuel cells for automobiles, the PEM fuel cell technology developed by Ballard in the late 1980s was the only technology of the time that could be practical in automobiles, due to the power density and reduced platinum loading. Ballard, with support from the Government of Canada and British Columbia, began to build a fuel cell powered bus in 1990 to show the feasibility of such a system, and embarked on a development program for commercial fuel cell buses. The first bus provided a power of 120 kW and was powered by hydrogen. It was first displayed in California as an example of a Zero Emission Vehicle (ZEV) in 1993.

Daimler-Benz was the first company to evaluate the new Ballard fuel cell for automobile application around 1990, and subsequently started a cooperation with Ballard in 1993. This resulted in a four-year cooperative agreement to develop PEM fuel cells for use in automobile prototypes, with Daimler-Benz contributing $15 million in funding to Ballard (Kordesch and Simader, 1996:285). Ballard Power Systems was taken public in the same year, and became a fast growing R&D company with revenues solely generated from the sale of fuel cell prototypes. The company has since sold fuel cell prototypes to almost all automobile companies involved with fuel cell research, including DaimlerChrysler,

[8] The company was sold to K-H-Deutz AG of Germany in 1985, and later liquidated.

General Motors, Ford, Volkswagen, Volvo, Honda, Mazda, Nissan and Yamaha. Ballard also develops fuel cells for stationary power generation. Over the period since the company went public, Ballard has seen its market value rise to more than $2 billion by 1998, while its revenues from the sale of fuel cell prototypes still only amount to $25 million (Ballard, 1998).

Daimler-Benz has been active in fuel cell research since the 1960s through its aerospace division. In 1985, the Daimler-Benz group acquired a stake in Dornier GmbH, a German aircraft and aerospace company, and integrated the company into its aerospace and defense division, Daimler-Benz Aerospace. Dornier was involved with fuel cell research in connection with the European space shuttle program Hermes, which was created in 1987, but discontinued in 1992. Dornier led an industrial team with funding from the European Space Agency (ESA) involving Elenco of Belgium, and Siemens and Varta of Germany, that evaluated and developed several fuel cells including the PEM fuel cell (Baron, 1990). When Ballard published its breakthrough in PEM fuel cells, researchers from the Dornier and Daimler-Benz Aerospace fuel cell teams initiated the contacts with Ballard.

The first agreement between Ballard and Daimler-Benz was the cornerstone for a continuing partnership that provided Daimler-Benz with access to breakthrough technology and gave Ballard access to automotive expertise. Daimler-Benz unveiled its first prototype vehicle, NECAR I, using a Ballard fuel cell in 1994, and made the first public announcement of Daimler-Benz' interest in fuel cells. This event created widespread attention for fuel cells in the automobile industry. Additional Daimler-Benz prototype fuel cell vehicles were developed and unveiled in subsequent years. In 1997, Daimler-Benz and Ballard negotiated a new alliance that involved a $400 investment by Daimler-Benz and included Daimler-Benz acquiring 25% of Ballard (Ballard, 1997). The two companies created two joint ventures, dbb Fuel Cell Engines and Ballard Automotive. Dbb Fuel Cell Engines is responsible for developing and commercializing fuel cell engines, and Ballard Automotive is a sales company with the goal of marketing and selling fuel cell engines to automobile manufacturers worldwide. Ballard also reinforced its cooperation with Johnson Matthey for the joint development and supply of catalysts. Daimler-Benz merged in 1998 with Chrysler Corporation to form DaimlerChrysler. Before the merger, Chrysler only had limited activities in fuel cells.

In 1998, Ford Motor Co. joined Daimler-Benz and Ballard through a $500 investment that included the formation of a joint venture and Ford acquiring 15% of Ballard (Ballard, 1998). The joint venture, Ecostar, is responsible for developing electric drivetrain technology for fuel cell vehicles, based on the extensive experience that Ford acquired in the development of electric vehicles. Mazda, a minority-owned subsidiary of Ford, participates through Ford in the alliance. Mazda has a long history of research into the combustion of hydrogen in rotary engines.

In 1998, Ford also announced a strategic alliance with Mobil Corporation to develop cleaner fuel and engine systems, including technology for fuel reformers. DaimlerChrysler entered into a similar alliance with Shell Oil to cooperate on fuel cell and reformer technology, and to evaluate Shell's catalytic partial oxidation technology, which transforms conventional fuel into hydrogen-rich gas. These two alliances with oil companies also target the evaluation of a methanol-based fuel infrastructure, which is one of the critical issues remaining for a commercial introduction of fuel cells.

Under the current agreements of the DaimlerChrysler / Ford / Ballard partnership, Ballard is responsible for developing fuel cells. The joint venture dbb Fuel Cell Engines develops fuel cell powertrains, while DaimlerChrysler and Ford purchase fuel cells from Ballard, and perform their own proprietary research and development, including the integration of fuel cells into vehicle prototypes.

3.5. Emerging interest of other automobile manufacturers

Other automobile companies have gained interest in fuel cells parallel to the developments around Daimler-Benz, Ford and Ballard, and have started to develop automotive fuel cell prototypes (see Table 1 for an overview). Several of the large automakers currently have announced that they intend to sell commercial fuel cell vehicles by the year 2003 or 2004, a target that seems very ambitious given traditional product development cycles of around four to six years.

General Motor’s involvement in fuel cells goes back to the 1960s when the company developed one of the first fuel cell prototypes. Thereafter, General Motors activities in this field focused mainly on electric vehicles and battery research, and the company again started an active fuel cell project in 1990 with support from the US Department of Energy (DOE) and in cooperation with Los Alamos National Laboratory (LANL) (Creveling, 1993). Besides the fuel cell prototypes that General Motors bought from Ballard, the company develops its own proprietary technology at GM’s Global Alternative Propulsion Center and in cooperation with GM’s German subsidiary, Opel. General Motors

Year	Company	Vehicle type	Fuel cell type	Fuel, Power
1959	Allis Chalmers	Tractor	Alkaline	15 kW, fuel cell weight 917 kg
1967	General Motors	Van	Alkaline	160 kW, fuel cell weight 1500 kg
1993	Ballard Power Systems	Bus	PEM	Hydrogen, 120 kW
1994	Daimler-Benz	Van (NECAR I)	PEM	Hydrogen, 50 kW
1994	City Bus project, Belgium	Bus	Alkaline	Hydrogen
1994	EnergyPartner	Car	PEM	Hydrogen, 15 kW
1994	DOE, H-Power and Fuji	Bus	PAFC	Methanol, 60 kW
1996	Daimler-Benz	Van (NECAR II)	PEM	Hydrogen, 50 kW
1997	Daimler-Benz	Bus (NEBUS)	PEM	Hydrogen, 250 kW
1997	Daimler-Benz	Car (NECAR 3)	PEM	Methanol, 50 kW
1997	Toyota	Car (RAV-4)	PEM	Methanol, 20kW
1997	Mazda	Car (Demio)	PEM	Hydrogen, 20 kW
1998	General Motors	Car (Zafira)	PEM	Methanol, 50 kW
1998	Renault	Car (Fever)	PEM	Hydrogen, 30 kW
1999	DaimlerChrysler	Car (NECAR 4)	PEM	Hydrogen, 55 kW
1999	Ford	Car (P2000)	PEM	Hydrogen, 60 kW
1999	Nissan	Car (R'nessa)	PEM	Methanol, 60 kW
1999	Honda	FCX-V1 (EV Plus)	PEM	Hydrogen, 60 kW
1999	Honda	FCX-V2 (EV Plus)	PEM	Methanol, 60 kW

Table 1: Fuel cell vehicle prototypes.

announced partnerships with the oil industry on fuel cell related reformer technology through a cooperation with Amoco, and between General Motors' subsidiary Delhpi[9] and Atlantic Richfield Co.[10] (ARCO) and Exxon Corp[11].

Toyota started fuel cell research around 1990 and worked closely with the suppliers of its keiretsu, including Asahi, Denso and Aisin Seiki. Fuel cell R&D is carried out in three centers, Toyota's Higashi-Fuji and Jido Technical Center, and Aisin Seiki's technical center (Hoogma, 1998). In 1997, Toyota unveiled its first fuel cell prototype vehicle with proprietary technology, including the fuel cell stack and metal hydride storage for hydrogen. Benefiting from the experience in developing hybrid vehicles, Toyota's second fuel cell prototype vehicle was based on a hybrid configuration involving a fuel cell and power-assisting batteries. In 1999, General Motors and Toyota announced a five-year collaboration on advanced automotive technologies, including the development of fuel cell vehicles, hybrid electric and battery electric vehicles. The collaboration is expected to provide serious competition to the DaimlerChrysler / Ford / Ballard alliance.

