15.965 TECHNOLOGY AND STRATEGY

Fuel Cell Technology

Paper 1: Technological Innovation

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Global climate change is an issue that has moved to the forefront in recent years as scientists accumulate evidence attributing global warming to human influence. The issue dates back to 1938, when G.S. Callendar argued that the level of carbon dioxide was climbing and raising global temperatures, but of course most scientists found his arguments implausible and dismissed them. Today's scientists are quick to agree with Callendar's hypothesis and global climate change has become an international policy issue. The Intergovernmental Panel on Climate Change (IPCC) has released statements saying, "Warming of the climate system is unequivocal and is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations." The IPCC goes on to say, "Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system."[1] The environment is a worldwide concern and there has been a global movement toward "green" or environmentally friendly technologies in recent years. Fuel cell technology is an exciting energy technology that could possibly become the environmentally benign successor to the internal combustion engine for automobile propulsion.

A fuel cell is an electrochemical device that produces direct current electricity as long as fuel and oxidant are supplied to the anode and cathode respectively. A fuel cell is more simply described as an un-rechargeable battery. Practical fuel cells today operate with hydrogen fuel, generating only power and drinking water.[2] Thus, it is often called a "zero emission engine". A fuel cell system consists of several sub-systems including the fuel processor, fuel cell and stack, and power management. The most promising type of fuel cell for automotive operation uses a polymer exchange membrane (PEM) as an electrolyte. The advantage of the PEM fuel cell is its low operating temperature of about 80°C. A schematic of a hydrogen-fueled fuel cell is shown in Figure 1.

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[1] IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[2] Lester & Deutch (2004). *Making Technology Work: Application in Energy and the Environmnet.* Cambridge, UK: Cambridge University Press.

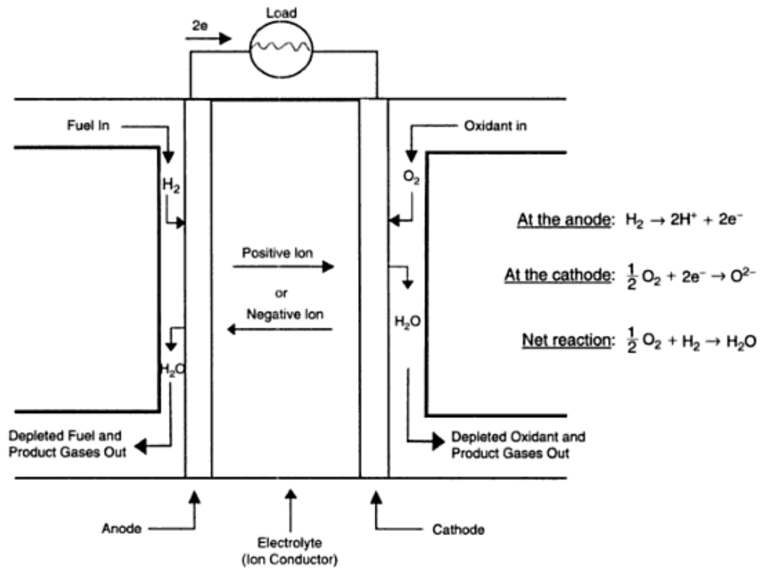

Figure 1: Schematic of a hydrogen-fueled fuel cell
(Source: J.H. Hirchenhofer et al, *DOE Fuel Cell Handbook (4th ed.)*,
DOE/FETC-99/1076, November 1998)

There are many applications for fuel cell technology, including stationary power, vehicle power, household appliances, and consumer electronics; however, the enthusiasm behind fuel cells is directed toward vehicle power. This enthusiasm is based on the idea that this technology can power automobiles more efficiently and with less environmental insult.

Fuel cell technology can be characterized in terms of key parameters in order to evaluate the technology. These key parameters with descriptions are presented in Table 1.

Key Parameter	Description
Upfront Cost	The cost of producing fuel cells in volume is unknown.
Operating Cost	The cost of maintaining fuel cells in the field is unknown & hydrogen supply infrastructure not established
Reliability	Unproven reliability of fuel cells under realistic operating conditions over a period of many years.
Operating Temperature	PEM fuel cells have low operating temperature of 80°C
Efficiency	More efficient than internal combustion engine (ICE)
Direct Current	Direct current negates idling losses in automobiles (which represent about 50% of all ICE losses in a typical drive cycle)
Emissions	With hydrogen fuel there are no NO_x, CO_2, particulate or volatile

	organic compound emissions (The only product is water). With methanol fuel, there are some CO_2 emissions.
Sound	Fuel cells are extremely quiet, which could be important from the viewpoint of an automobile consumer
Smell	Less odor is emitted from a fuel cell when compared to an ICE
Catalyst	The performance of the fuel cell depends critically on the effectiveness of the catalyst (determines reaction rates at the electrodes)
Fuel	Limited fuel options, usually Hydrogen, except for Solid Oxide High Temperature Fuel Cell
Moving parts	There are no moving parts in a fuel cell
Electrolyte	Various types used in fuel cells

Table 1: Fuel Cell Key Parameters

Fuel cells provide a viable power option with no emissions, but the reliability and cost of fuel cells is questionable. This is a key trade-off inherent in this technology. The world wants alternative power sources that do not have an adverse effect on the environment; however, there is an associated cost and reliability risk. The resulting performance envelope has not yet expanded to its full potential. Until large scale fuel cell costs are measured and reliability improved, there will remain an inherent trade-off for the lack of emissions.

