International Journal of Automotive Technology, Vol. 1, No. 1, pp. 9–16 (2000)

1229-9138/2000/001–02

FUEL CELL ELECTRIC VEHICLES: RECENT ADVANCES AND CHALLENGES – REVIEW

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(*Received 12 June 2000*)

ABSTRACT–The growing concerns on environmental protection have been constantly demanding cleaner and more energy efficient vehicles without compromising any conveniences provided by the conventional vehicles. The recent significant advances in proton-exchange-membrane (PEM) fuel cell technology have shown the possibility of developing such vehicles powered by fuel cells. Several prototype fuel cell electric vehicles (FCEV) have been already developed by several major automotive manufactures, and all of the favorable features have been demonstrated in the public roads. FCEV is essentially a zero emission vehicle and allows to overcome the range limitation of the current battery electric vehicles. Being motivated by the laboratory and field demonstrations of the fuel cell technologies, variety of fuel cell alliances between fuel cell developers, automotive manufactures, petroleum companies and government agencies have been formed to expedite the realization of commercially viable FCEV. However, there still remain major issues that need to be overcome before it can be fully accepted by consumers. This paper describes the current fuel cell vehicle development status and the staggering challenges for the successful introduction of consumer acceptable FCEVs.

KEY WORDS : Fuel cell, PEM, Fuel reformer, Hydrogen, Electric vehicle, Zero emission vehicle

1. INTRODUCTION

The growing concerns on environmental issues have been constantly demanding cleaner and more energy efficient vehicles without compromising any convenient features of the conventional internal combustion engine vehicles. To meet such demands, major automotive manufacturers have introduced a variety of alternative fuel and battery powered vehicles. Those are natural gas, flexible fuel, battery electric and hybrid electric vehicles. However, such vehicles have only been partially accepted by the consumers and still pose variety of technical and economic issues that need to be overcome. For zero emission vehicles, battery electric vehicles have been one of the most viable alternatives and have been introduced to the market by several major automotive manufacturers. However, the shortcomings associated with the battery performance, such as weight, charging time, cycle life and driving range, have been the major inhibitors against the wide spread acceptance by consumers.

The recent technological advances in the proton exchange membrane (PEM) fuel cells have been showing promising results for transportation applications complementing the drawbacks of battery technologies. Basically, a fuel cell vehicle uses a fuel cell stack instead of a battery as the major source of electric power to drive an electric traction motor. The simplest configuration is supplying hydrogen directly from a hydrogen tank stored as a compressed gas or cryogenic liquid. To overcome the difficulties of hydrogen storage and lack of infrastructure, a methanol or gasoline fuel processor can be incorporated to produce a hydrogen rich gas stream on board. Another recent advance in fuel cell technologies is the development of direct methanol fuel cells (DMFC). All of these alternatives are not problem free and pose major technical challenges. The on board fuel processor provides additional cost and complexity to the vehicle, and has inherently slow response time. Although DMFC made a substantial advances in recent years, it still requires significantly greater amount of precious metal catalyst than the direct hydrogen PEM fuel cells. Another issue is to overcome the problem of methanol crossover through the membranes.

In recent years, major automotive manufacturers

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have developed and introduced several prototype FCEVs with various fuel options. Although there is a major issue with the hydrogen supply infrastructure, these prototype FCEVs have been demonstrating various favorable features of FCEVs as well as providing the guidelines for the future development directions. The recent growing worldwide interest in the transportation application of fuel cell technologies initiated to form a variety of strategic alliances between fuel cell developers, automotive manufacturers, petroleum companies and government agencies. The common motivations of these alliances are to share the complementary technical expertise and the initial investment risks, to promote the public awareness, and to accelerate the development and marketing of the commercially available FCEVs. With such a combined global efforts among the various industries, the various obstacles ahead in the commercialization of FCEVs will be overcome in a faster pace. In this paper, the current status of the worldwide FCEV development activities and the fuel cell alliance/ partnership activities will be introduced after brief discussions on the basic PEM fuel cell and the related systems. The FCEVs to be fully acceptable to the consumers, there are several major issues that need to be overcome. In an effort to seek some viable solutions, this paper will also introduce and discuss these challenging issues.