Other Japanese automakers also have strong fuel cell R&D programs. Honda has developed a proprietary fuel cell stack, and has also licensed fuel cells from Ballard.

9 A public company, Delphi Automotive Systems Inc., since 1999.
10 ARCO agreed to merge with BP Amoco on March 31, 1999.
11 Exxon agreed to merge with Mobil Oil to form Exxon Mobil in 1999.

Mitsubishi is developing fuel cells and methanol reformers in cooperation with Mitsubishi Heavy Industries. Nissan licensed fuel cells from Ballard and is investigating direct methanol fuel cells as a longer term solution.

United Technologies Corporation was long active in fuel cells for stationary power generation through its subsidiary ONSI Corporation, and began work on PEM fuel cell technology again in 1984 through its subsidiary International Fuel Cells (IFC) and a joint venture with Toshiba Corporation. United Technologies acquired PEM technology from General Electric in 1984, and worked on improving the efficiency of the PEM fuel cell, but did not achieve the same breakthrough that Ballard had achieved by 1987. Today, International Fuel Cells and ONSI together have about the same number of employees as Ballard.

European companies other than Daimler-Benz rediscovered PEM fuel cells around 1994. Siemens of Germany had developed alkaline fuel cells for submarine applications, and started to license PEM technology from United Technologies Corporation (Greksch and Moser, 1996). Renault developed a fuel cell powered vehicle in cooperation with Ansaldo Ricerche and De Nora of Italy, Air Liquide of France, and support from the European Commission. In 1999, Renault and Peugeot started a new R&D project with government support for a hydrogen fuel cell car. Among the automakers that have announced little or no activity in fuel cells are Volkswagen and BMW, as well as less research-oriented companies such as the Korean automakers. Volkswagen announced a fuel cell evaluation program with minor funding ($6 million) in 1998.

Several aspects of this brief history of fuel cell research will be analyzed in the following sections. Many of the major automobile manufacturers today are involved in fuel cell research and development. Companies that were involved with fuel cells early on are again among the most active in fuel cell development, such as Daimler-Benz, General Motors, United Technologies, and Siemens.

In their attempts to acquire competence in the technology, automakers are choosing very different approaches. While companies such as DaimlerChrysler and Ford are engaging in cooperative research and development, others such as Toyota are developing the technology predominantly in-house. The growing network of companies involved in fuel cell research and development includes not only automotive manufacturers, but also automotive suppliers, oil companies, chemical companies and other specialty firms.

4. R&D STRATEGIES FOR NEW AUTOMOTIVE TECHNOLOGIES

4.1. The challenge of fuel cells

The technology dynamics of fuel cells are different from conventional automotive technologies. Because fuel cells are a fundamentally different technology that has not been part of the traditional technology portfolio of automakers and, at the same time, competes with a core competence of automakers, decisions about how to manage R&D for fuel cells are strategic in nature. An analysis of the R&D strategies for developing fuel cells in the automobile industry gives insight into the decision-making process of automakers and the dynamics of technological competition. More generally, the analysis may provide answers about how new technologies can be successfully managed in the automobile industry. The analysis begins with a summary of conventional approaches to R&D.

Successful strategies for managing conventional R&D are described in a broad literature on R&D management and case studies about the automotive industry (Clark and Fujimoto, 1991; Wheelwright and Clark, 1992; Hauser, 1996; Tushman and Anderson, 1997). In a detailed study of the automobile industry, Clark and Fujimoto (1991) describe the product development process from concept to market, and emphasize strategies for achieving total product quality, lower lead times and higher development productivity. Even though certain of these strategies can be applied to the development of fuel cell vehicles, fuel cell R&D needs to be analyzed with a different framework, because it concerns longer term technology planning than conventional product development with lead times between two to five years.

Technologies such as fuel cells involve great uncertainty and complexity about future benefits and costs. R&D strategies that are appropriate for decision-making under uncertainty have been developed both in theory and practice (de Neufville, 1990; Dixit and Pindyck, 1994; Trigeorgis, 1996; Neely, 1998). An obvious strategy suggested by this literature is the split of R&D investments in discrete phases with decision points about further investments at the end of each phase. This approach is applied in many areas of automotive research, and can also be observed in the case of fuel cells. Most automakers proceed with the development of fuel cells in phases, making the decision for further investment based on the successful outcome of previous efforts. The investment decisions of most fuel cell projects are spaced anywhere between several months and a few years. A second strategy derived from the theory on decision-making under uncertainty suggest that risky R&D is preferably done using a portfolio of competing solutions rather than making a single bet on one technology. This strategy can also be observed in many areas of automotive R&D. Automakers invest in fuel cells alongside with competing alternative technologies such as electric, hybrid, and advanced internal combustion engines.

The challenge of fuel cells is that this technology has not been part of the traditional portfolio of automaker technologies. The core knowledge required for the development of fuel cells is grounded in the electrochemistry of hydrogen and the electrocatalysis of hydrocarbon fuels, representing science that is fundamentally different from the experience acquired over decades of intensive research and development on internal combustion engines. Fuel cells that were used for aerospace application were initially too costly, too bulky, and too low in power density to even be considered for automotive application, so a fundamental issue of R&D management concerns the identification of fuel cell technology for automotive use. Because fuel cells were not a technical core competence of automakers, the automobile industry did not identify fuel cells as a potential technology for automotive propulsion, and largely ignored the technology at an early phase. Most automakers started to invest in fuel cells when Daimler-Benz demonstrated its first prototype fuel cell vehicle, and thereby gained a significant lead in developing the technology. Automakers were subsequently faced with the challenge to acquire knowledge in fuel cells, in which they had no prior experience. Then, as companies continue to invest into the development of fuel cell vehicles, and more prototypes are being built, automakers are faced with the question of what value can be derived from fuel cells if they are being commercialized.

Section 5, 6 and 7 deal with these issues in detail. The framework for the analysis is shown in Figure 3. The R&D process is split into three phases, the identification of new technologies, technology development, and exploitation and protection of technology. Compared to the traditional R&D process in the automotive industry, which is mostly preoccupied with Phase 2 and 3, this framework emphasizes the importance of identifying a technology that is not a core competence, and the importance of exploiting this technology in potential future commercial applications.

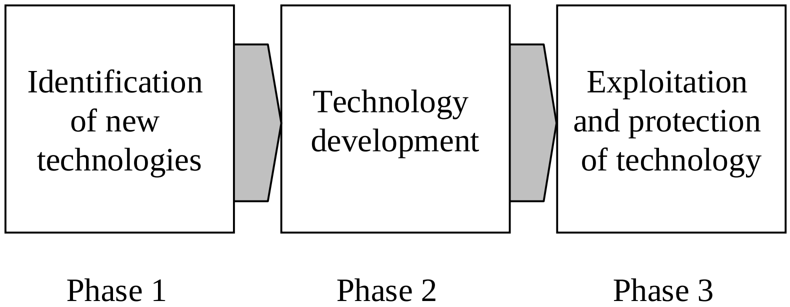


Figure 3: Framework for analysis of R&D for new technologies.

This framework is not only useful for an analysis of fuel cells, but could potentially be applied to other new technologies in the automotive industry that compete with core competencies. The framework could also be applied to the question of technology integration between automakers and suppliers, including the decision of whether to retain technical competencies in-house or whether to outsource competencies to suppliers.

5. EARLY IDENTIFICATION OF FUEL CELLS AND TECHNOLOGY LEADERSHIP

The history of fuel cell research illustrates that fuel cells have first been developed for aerospace application, then for stationary power generation, and finally for automotive application. This technology path may give an indication of who was among the first automotive companies pursuing fuel cells, and whether these companies have been able to establish themselves as technology leaders due to the early identification and involvement in fuel cells. Section 5.1 discusses the implications of the breakthrough in fuel cell technology achieved by Ballard around 1987, and Section 5.2 and 5.3 discuss the technology dynamics of fuel cells with the use of patent data. Patents are an indicator for R&D activity that is frequently used in the literature[12]. For comparability reasons, only patents filed in the United States are considered. The United States automobile market is strategically very important, and foreign automakers typically file patents in the United States to protect technology targeting this market. Patents are counted by application

[12] See for example Hauser (1996) for an overview, Grupp and Schmoch (1999) for issues of international patent statistics; and Griliches (1990) for the application of patent data in econometric studies. Trajtenberg (1990) suggests improving the patent count method by weighting patents by citations as an indicator of the value of innovations, a method that has not been applied here.

date rather than by issue date, to keep the dates close to the actual historical dates of R&D activity. Because the application date is used, patents are only counted until 1996, because patents only appear in the database once a patent is issued, which may take up to three years from the date of application.