Fuel cell technology has certainly evolved over time. The technology had its beginnings in 1839 when William Grove discovered the basic operating principle of fuel cells by reversing water electrolysis to generate electricity from hydrogen and oxygen. His first fuel cell, called the "gaseous voltaic battery" was a fragile apparatus filled with dilute sulfuric acid in which platinum electrodes were dipped.[3] The path from there to modern fuel cell technology has taken many turns. The key parameters that have evolved over time include the catalyst, the fuel, the electrolyte, and the operating temperature. In 1889, Ludwig Mond and Charles Langer first coined the term "fuel cell", and attempted to build a working fuel cell using air and industrial coal gas. William Jaques was the first researcher to use phosphoric acid in the electrolyte bath. Early cell designers used expensive porous platinum electrodes and corrosive sulfuric acid as the

[3] Hoogers, Gregor. (2003) *The Fuel Cell Technology Handbook*. CRC Press LLC.

electrolyte bath. In 1932, Francis T. Bacon improved on the expensive platinum catalysts with a hydrogen and oxygen cell using a less corrosive alkaline electrolyte and inexpensive nickel electrodes. In 1955, W. Thomas Grubb, a chemist working for the General Electric Company, further modified the original fuel cell design by using a sulphonated polystyrene ion-exchange membrane as the electrolyte.[4] Three years later, Leonard Niedrach found a way of depositing platinum onto the membrane, which served as catalyst for the necessary hydrogen oxidation and oxygen reduction reactions. In 1959, a team led by Harry Ihrig built a 15 kW fuel cell tractor that used potassium hydroxide as the electrolyte and compressed hydrogen and oxygen as the reactants.[5] There are many fuel cell types in existence today that exhibit various electrolytes, fuel sources, catalysts, and operating temperatures (as shown in Table 2).

Fuel Cell Type	Type of Electrolyte	Operating Temp. (°C)	Current Density	Need for Fuel Processor	Compatibility with CO_2	Stage of Development	Current Prospects For	
							High Efficiency	Low Cost
PEMFC	Proton Exchange Membrane	70-80	High	Yes	Yes	Early prototypes	Good	Good
AFC	Aqueous Alkaline	80-100	High	Yes	No	Space application	Good	Good
PAFC	Phosphoric Acid	200-220	Moderate	Yes	Yes	Early commercial applications	Good	Fair
MCFC	Molten Carbonate	600-650	Moderate	Yes[a]	Yes	Field demonstrations	Good	Fair
SOFC	Solid-Oxide	800-1000	High	Yes[a]	Yes	Laboratory demonstrations	Good	Fair-good
DMFC	Proton Exchange Membrane	70-90	Moderate	No	Yes	Research	Poor	Poor-fair

[a]Except for natural gas fuel

Table 2: Fuel Cell Types (Source: Report of the ARB Fuel Cell Technical Advisory Panel)

Fuel cell technology has progressed relatively quickly since aggressive development began in 1993. However, the innovation trajectory of hydrogen fuel cell vehicles is still in the painful beginning stages, despite the fact that the basic principles have been around for 170 years. Figure 2 shows where the current vehicle fuel cell technology stands with respect to the theoretical technology “S-Curve”.

[4] http://americanhistory.si.edu/fuelcells/intro.htm
[5] http://americanhistory.si.edu/fuelcells/intro.htm

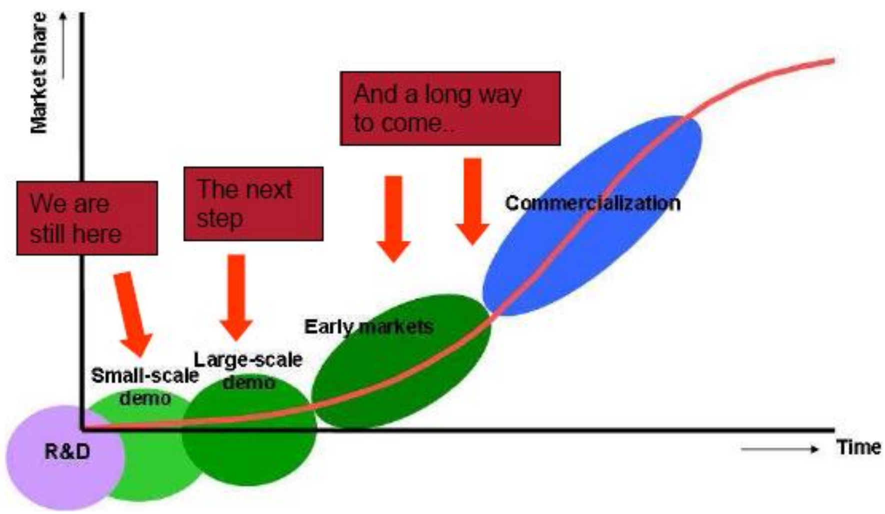

Figure 2: Fuel Cell Technology (www.ecn.nl)