2. FUEL CELL ELECTRIC VEHICLES

Fuel cell vehicles are basically electric vehicles where the fuel cell is being used as the source of electric power to drive an electric traction motor. Fuel cell stack is the major component of the power generation system and it requires proper supply of hydrogen and air with certain level of humidity. For efficient generation of electricity, effective management of the generated heat and water is essential. To overcome the lack of hydrogen supply infrastructure, on board fuel processors have been proposed with a relatively high penalty on the cost, weight and complexity. Although it is still too early to be practical for vehicle applications, DMFC has been gaining a lot more attention recently. To better understand the critical issues related to the commercialization of the FCEV, brief discussions on the PEM fuel cell operation, related subsystems and powertrain configurations are introduced in the following subsections.

3. PRINCIPLE OF FUEL CELL OPERATION

Figure 1 shows the principle of electric power generation generation of a typical proton exchange membrane (PEM) fuel cell. A fuel cell consists of a fuel electrode (anode) and an oxidant electrode (cathode) separated by an ion-conducting electrolyte. When hydrogen is supplied through the porous anode, the catalyst (plati num) dissociates the hydrogen into protons (H^+) and electrons (e^-). Since only protons can flow through the electrolyte, the electrons can be drawn as a source of electricity flowing through a load circuit to the cathode and forming water reacting with protons and oxygen helped by the catalyst. Depending on the type of electrolyte used for conducting ions, there are different types of fuel cells (Lynn et al., 1983). It has been acclaimed by various studies that the solid polymer electrolyte fuel cell is the most suitable for automotive applications with the advantages of high power density, low temperature operation, fast start-up, compactness and robustness (Lynn et al., 1983; Swan and Dicknison, 1995). A fuel cell is a power generation device different from the energy storage device such as battery. The power is generated on demand and the reaction response time is in the order of a 10th of a micro second. For automotive application, air is used as a source of oxygen supplied by an air compressor.

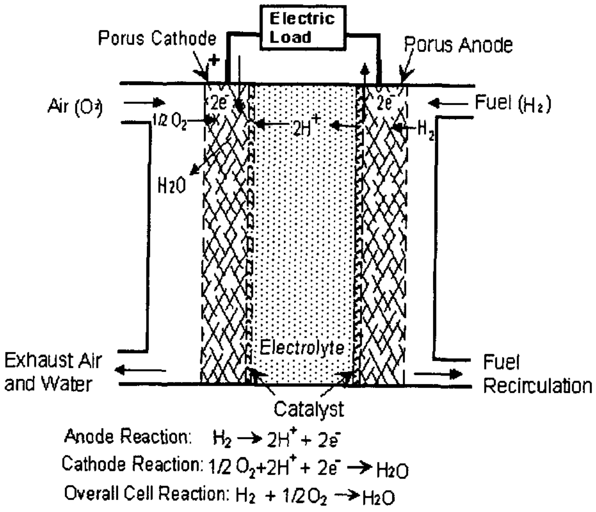
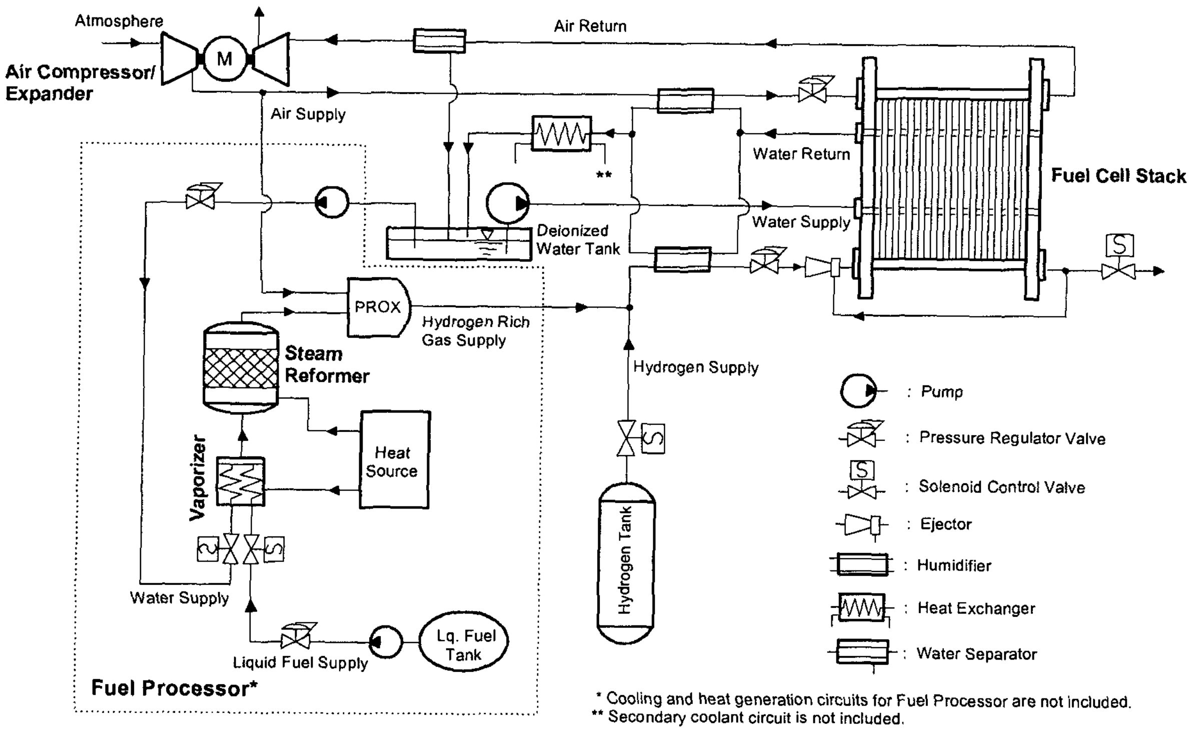