5.1. Technological breakthrough

Ballard's breakthrough in PEM technology in 1987 had a crucial impact on the interest of automobile companies in fuel cells because it opened up the possibility for application of fuel cells in automobiles[13]. Understanding the factors that contributed to this technical breakthrough is of interest in studying why automotive companies have not been interested in the fuel cell technology before. Two developments contributed to the rapid breakthrough of PEM fuel cell technology: reduction in platinum loading requirements, and increase in power density of polymer fuel cell membranes.

Platinum coated on the polymer membrane was the main cost factor in PEM fuel cells for aerospace application in the 1960s. These costs were prohibitively expensive and ruled out any application of fuel cells in automobiles. In the following two decades, basic research at Los Alamos National Laboratory (LANL) and Texas A&M University achieved a significant reduction of the platinum requirement by several orders of magnitude. Figure 4 shows this impressive drop in platinum loading achieved in laboratory experiments. Within a few years, the approximate platinum cost for PEM fuel cells dropped from more than $50,000 per automobile to levels of a few hundred dollars, a cost range that is much closer to the price of components for an internal combustion engine.

A second progress factor that reduced the relative fuel cell cost even further was the increase of power density achieved during the late 1980s. While power density was not a critical parameter for aerospace fuel cells, it is crucial for automotive propulsion, where maximum power is needed for acceleration and maintaining top speed of an automobile. Ballard's breakthrough brought the power density of PEM fuel cells close to the performance range of internal combustion engines, which achieve power densities of 250-500 W/kg (Heywood, 1988:58).

[13] See Prater (1990) and Prater (1996) for confirmation of this impact.

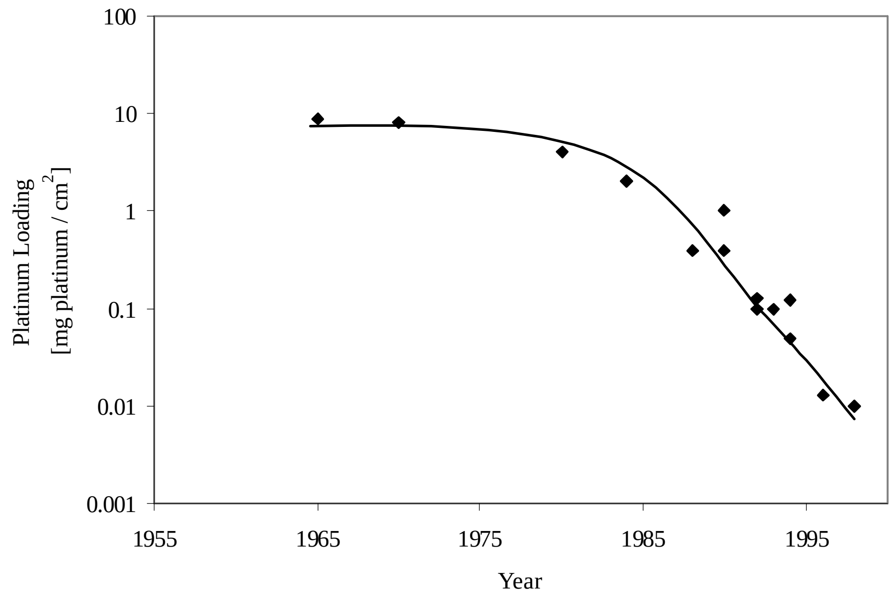


Figure 4: Reduction in platinum loading requirements for polymer electrolyte membranes (In laboratory experiments, based on technical publications).

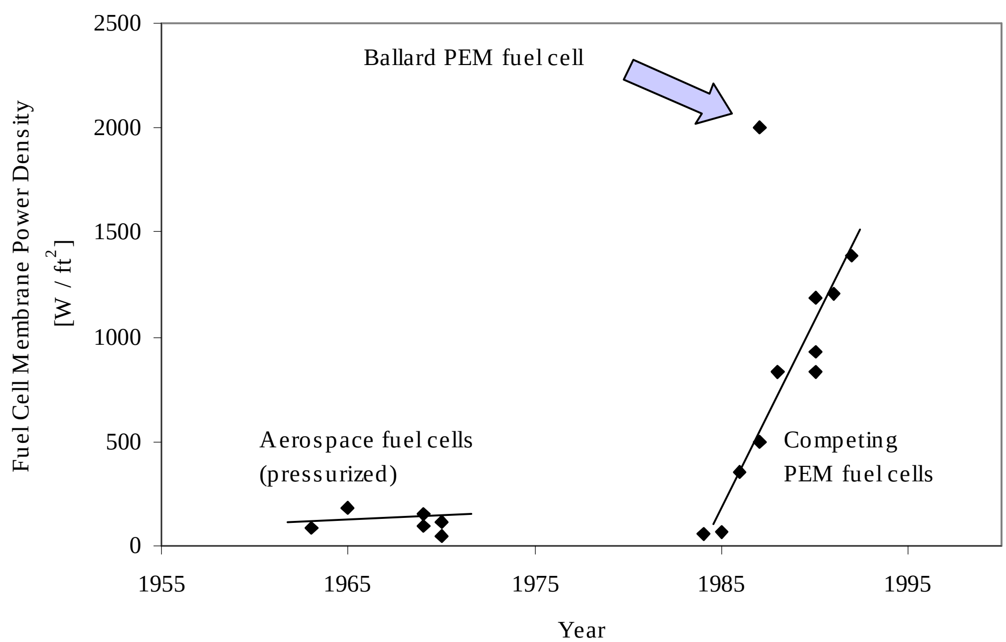


Figure 5: Progress in power density of fuel cell membranes achieved by Ballard in 1987, and competitor fuel cells (In laboratory experiments, based on technical publications).

Figure 5 illustrates the remarkable progress in power density achieved by Ballard by 1987. With its own improved membrane, Ballard achieved an increase in power density of almost four times that of the previously available Nafion membrane from DuPont. Ballard therefore gained a technological lead of about three to five years on its competitors.

It was shown that the elimination of two previously limiting factors of PEM fuel cells, costs and power density, opened up the possibility for application of fuel cells in automobiles. This progress was made by Ballard, a small company with support from the Canadian Department of National Defense, and by researchers at LANL and Texas A&M. The automotive industry was not involved in these events, but certain automotive companies, among them Daimler-Benz, immediately realized the potential of this breakthrough.

5.2. Identification of new technology

The events around Ballard's fuel cell technology suggest that automotive companies that had some, even if minimal, involvement in fuel cells could have recognized the potential of technical progress made by Ballard, but automotive companies with no prior involvement in fuel cells could not identify the progress that was made. The importance and mechanism of technology identification is therefore discussed in the following section.

Table 2 lists companies and institutions that were involved in fuel cell research in the 1950s and 1960s when fuel cells were developed for aerospace application. Among the companies was only one automobile manufacturer, General Motors, who had considerable activities in the aircraft, space and defense industry, and built one of the first fuel cell vehicles in 1967. Most of the other companies in Table 2 are from the aerospace, chemical, oil and gas, and electric power industry. Dow Chemical, DuPont, General Electric and United Technologies were involved in the early development of PEM fuel cells for the Apollo and Gemini programs of NASA. The efforts of Dow Chemical later led to the creation of a membrane that provided the breakthrough success for Ballard, while DuPont and General Electric's technology ended up with United Technologies. These few historical facts indicate that modern PEM technology can be traced back to fuel cell R&D for aerospace applications in the 1950s and 1960s.

Companies and institutions involved with fuel cell research from 1950-1970	
Allis Chalmers	General Motors
American Cyanamide Co.	Institute Francaise du Petrole (IFP), France
ASEA, Sweden	Institute of Gas Technology
British Petroleum, UK	Japan Storage Battery Co., Japan
Broers, Holland	Matsushita Electrical Industrial Co., Japan
Brown Boveri & Co., Switzerland	Monsanto Research Co.
Centre National de la Recherche Scientifique, France	NASA
CGE, France	Shell Research, UK
Compagnie Francaise Thomson Houston, France	Siemens, Germany
Dornier GmbH, Germany	Union Carbide
Dow Chemical	United Aircraft Co. (United Technologies Corp.)
Du Pont	Hamilton Standard Division
Electricite de France, France	Pratt and Whitney Aircraft
Esso Research and Engineering	Varta, Germany
Gas de France, France	Westinghouse Electric Co.
General Electric Co.	Yuasa Battery Co., Japan

Table 2: Companies and institutions involved with fuel cell research from 1950-1970 (based on Barak, 1967).

Top 10 patent holding firms in fuel cell technology

	US fuel cell patents, 1970-1996 *)
United Technologies Corp. / International Fuel Cells	223
Siemens AG / Westinghouse Power Corp.	121
United States of America (National labs)	112
Hitachi, Ltd.	52
Energy Research Corporation	52
Fuji Electric Co., Ltd.	46
Mitsubishi group	44
NGK Insulators, Ltd.	39
Ballard Power Systems Inc.	36
Exxon Research & Engineering Co.	34

*) US patent classifications 429-012 to 429-046; Source: US Patent Office database.