Assessing technological innovation requires an assessment of competitive technologies. The potential applications for fuel cell technology include stationary power generation, portable applications including consumer electronics, household appliances, and automotive application. Concentrating specifically on automotive applications, there are many competing technologies in existence. The competing technologies include the obvious internal combustion engines (ICE), emission control for ICE, electric vehicle technology, compressed natural gas, and hybrid technology. The matrix below (Table 3) outlines the advantages and disadvantages of automotive fuel cells compared with the leading competing technologies, ICE, Hybrid ICE, and advanced diesel engines.

	Fuel Cell (FC)	**ICE**	**Hybrid ICE**	**Advanced Diesel**
Advantages	• High efficiency • No idling losses • No moving parts • No emissions (hydrogen) • Quiet • No smell	• Well established technology • Relatively cheap • Fuel supply infrastructure	• higher efficiency than ICE • Equal energy efficiency to FC • captures portion of idling loss • Fuel supply infrastructure	• 15% more efficient than ICE • less CO_2 emissions than ICE, more than FC • Possibly lower price than gasoline (Europe)

Disadvantages	• Cost • Reliability/ Lifetime • Limited fuel choices • Fuel carriage & range • Hydrogen supply infrastructure non-existent	• less efficient (idling losses) • emits harmful CO_2 • Noisy • Odor • Moving parts	• More expensive than ICE • Moving parts • Not as quiet as FC	• Production of particulates • Odor • Noisy

Table 3: Competing Technologies

Figure 3 shows the GM Precept concept car for fuel cell technology.

Figure 3: GM Precept concept car

There are major uncertainties in technical characteristics, costs, and user acceptance of fuel cell powered vehicles. Additionally, the hydrogen fuel cell vehicle confronts a difficult design issue with respect to fuel carriage and range. Specifically, use of hydrogen as the onboard fuel means either that the fuel must be stored in gaseous form (limiting range), or, if a liquid fuel such as methanol or gasoline is carried on board instead, the problem of reforming the liquid fuel into hydrogen must be resolved. From the advantages and disadvantages outlined in Table 3, it would appear that the fuel cell (FC) powered vehicle would be significantly superior to ICE with respect to energy use and emissions. However, any conclusion about the relative merits of the two technologies would require a comparison of the ICE gasoline infrastructure with the projected hydrogen infrastructure on which a fuel cell-powered fleet would run.[6] The ICE

[6] Lester & Deutch (2004). *Making Technology Work: Application in Energy and the Environmnet.* Cambridge, UK: Cambridge University Press.

system employs gasoline as fuel with a production and distribution system that is relatively energy efficient. Conversely, the FC system uses hydrogen as fuel, and the hydrogen must be produced and distributed somehow and we must include this process in the overall energy balance.

It is difficult to predict which technology in this domain will surpass the others. There is no doubt that all the technologies will continue to evolve in the short term in response to the global push for environmentally friendly solutions. It is not clear yet whether fuel cell technology will prove superior to other alternatives, notably ICE hybrids, advanced diesel engines, or compressed natural gas vehicles. The eventual outcome will depend on several factors: technical advances that remain unknown as of yet; the demonstrated cost of ownership of the systems in field use; and the direction of environmental regulation.[7]

Many scholars argue that a new technology invades an industry when the old technology is approaching its performance limits. Sahal (1985) proposed that a particular technology will develop along a particular path until the natural limits of scale and complexity severely restrict the potential for additional improvements, at which point the new technology takes over.[8] The technologies in this domain, including fuel cells, hybrids, compressed natural gas, and advanced diesel engines, will likely be subject to "natural technological limits" described by Sahal eventually, but not for quite some time. The S-Curve shown in Figure 2 emphasizes the relative youth of fuel cell technology. Several major auto companies, including Ford, General Motors, and Daimler Chrysler, have launched major fuel cell programs because of the potential they see for this technology to compare favorably with conventional internal combustion engines. As societies around the world become increasingly aware of the environmental impacts of energy supply, fuel cell technology will only gain popularity, and only time can tell if this technology will come to fruition.

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[7] Lester & Deutch (2004). *Making Technology Work: Application in Energy and the Environmnet.* Cambridge, UK: Cambridge University Press.

[8] Tripsas, Mary. (2008) *Customer Preference Discontinuities: A Trigger for Radical Technological Change.* Harvard Business School, MA, USA.