Figure 1. Principle of PEM fuel cell operation.

4. FUEL CELL SYSTEMS

To form a fuel cell stack as an autonomous power gen-erating plant, it requires four major subsystems: hydrogen supply, air supply, water management and heat management. Figure 2 shows a typical fuel cell power plant for automotive applications. For direct hydrogen fuel cell systems, liquid or compressed gas hydrogen is stored in a tank installed in the vehicle. The hydrogen is supplied to the anode manifold through a de-ionized water humidifier. The membrane



* Cooling and heat generation circuits for Fuel Processor are not included.
** Secondary coolant circuit is not included.

Figure 2. Fuel cell system schematic.

needs to be water saturated to properly conduct hydrogen ions through the solid electrolyte. A level of recirculation of hydrogen is necessary to keep the system flooded with gas and to improve the power demand transient responses. In the case of using dilute hydrogen gas supplied from a fuel processor, the exhaust gas cannot be recirculated because of low hydrogen content.

Unlike a naturally aspirated internal combustion engine, a fuel cell stack requires a forced air supply at a specific system pressure. It is important that the flow through each cell in the fuel cell stack should be evenly distributed, especially when dilute reactant gas such as air or reformate gas is used. To ensure the flow through each cell at an optimum operating pressure, the air supply system requires coordinated pressure and flow control systems. An air compressor/supercharger with speed control feature can be used to supply variable amounts of air. Also to recover the energy from the compressed exhaust air, an expander can be incorporated with the air compressor as shown in Figure 2. One of the most important vehicle performance criteria is the transient response on power demand. The fuel cell itself has a very fast dynamic response. However, the response time of the fuel and air supply system is dependent on the system design and may affect the overall system transient performance.

The three major functions of water management systems are humidification of the reactant gases to properly hydrate the membranes, removal of the produced water in the stack, and cooling of the stack to control the operating temperature. The ion conductivity through the membrane is highly dependent on the degree of membrane hydration affecting the stack performance, especially at the high power density operation. Four types of humidification system designs with and without additional water injection are introduced in (Nguyen and White, 1993). A conventional design with water saturated gas stream is shown in Figure 2. Proper removal of the produced water in each cell is important to preventing the air flow passage from being blocked by the accumulated water and thus preventing the degradation of the cell performance.

Most of the losses in the fuel cell reaction process are converted into thermal energy producing significant amounts of heat and requiring substantial heat removal from the fuel cell stack. In most of the PEM fuel cell stack designs, a cooling circuit using de-ionized water as a cooling medium is incorporated as shown in Figure 2. For automotive applications, a second stage heat exchange circuit is incorporated using a higher thermal capacity coolant and a radiator as used in internal combustion engine cooling. This removed heat can also be used to heat the vehicle passenger comparment.

As an alternative to the direct hydrogen supply to the fuel cell stack a fuel processor can be incorporated on-board the vehicle to produce a hydrogen rich gas stream from a liquid fuel such as methanol or gasoline. Although it still requires several major technical advances for on-board vehicle applications, the concept has been well proven by many studies (Geyer et al., 1996; Ohl et al., 1996) and it has been demonstrated on a small size passenger vehicle using methanol as the fuel. One of the most significant drawbacks of the on-board fuel processors in vehicle application, besides the packaging issues, is the system time constant which can be considerable depending on the design. Slow dynamic response is mainly due to the slow heat transfer processes and mass transfer and mixing delays.