Table 3: Top 10 patent holding firms in fuel cell technology from 1970-1996.

The list in Table 2 also contains a large number of companies that were involved in the European space programs. Among these are Siemens, Dornier and Elenco, companies that today are investing in fuel cell R&D for automobiles. Dornier GmbH was acquired by the Daimler-Benz group in 1985, and today is a majority-owned subsidiary of DaimlerChrysler Aerospace. The company was founded at the beginning of the century to manufacture zeppelins, and since then has remained involved with hydrogen research for aerospace application. Daimler-Benz' early identification of PEM fuel cells for automotive application was mainly due to the long corporate history in hydrogen and fuel cells research at Dornier, and Daimler-Benz' involvement in aerospace research in the 1960s.

The enormous boom in patents for stationary power fuel cells is illustrated in Figure 6. With the global energy crisis in 1973, numerous companies in the oil and gas, and energy industry started to investigate alternative power sources, including fuel cells. Considerable government funding for fuel cell research supported this trend in the United States (through the Department of Energy) and Japan (through the Ministry of International Trade and Industry). According to Table 3, the worldwide leading patent-owning company is United Technologies Corporation with its divisions Hamilton Standard (aerospace), ONSI (fuel cells for stationary power) and International Fuel Cells (fuel cells for transportation), followed by Siemens/Westinghouse[14]. United Technologies and Siemens acquired substantial experience on fuel cells from aerospace research and successfully expanded this knowledge to other applications. But an application of fuel cells in automobiles was still not feasible until the late 1980s, because the most promising fuel cell types for power generation were phosphoric acid and molten carbonate fuel cells, which are corrosive, heavy, and require high temperature operation (200°-600°C). Even though many companies acquired substantial experience with fuel cells for electric power generation, the difference in technology did not automatically put these companies in an advantageous position for automotive fuel cells, but United Technologies and Siemens today are both found among the most active companies pursuing PEM fuel cells for automotive and other applications. It is probably no coincidence that these two companies also have subsidiaries in the automobile industry, which may have facilitated the transfer of research knowledge and to focus attention to automotive fuel cells.

Figure 7 shows fuel cell patenting of automobile companies and Ballard. Automobile manufacturers with less than three fuel cell patents over the whole period were not included in the figure. Before 1990, the only companies with fuel cell patents were General Motors, Daimler-Benz with its subsidiaries Dornier and Daimler Aerospace, Toyota and Ford (through Ford Aerospace). With the exception of Toyota, these companies all have aerospace divisions, which could have increased awareness for fuel

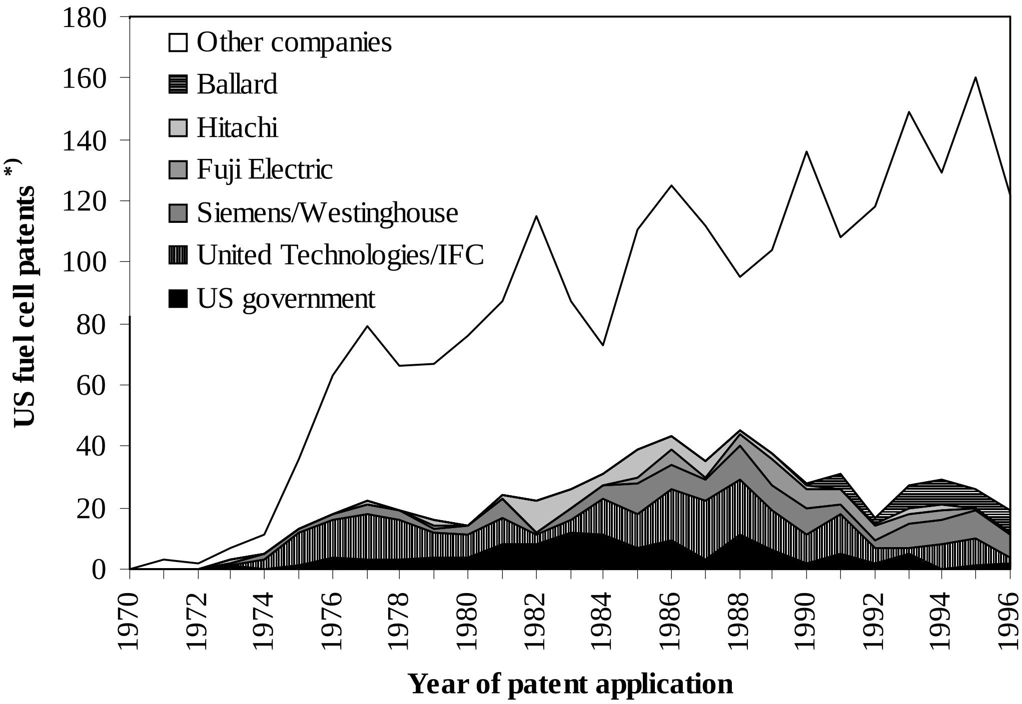
[14] Siemens AG acquired Westinghouse Power Generation in 1998.

cell technology. After 1990, Ballard initiated a remarkable explosion in fuel cell patenting with the publication its breakthrough in PEM technology (Prater, 1990). The fastest followers in patents were Daimler-Benz and General Motors, and with a delay of two to three years also Toyota and Honda, all of which filed several fuel cell patents in the years subsequent to 1990.

These observations suggest the following conclusions. Decade-long lead times of fuel cell research preceded a phase of very rapid developments of fuel cell technology for automotive application. After a breakthrough occurred, leadership in fuel cell technology have been taken by a small R&D company, Ballard, and automotive companies with an early involvement in fuel cell technology through the aerospace industry.

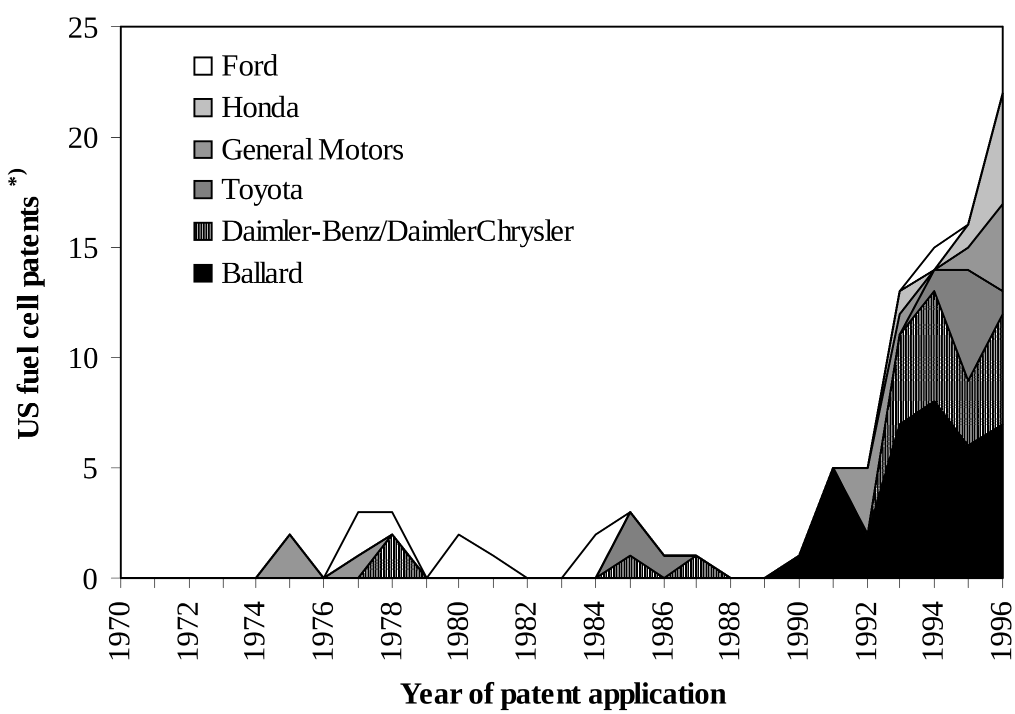
This suggests that automotive manufacturers with links to related industries may be more likely to recognize and pursue technology leadership when a breakthrough occurs. Also, an entrepreneurial approach to funding emerging technology and small companies with seed money may be appropriate. This suggestion may be more relevant than it seems at first. A large automotive company with several billion dollars in R&D expenditure could easily take a wait-and-see approach to a new technology. However, from the example of fuel cells, it does not appear that companies with an early awareness of breakthrough technology take such an approach. Rather, companies with early identification capabilities quickly invested in more R&D, while companies that had no prior exposure to fuel cell technology were not aware of its potentials, and later faced costly access to the rapidly developing technology through licensing.