4. FUEL CELL VEHICLE CONFIGURATION

Figure 3 shows typical FCEV powertrain configuration with optional on-board fuel processor and energy storage for hybrid application. The most viable configuration from the consumer point of view is using compressed hydrogen storage where the stored hydrogen is supplied directly to the fuel cell stack. However, this raises the question of hydrogen supply infrastructure. As an answer to the question is to use an on-board fuel reformer using methanol or gasoline to produce a hydrogen rich gas stream. Since the fuel processor has inherent slow response time with order of several minutes, an energy storage device such as ultra capacitor or battery can be incorporated in parallel to the fuel cell as shown in Figure 3 to compensate for the slow start-up and transient operations. This hybrid configuration provides additional benefit of capturing regenerative energy from vehicle deceleration and braking. Another attractive alternative to overcome the infrastructure issue is to use DMFC.
Although DMFC technology has made significant advances in recent years, it still needs to overcome two major issues of low cell performance and methanol crossover.

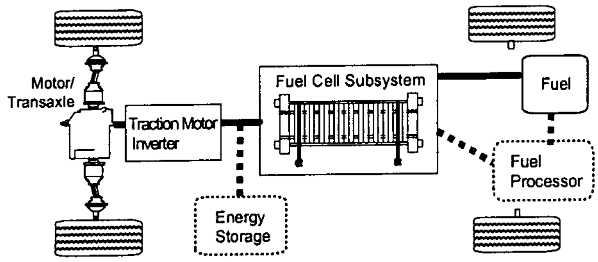


Figure 3. Fuel cell vehicle powertrain.

5. STATUS OF FCEV DEVELOPMENT

The current status of FCEV research and development activities by automotive manufacturers is summarized in (Adams et al., 2000). As discussed in Adams et al., (2000), most of the leading automotive manufacturers have been involved in FCEV development with different types of fuel supply and power distribution configurations. DaimlerChrysler (DC), partnered with Ballard Power Systems, has been pioneering FCEV research, and developed a series of progressive prototype vehicles to demonstrate the feasibility of fuel cell powered vehicles with and without on-board fuel reformers. From various fuel cell vehicle development and demonstration activities, it has been well recog

Figure 4. Ford P2000 FCEV.

Table 1. P2000 FCEV Vehicle and performance data.

Platform	Extended Contour 5 Passenger Car
Curb Weight	1518 kg (3340 lb)
Drive Train	Front Wheel Drive with Single Gear Ratio (10.1)
Power Steering	Electro-Hydraulic
Fuel Cell Stack	3 x 25kw (75 kW gross)
Traction Motor	3 Phase Asynchronous AC (56 kW)
Fuel Tank (vol/pressure)	82 liter / 3600 psi
Driving Range (EPA 75)	Over 100 miles
Fuel Economy (EPA 75 /Highway)	58/81 miles per gallon of equivalent gasoline
Acceleration (0-30/0-60)	4.2/12.3 sec.

nized that on-board fuel processing and hybridization with an energy storage device still requires major breakthrough to be acceptable by consumers. In 1997, Ford has made a sizable investment for fuel cell vehicle development forming an alliance with Ballard and DC. As a result of this alliance, Ford made a significant advancement in FCEV development and introduced a fuel cell vehicle in early 1999. This prototype vehicle is named as P2000 FCEV, Figure 4, and acclaimed as "the World's First Full-size, Full-performance Vehicle Powered by a Fuel Cell". The vehicle and performance data for P2000 FCEV is given in Table 1. The encouraging results from this vehicle are the excellent fuel economy and the vehicle performance comparable to internal combustion passenger cars.

6. FUEL CELL ALLIANCES

The increasing worldwide interest in the transportation application of fuel cell technologies initiated to form variety of strategic alliances between fuel cell developers, automotive manufacturers, petroleum companies and government agencies in the last several years. The common motivations of these alliances are to share the complementary technical expertise and the initial investment risks, to promote the public awareness, and to accelerate the development and marketing of the commercially available FCEVs.

7. BALLARD/DC/FORD ALLIANCE

In December 1997, a major fuel cell alliance has been formed between Ballard, DC and Ford to take the lead in realizing the mass production and distribution of the fuel cell components, systems and electric vehicles. Figure 5 summarizes the ownership relations between those three companies. In this three way alliance, Ballard Power Systems will continue to develop and supply fuel cell stacks while the newly formed XCELL SiS is responsible for providing the complete power generation systems including fuel reformers. Another newly formed Ecostar is responsible for providing electric drive components and systems including auxiliary electric/electronic systems. Ballard Automotive is another new company formed by this alliance and equally owned by Ford, DC and Ballard. The main function of this company is marketing the products of Ballard, XCELLSiS and Ecostar.