There are countless other examples where the automotive industry has adopted technology developed elsewhere, and early adopters have remained leaders in the technology. A prominent examples is the turbocharger, adopted from the aircraft engine (Altshuler et al., 1984). This technology required specific adaptation for use in automobiles. At the beginning of the century, General Electric and later also the Garrett Corporation (now part of AlliedSignal Corp.) developed turbochargers for use in military aircraft engines. After the application in aircraft followed the use of turbochargers in industrial diesel engines, and only later was the turbo introduced in automobiles. AlliedSignal today remains among the market leaders in turbochargers for automobiles.



*) US patent classifications 429-012 to 429-046, excluding automobile manufacturers; Source: US Patent Office database.

Figure 6: Fuel cell patents for electric power generation.



*) US patent classifications 429-012, 429-013, and 429-017 to 429-046; Daimler-Benz/DaimlerChrysler includes patents of subsidiaries Dornier and Daimler Aerospace; Source: US Patent Office database.

Figure 7: Fuel cell patents for automobiles.

5.3. Identification of fuel cell technology at Daimler-Benz and Ford

In interviews held at Daimler-Benz and Ford for this study, managers confirmed the importance of early technology identification, and the lead role of aerospace activities at Daimler-Benz for its leadership in fuel cells. Daimler-Benz' early involvement in aerospace fuel cells led the company to further develop the technology as it became feasible for automotive application. Ford, on the other hand, had sold its Aerospace & Communications Corporation in 1990 and was therefore missing historical links. But the company has developed broad expertise in drivetrains for electric vehicles, which proved to be an important component for fuel cell vehicles, and which motivated Ford to join the Daimler-Benz / Ballard partnership.

According to interviews held at Daimler-Benz, the company's interest in fuel cells goes back several decades, and involved the company's activity in the aerospace industry as well as early experiments of using hydrogen as an automotive fuel. Daimler-Benz has a long history of leadership in automotive technology, and investigated several alternative power sources in the 1970s and 1980s. During this period, Daimler-Benz also evaluated hydrogen for automobiles, and has produced several hydrogen combustion vehicles in the period between 1984 and 1988 (Zieger, 1996). The strong interest in hydrogen is partially based on Daimler-Benz' involvement in aerospace, but also reflects a longer tradition of energy research in Germany. Hydrogen was key to the evolution of the German chemical and aerospace industry early in the century. Therefore, Daimler-Benz was among the few companies that had broadly investigated the use of hydrogen in combustion engines for automobiles, except for BMW of Germany. The key event, however, was the Daimler-Benz acquisition of Dornier. The Dornier research division, which included a fuel cell research group, was integrated into the Daimler-Benz R&D division in 1985. When Ballard published its breakthrough in PEM fuel cell technology, researchers of the Daimler-Benz/Dornier fuel cell group immediately became interested, recognizing the potential for automobile use. Subsequently, contacts were established with Ballard that led to the cooperation between the two companies.

Daimler-Benz' corporate interest in fuel cells was based on a long term vision of automotive propulsion technology that would reduce concerns about fossil fuel resources and climate change, and would alleviate emissions from automobiles. Compliance with future regulations of fuel economy and exhaust emissions are of immediate concern to the company, whose large-sized Mercedes-Benz cars are particularly exposed to such regulations. In addition, the political debate about climate change and carbon taxation seemed more imminent in Germany than in the United States. Developing fuel cells also fell in line with Daimler-Benz' tradition of pursuing technological leadership. As a company with a rich tradition in innovation and quality products, Daimler-Benz relies on differentiating its products through innovative technology, as illustrated by the following quote:

> "Having great products and excellent know-how today is not enough to secure our success tomorrow. Innovation is what drives growth further. Only companies with a culture of innovation from top to bottom are price-value leaders, stay ahead of competitors, capture market share, earn a premium return on their products and services and are able to both finance expansion and appropriately reward shareholders and employees." Juergen E. Schrempp, Chairmain of the Board of Management. Daimler-Benz (1998).

Top management at Daimler-Benz decided to support major investments in R&D for automotive fuel cells. Early identification of the technology coupled with strong backing for financial investments allowed the company to further develop technical competence and make rapid progress in fuel cell technology thereafter.

Ford's motivation to get involved in fuel cells was also driven by environmental concerns through the company's Ford 2000 program, which has had a major impact on the environmental policy of the company. In light of the California emission standards, the CAFE standard, and the Kyoto Conference, fuel cells were viewed as a potential solution to the carbon dioxide and exhaust emission problems. The decision to join the partnership of Daimler-Benz and Ballard was made because it would have been difficult to develop the technology quickly in-house. Ford sold its Aerospace & Communications Corporation in 1990 to Loral and had no more research in fuel cells. Joining the partnership allowed Ford to acquire competence in fuel cell technology, and to participate in further fuel cell R&D. Ford provided the partnership with expertise in electric drivetrain technology, access to the North American market, and experience in low-cost manufacturing for large volumes. Ford had acquired extensive knowledge in electric drivetrains that are today used in several commercial electric vehicles. Ford started to develop electric vehicles in the late 1980s with funding from DOE, and in 1990 started a serious effort to develop electric vehicles as a direct result of the announcement of the California ZEV mandate. A demonstration program of 150 vehicles was built and tested for three years. For Ford, this early involvement in electric vehicle technology proved to be crucial for access to fuel cell technology.

The examples of Daimler-Benz and Ford underline the importance of early identification of breakthrough technology for gaining leadership in a new technology. Daimler-Benz was aware of progress that occurred in fuel cells due to its involvement in aerospace, and decided to make major investments in fuel cells after Ballard published its breakthrough results. Ford became interested in fuel cells only later as the technology began to attract increasing attention from the automotive industry. Ford joined the partnership of Daimler-Benz and Ballard to acquire knowledge in fuel cells and provided the partnership with expertise in electric drivetrains, an important component of fuel cell vehicles. For Ford, leadership in electric drivetrain technology proved to be crucial for gaining access to fuel cell technology.

6. TECHNOLOGY DEVELOPMENT

6.1. Gaining competence in fuel cells: From components to systems

In the years since Ballard achieved the breakthrough in PEM technology, fast progress has been made by the automotive industry to develop fuel cell vehicles. Even though automobile companies with prior experience in fuel cells quickly acquired knowledge in PEM technology, these companies soon came to realize that the technological know-how needed for applying fuel cells in automobiles involves additional components and expertise. The attention of technological development has since shifted from the fuel cell stack to the overall fuel cell system and integration of the system into the automobile. Also the focus shifted from technical challenges towards reducing cost of fuel cells and the question of fuel choice and infrastructure. This view is expressed in Kalhammer et al. (1998) in an extensive study on the state of fuel cell developments in 1998:

> "The integration of stacks, fuel processors and balance-of-plant components into complete fuel cell electric engines poses a number of very difficult technical challenges. Nevertheless, systems integration has reached the breadboard stage in the leading programs, and Daimler-Benz has achieved the first in-vehicle operation of an experimental methanol-air fuel cell engine. While not yet a prototype, D-B's NeCar 3 vehicle demonstrates the basic feasibility of powering an automobile with a methanol fuel cell, …" Kalhammer et al. (1998:IV-3).

> "The prospects for successful development and commercialization of fuel cell electric engines and vehicles in the coming decade still have substantial uncertainties and risks associated with them. The main technical uncertainties are likely to become resolved and the largest cost uncertainties

> substantially reduced during the next 2-3 years. During the same time, fuel choice(s) and specifications should become clear. The ultimate uncertainty – acceptance of fuel cell electric vehicles by customers – can be reduced only gradually as user experience with prototypical and market test vehicles is being acquired in the subsequent 2-3 years, in parallel with further engineering and manufacturing development, testing, demonstration and manufacturing of automotive fuel cell electric engines and vehicles." Kalhammer et al. (1998:IV-6).

This phase of fuel cell R&D, the actual technology development phase, is therefore characterized with iterations of research, development, engineering and testing, which is in contrast with the sequential nature of conventional R&D. This is because certain components of the fuel cell system are more developed and have undergone extensive testing, such as the fuel cell stack, while other components are still at an early research stage, such as for example reformer technology for methanol or gasoline fuel. For automakers trying to gain competence in fuel cell technology with the goal of integrating fuel cells into automobiles, this suggests that fuel cell technology needs to be viewed from a systems perspective early on. Automakers not only need to gain competence about the fuel cell stack, but about all key components of a fuel cell system, similar to the knowledge they have acquired about the powertrain system of internal combustion engines.

The need for a systems perspective led companies to establish cooperation with oil companies, which provide access to expertise about hydrocarbon catalysis and chemistry. This knowledge is necessary for fuel processing in an on-board fuel reformer for a fuel cell system. Such cooperation was established by General Motors (with Exxon, Amoco and Arco), Ford (in alliance with Mobil Oil), and DaimlerChrysler (in partnership with Shell Oil). Traditionally, such alliances between auto and oil companies are rare and tend to happen around concrete objectives. In the area of fuel cells, however, such alliances allow both parties to benefit from complementary technical expertise and to monitor technological developments.

Another technology where alliances were established was that of fuel cell membranes. Today, there are only three commercial producers worldwide of polymer electrolyte membranes, which are manufactured primarily for the chlor-alkali industry. These are Asahi Chemical, Asahi Glass, and DuPont. Other companies started to develop polymer membranes specifically for fuel cells, including Ballard, Johnson Matthey, 3M, Hoechst, Dow Chemicals, and W.L. Gore. To gain more competence in fuel cell membranes, Ballard started a cooperation early on with Johnson Matthey to develop membranes for automotive fuel cells. General Motors initiated a cooperation with DuPont, and Daimler-

Benz has worked with Degussa, a German company with expertise in catalytic technologies. This strategy of collaborative research allows the automotive companies to gain access to competence in a key component for PEM fuel cell stacks.

The above examples underline the importance of a systems perspective for developing fuel cells. While automotive fuel cell research initially focused primarily on the fuel cell stack, automotive companies soon started to take into account other important components of the system, including the choice of fuel, fuel reformer, control technology, and the integration of components into the automobile.

6.2. Develop-or-Buy decision

In the attempt to acquire competence in automotive fuel cells, automakers have engaged in an extensive research network worldwide, as shown in Figure 8. The figure shows the central position of Ballard, DaimlerChrysler, Ford, General Motors, and Toyota, but it also shows the numerous links with non-automotive companies. Smaller automobile manufacturers, and others that have decided to take a wait-and-see approach, are relying on licensing the technology from Ballard. Companies that have invested in fuel cell R&D early on have chosen to either develop fuel cells internally or through collaborative research.

This decision to develop or buy fuel cell technology is similar to the make-or-buy decision that automakers face when deciding whether to integrate or outsource a core competence (Fine and Whitney, 1996). The decision to develop fuel cell technology bears substantial financial and business risks, but rewards these automakers in case of successful commercialization, technology-push by regulation favoring fuel cells, or spill-over of fuel cell technology for other uses. The decision to license fuel cell technology eliminates the need for risky investments in fundamental technology development, but

Internal development:	Toyota, Honda
Collaborative research:	DaimlerChrysler, Ford, General Motors
Licensing technology:	Nissan, Volkswagen, Volvo, small OEMs

Table 4: Develop-or-buy approaches in fuel cell R&D.

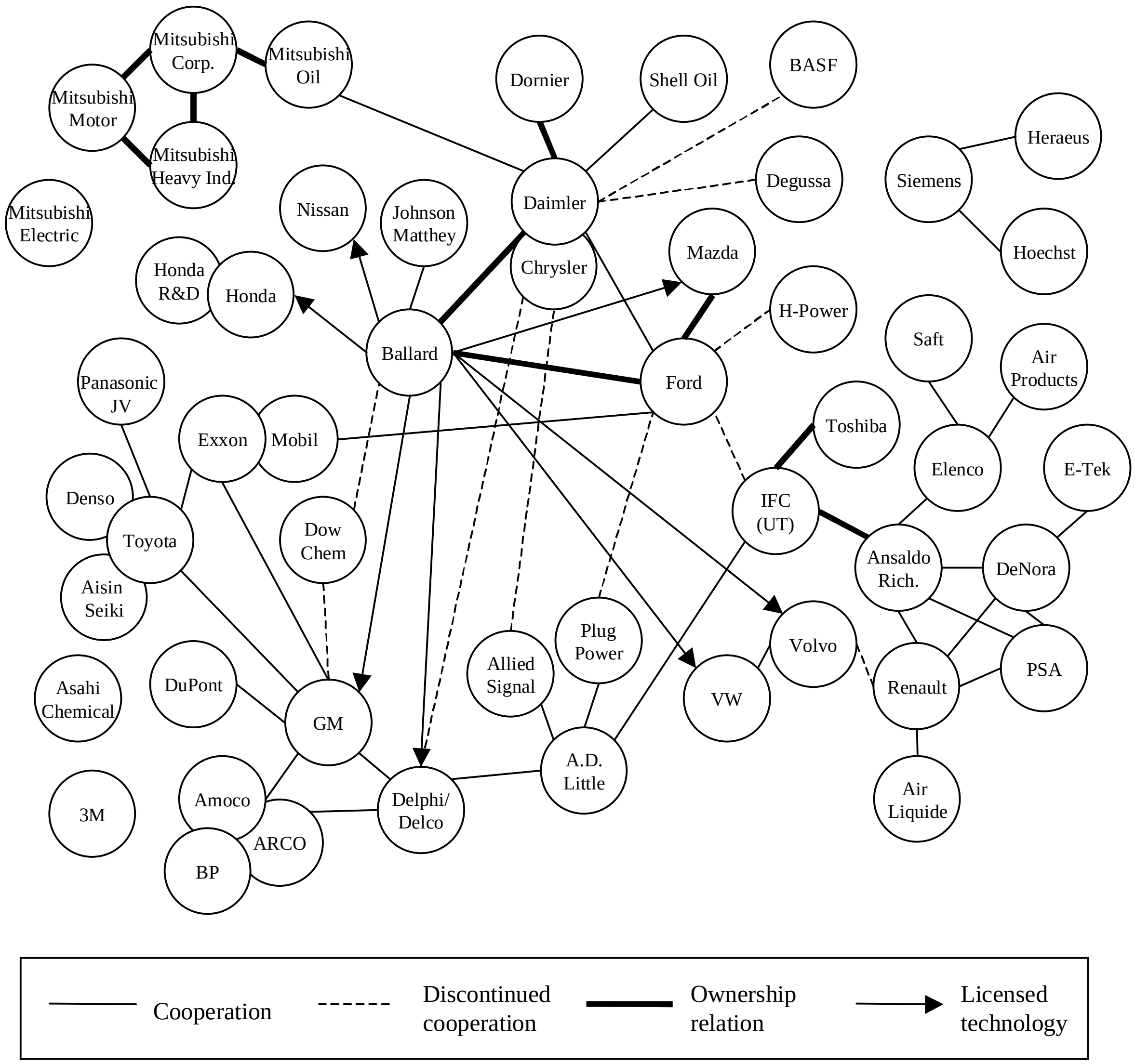


Figure 8: Global research network of companies pursuing the development of fuel cells for automobiles (Source: News reports; Norbeck et al., 1996; Kordesch and Simader, 1996; Kalhammer et al., 1998).

increases the price to be paid for the technology later, and excludes these automakers from a potential future market segment of fuel cell engines. Companies with a long historical involvement in fuel cell technology, such as Daimler-Benz, General Motors and Toyota, are taking an active development approach, while automakers without such experience rely on licensing the technology, as seen in Table 4.

Figure 9 shows details of the organizational R&D approaches of DaimlerChrysler / Ford / Ballard, General Motors / Toyota, and Honda. DaimlerChrysler, Ford and Ballard have established a truly collaborative network of alliance partners covering all major components of a fuel cell system. The alliance includes equity investments of the automakers in Ballard, three joint ventures that are majority-owned by DaimlerChrysler (dbb Fuel Cell Engines), Ford (Ecostar), and Ballard (Ballard Automotive), and links with oil companies. This research partnership is discussed in more details further below.

General Motors and Toyota have established a similar alliance involving automotive suppliers, oil companies, and chemical companies. While General Motors has licensed fuel cells from Ballard and cooperated with several partners on fuel cells in the past, Toyota has previously developed fuel cells almost entirely internally, involving only suppliers that are immediate members of its keiretsu. Through a joint venture with Panasonic, Toyota has also gained experience in electric motors for electric vehicles.

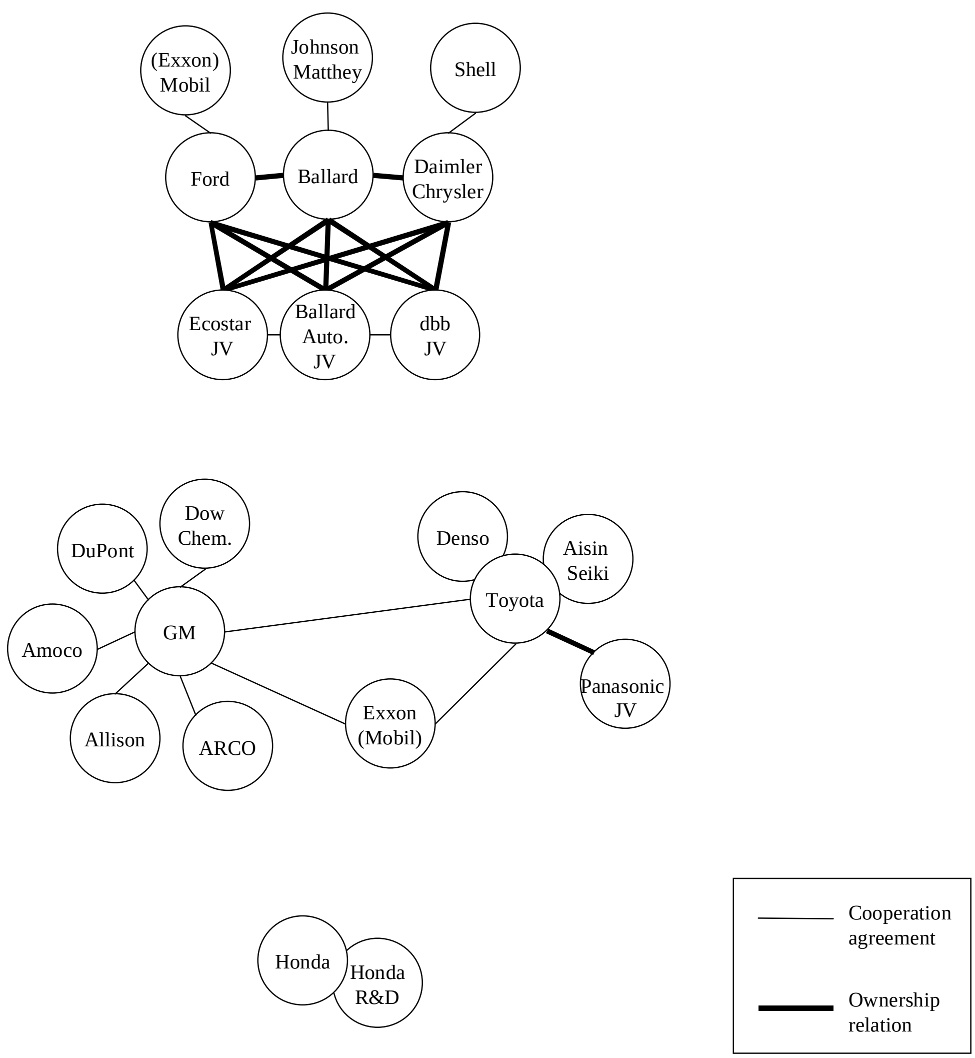


Figure 9: R&D networks of DaimlerChrysler / Ford / Ballard, General Motors / Toyota, and Honda in fuel cell technology (Source: News reports).

Exxon had established an alliance with both General Motors and Toyota for fuel cell reformer and other alternative vehicle technologies. The fact that Exxon has recently agreed to merge with Mobil Oil, who is involved in a cooperation with Ford, puts this company in a strategically important position. Also in 1999, Toyota and General Motors announced a five-year cooperation of the two companies in fuel cell, hybrid and electric vehicle technologies. This strategic alliance provides both companies with complementary access to fuel cell technology, and enhances the technology coverage of an overall fuel cell system in this R&D phase. It should also be noted that the General Motors/Toyota and DaimlerChrysler/Ford/Ballard alliances not only established themselves as the leaders in fuel cell technology, but at the same time represent the four largest automobile companies in the world.

Honda followed a strategy of almost complete internal development of fuel cell technology. Honda announced in 1999 that the company has developed a fuel cell vehicle prototype at its subsidiary Honda R&D. Honda licensed fuel cells from Ballard, but developed its own fuel cells in parallel. Such an internal development strategy seems much more risky and missing the breadth of other alliances in covering all components of a fuel cell system, but may reflect Honda's strong emphasis on R&D in engines and power products, which is regarded as one of the company's core competencies (Nelson, Mayo and Moody, 1998).

The experience of research alliances shows that it is difficult for automakers to acquire competence in a technology that is not a core competence through internal development only. Daimler-Benz, General Motors and Toyota initially developed fuel cells internally during the early years of investing in fuel cell R&D, but as the need for a broader perspective on fuel cells arose, these companies started to collaborate with partners that contributed with expertise on various components of the overall fuel cell system. Insights from the alliance between DaimlerChrysler, Ford and Ballard may clarify this argument.

6.3. Technical competence in the DaimlerChrysler / Ford / Ballard alliance

The alliance between DaimlerChrysler, Ford and Ballard is organized along technical dimensions and covers all components of a fuel cell system, as shown in Table 5. Ballard is responsible for developing the fuel cell stack. Table 5 clearly shows the lead in patenting of fuel cell stack, membrane and electrodes that Ballard has gained. By partnering with Johnson Matthey, a leading company in materials technology and precious metal based fuel cell catalysts, Ballard can draw on Johnson Matthey's expertise

	Ballard	Johnson Matthey	Mobil Oil	Shell Oil	Ford [1)]	Daimler-Chrysler [2)]
Fuel cell stack	**37**	4	-	-	1	11
Polymer membrane	**4**	-	3	2	-	1
Fuel cell electrode	**8**	**12**	-	-	-	-
Fuel reformer	4	5	**5**	**16**	3	2
Electric drivetrain	-	-	3	-	**63**	52
Automobile integration	-	-	-	-	**186**	**211**

1) Includes Ford Motor and Ford Global Technologies

2) Includes Daimler-Benz, DaimlerChrysler, and Chrysler

Numbers represent US patents held by companies in the following US patent categories, issued in the period 1985-1999: Fuel stack (429-012 to 429-013, 429-017 to 429-039), Polymer membrane (521-025 to 521-039), Fuel cell electrode (429-040 to 429-046), Fuel reformer (423-650 to 423-657, 423-246 to 423-248, 423-437 to 423-438), Electric drivetrain (180-065, 318), Automobile integration (180). Source: US Patent Office database

Table 5: Competencies in fuel cell related technology in the DaimlerChrysler / Ford / Ballard partnership (gray areas highlight technical competence, numbers represent patents held by the companies).

in the area of fuel cell electrodes. The cooperation with Johnson Matthey has contributed significantly to the improvement of Ballard's fuel cells. Johnson Matthey, on the other hand, is seeking for new markets for its products, and can rely on the broad experience of its business in catalyst technology and electrochemical products. DaimlerChrysler and Ford rely on Ballard to develop fuel cells, but both companies also develop their own proprietary fuel cell technology. The patent statistics suggest that this knowledge is not easily acquired, and that DaimlerChrysler therefore has a lead on Ford in terms of patents. According to the patent statistics, DaimlerChrysler and Ford do not develop fuel cell electrodes, leaving the responsibility for this component to Ballard and Johnson Matthey in the alliance. The oil companies in the alliance focus on fuel reformer technology. Oil companies have vast resources and experience in hydrocarbon processing and catalytic technologies, both of which are the scientific basis for fuel reformers. Instead of trying to replicate this expertise, Ford and DaimlerChrysler decided to develop fuel reformers cooperatively with Mobil and Shell.

DaimlerChrysler and Ford's role in the alliance is clearly centered around the integration of fuel cell technology into the automobile. While both companies are also involved in the development of components, they regard the integration of the fuel cells into the automobile as their main responsibility. Within DaimlerChrysler, the management unit *Projekthaus* is responsible for supervision of all fuel cell related activities. DaimlerChrysler's R&D division is responsible for continued research on proprietary fuel cells and fuel reformer, as well as vehicle-related issues. Temic, the automotive electronics and semiconductor subsidiary of DaimlerChrysler, develops electronic controls for the fuel cell vehicle prototypes, and dbb Fuel Cell Engines, the majority owned joint venture of DaimlerChrysler, is responsible for control systems and the fuel processing unit. Within Ford, the R&D division (Ford Research Laboratory) focuses on basic research issues and proprietary fuel cell technology, while Ford's Environmental Vehicle group is responsible for the overall vehicle integration. Ford's majority-owned joint venture in the partnership, Ecostar, is responsible for developing electric drivetrains based on the experience Ford has acquired in electric vehicles.

The alliance around DaimlerChrysler, Ford and Ballard clearly builds on technical complementarities of the partners in the alliance. The organizational split of the DaimlerChrysler/Ford/Ballard research alliance into units with technical responsibilities allows the companies to focus on technological capabilities and to divert non-core technologies to other units. In terms of intellectual property protection, the alliance provides an effective way of broadening the patent coverage. A strong intellectual property position is imperative for protecting future revenues of a new technology. This is particularly important for new technology with long term prospects, such as fuel cells. In a strategic alliance, intellectual property agreements also provide the basis for technology licensing and profit sharing in a future market. The early role of each partner within an alliance is therefore crucial, because it impacts future positioning in a potential market.

7. EXPLOITATION AND PROTECTION OF TECHNOLOGY

7.1. Role of automobile manufacturers in a potential market for fuel cells

Automobile manufacturers traditionally choose to develop and manufacture core components of the automobile, such as engine and transmission, and assemble and integrate components manufactured by suppliers. For a new technology such as fuel cells, automakers have to decide whether to acquire competence in all components of a fuel cell systems, or whether to focus just on the integration of the technology into the automobile. Automakers deciding to acquire competence in all components face risk and costly investments in R&D, and may face serious competition from companies with particular technological competencies in various components of a fuel cell system, including the fuel cell stack, fuel cell membrane, and fuel processor. On the other hand, if automakers rely merely on the integration of fuel cells into automobiles without developing and manufacturing key components, automakers run the risk of loosing control of the technology, and consequently loosing part of the value chain of a potential market for fuel cells to suppliers.

The current role of automakers in the network of companies involved with fuel cells gives an indication of the split of competencies between automobile manufacturers and specialized companies. Table 6 shows that automakers primarily target system integration of fuel cells into automobiles. The only other companies involved with system integration are companies with a broad historical experience in fuel cells, such as Ballard and International Fuel Cells. It is also apparent that companies that were among the early leaders in developing fuel cells cover a broader range of components. DaimlerChrysler, General Motors, Toyota and Honda develop fuel cell stacks, fuel processors, and overall system integration as well.

Among the companies developing the fuel cell stack, fuel cell membrane, catalyst, and fuel reformer are companies with specialized technological competencies. Polymer electrode membranes, for example, are predominantly developed by companies in the chemical industry, 3M, Asahi, Dow Chemical, DuPont, and Hoechst. Fuel processors are predominantly developed by oil companies and automakers.

In summary, it can be observed that automakers who were among the first to invest in fuel cells tend to become system integrators with control over several parts of the fuel cell system. This ability to control and integrate the fuel cell technology will be crucial

System Integration
AlliedSignal
Ansaldo Ricerche
Ballard Power Systems
DaimlerChrysler
Ford
General Motors
Honda
International Fuel Cells
Mitsubishi Motor
Nissan
Plug Power
Toyota

PEM Fuel Cell Stack
AlliedSignal
Ballard Power Systems
DeNora, E-Tek
DaimlerChrysler
Energy Partners
General Motors
Honda
H-Power
International Fuel Cells
Mitsubishi Motor
Nissan
Plug Power
Siemens
Toyota

Membrane and Catalyst
3M
Asahi Chemical
Asahi Glass
Ballard Power Systems
Dow Chemical
DuPont
Gore
Hoechst
Johnson Matthey
W.L. Gore

Fuel Processor
A.D. Little (Epyx)
Amoco
Atlantic Richfield
Ballard Power Systems
DaimlerChrysler
General Motors
Honda
International Fuel Cells
Johnson Matthey
Mitsubishi Oil
Mobil Oil/Exxon
Shell Oil
Toyota
Wellman CJB

Table 6: Companies active in research and development of fuel cell components and automotive system integration. (Source: News reports)

for exploiting the commercial value of fuel cells in a potential future market. Automakers with little competence in fuel cells will be excluded from such a market, and will only be left with the option to license the technology from leaders in the technology, such as for example Ballard. There are other similar examples where new technology around the core competence of automakers has been appropriated by technology leaders. Mitsubishi, for example, has successfully developed commercial direct-injection gasoline engine technology that improves fuel efficiency, while also increasing power of internal combustion engines. After decades of research and development, Mitsubishi has gained a lead in the technology, which it now licenses to several automakers, including Volvo, Fiat, Peugeot and Hyundai.

7.2. Emerging supply chain

A future market for fuel cells is hypothetical at this point, and it is unclear whether fuel cells will achieve successful commercialization. Nevertheless, a potential market structure emerges from companies currently active in developing components for a fuel cell system in automobiles. This structure reflects the technical capabilities and competencies of automakers and companies specialized in key components of fuel cells, according to Table 6 and Figure 8. A likely candidate for becoming a leading supplier of fuel cells is Ballard. Ballard, as an R&D company, has acquired substantial expertise in fuel cells, which it applies to fuel cells in automobiles, stationary power and consumer applications. Based on this expertise, Ballard and its close competitors are in an advantageous position to supply fuel cell engines to automakers that have little competence in fuel cells.

It is noteworthy that only a few first tier automotive suppliers have a significant stake in fuel cells, such as Delphi, AlliedSignal and Siemens. Instead companies from the chemical, aerospace, and oil industry possess expertise on key components of fuel cells. In a hypothetical market for fuel cells, these companies are likely to take a competitive role by capturing market share according to their technological capabilities. These companies may emerge as suppliers of materials and components for fuel cell stacks, fuel cell membranes, and fuel processors.

8. CONCLUSIONS

This study analyzes how the automobile industry is pursuing the development of fuel cells as a new propulsion technology for automobiles. Fuel cells represent a fundamentally new powertrain technology that competes technically with the internal combustion engine, which has traditionally been a core competence of automobile manufacturers. The emergence of fuel cells as a potential rival technology provides a challenge to automakers' competence in internal combustion engines, but also provides an opportunity for establishing a competitive position and gaining competence in a new technology. Even if fuel cells are never successfully commercialized, this study can still provide useful insights into the technology dynamics and strategic questions that automakers are faced with by fundamentally new technologies.

Decades ago, fuel cells were developed in the aerospace industry, and have only been discovered for use in automobiles after a technological breakthrough resulted in significant increase in the power density and reduction in cost that made fuel cells feasible for automotive applications. This breakthrough was achieved by a small R&D company, Ballard, with initial governmental support. Automakers with ties to the aerospace industry were among the first to recognize the potential of the breakthrough technology, and such early identification gave these companies a lead in R&D investment and patenting. The example of fuel cells supports the importance of early identification of new technologies and the importance of links to related industries as a source of such technologies.

The next phase of developments is characterized by an attempt of automakers to acquire competence in fuel cells. Three different organizational approaches are observed among the automakers: internal development of fuel cells, collaborative research, and a wait-and-see approach or licensing of the technology. Two important conclusions can be made about this phase of fuel cell development. First, the design of research alliances, such as the partnership between DaimlerChrysler, Ford and Ballard, suggests that the technology needs to be viewed from a systems perspective, covering all aspects of a fuel cell powertrain. Second, research alliances provide an effective way of broadening intellectual property protection, but also limit the control of the automaker over the technology.

The last part of the report discusses implications for automakers regarding the ability to control and derive value from fuel cells in a potential commercial phase of the technology. It is argued that new suppliers will participate in the future market for fuel cell powertrains according to their role as developers of components earlier on. For example, Ballard as a leader in fuel cell technology is likely to emerge as a major supplier of fuel cells powertrains in a future market for fuel cells. Automakers can keep control over the technology by becoming system integrators, and manufacturers of key components. It is shown that such a fragmentation of the future value chain of fuel cell powertrains may already be observed among current participants in the development phase of fuel cells.

This study of fuel cells as a new automotive technology may be applicable not only to fuel cells, but also to a host of similar technologies competing with established automotive technology. For example, the development of electric and hybrid vehicles has gone through similar phases and exhibits similar technology dynamics. The commercial success of electric and hybrid vehicles has been very limited to date, but other emerging new technologies are now commercial. Airbags, fuel injection systems for gasoline and diesel engines, exhaust gas catalysts, and anti-lock braking systems are among the examples of technologies that have not remained a unique competence of automakers, but instead have been appropriated and commercialized by suppliers to a varying degree. Similar strategic implications are conceivable for future automotive technologies such as communication and navigation systems, electronic systems, lightweight materials, advanced engine technologies, alternative propulsion systems, and even technologies regarding internet marketing and sales. Insights from the development of fuel cells provide a small glimpse at the dynamics of a new technology in the automobile industry that may be useful to the formulation of strategies for successfully mastering the challenge of future technologies.

9. ACRONYMS

CAFE	Corporate average fuel economy
DND	Department of National Defense, Canada
DOE	Department of Energy, United States of America
ESA	European Space Agency
IFC	International Fuel Cells Corporation
JV	Joint venture
LANL	Los Alamos National Laboratory
MITI	Ministry of International Trade and Industry, Japan
NASA	National Aeronautics and Space Administration, United States of America
OEM	Original equipment manufacturer (automobile manufacturer)
PAFC	Phosphoric acid fuel cell
PEM	Polymer electrolyte membrane
PNGV	Partnership for a New Generation of Vehicles
R&D	Research and development
SPE	Solid polymer electrolyte
ZEV	Zero emission vehicle

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