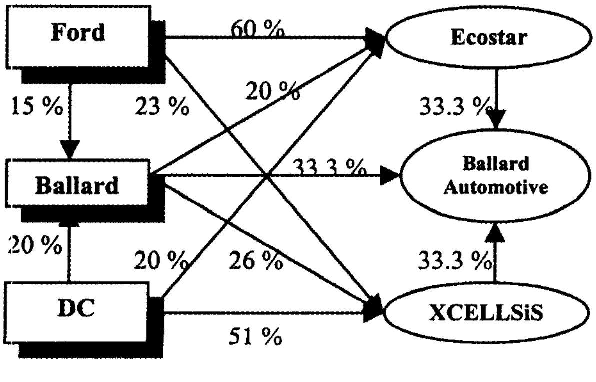


Figure 5. Ford-Ballard-DC alliance.

8. GM/Toyota ALLIANCE S

In April 1999, GM and Toyota announced five-year technology alliance agreement for collaborative development of environmentally friendly vehicles. One of the major collaboration of this alliance is developing commercially viable fuel cell electric vehicles with a goal of introducing them in the market as early as 2003. The combined fuel cell technologies and resources of Toyota and GM with hybrid/electric vehicle experiences will make this alliance to remain very competitive in the worldwide FCEV development race.

9. CALIFORNIA FUEL CELL PARTNERSHIP

As a part of the Ballard-DC-Ford alliance effort, and with support from the California Air Resources Board (CARB) and the California Energy Commission, a new fuel cell vehicle demonstration initiative was announced in April 1999, "California Fuel Cell Partnership - Driving for the Future". This partnership project will place about 45 fuel cell powered cars and buses on California roads by 2003 and will demonstrate the potential of FCEV in the real world applications, demonstrate the viability of integrating hydrogen and methanol refueling capability into the commercial infrastructure, investigate the path to commercialization by identifying potential problems, and improve the public awareness of the FCEV. In addition to the major driving members, other automotive manufacturers, Honda and VW, and petroleum companies, ARCO, Texaco and Shell, also joined the partnership.

10. OTHER ALLIANCES

Besides the fuel cell and automotive related alliances, there have been several other new alliances formed between automotive manufacturers and petroleum companies mostly to enhance the development of fuel reformer technologies. Ford announced an alliance with Mobil, GM with Amoco, and DC with Shell in the last two years.

11. CHALLENGES

The recent advances in fuel cell technology have proved the technical feasibility of the development of FCEVs. However, before FCEVs reach to the level of acceptance by widespread consumers, there remains a considerable amount of challenges that need to be tackled. Detailed discussions on various low and high level issues are well presented in (Yang et al., 1998; Adams et al., 2000).

12. HYDROGEN INFRASTRUCT URE

Two of the most significant challenges are the hydrogen supply infrastructure and the cost reduction of the fuel cell stacks. The amount of capital investment for establishing various alternative fuel infrastructure are well compared in Storbart and Bentley (1998) showing that the hydrogen requires the biggest investment of $95 billion to displace 1 million barrels per day. Significantly large portion of the investment is for the transportation and storage of the hydrogen. However, if a smaller scale stationary fuel processing facilities are used in hydrogen refueling station, then there would not be any investment needed for hydrogen storage and transportation significantly reducing the amount of investment. This arrangement will also provide flexible choice of fuels including natural gases as well as providing more affordable vehicles for consumers than fuel processor equipped vehicles. A study conducted under Ford's DOE fuel cell contract has shown that factory-built hydrogen refueling stations capable of supporting just 100 vehicles could produce hydrogen that is cost competitive with wholesale gasoline (Directed Technologies,' 1997a). These hydrogen refueling stations would produce hydrogen by steam reforming natural gas or electrolysis of water and would utilize the existing natural gas and electric power infrastructures, eliminating the need for development of a costly hydrogen infrastructure.

13. FUEL CELL STACK COST

The performance of present fuel cell stacks is now adequate to meet automotive demands, but the present cost of stacks is approximately ten times too great. The projected cost breakdown for fuel cell stack components manufactured in high volume is shown in Figure 6 and shows that the majority of the stack cost resides in the catalyst and bipolar plates (Directed Technologies, 1998). Catalyst loading for direct hydrogen have been reduced by an order of magnitude over the last five years and current laboratory research suggests another order of magnitude reduction may be possible.

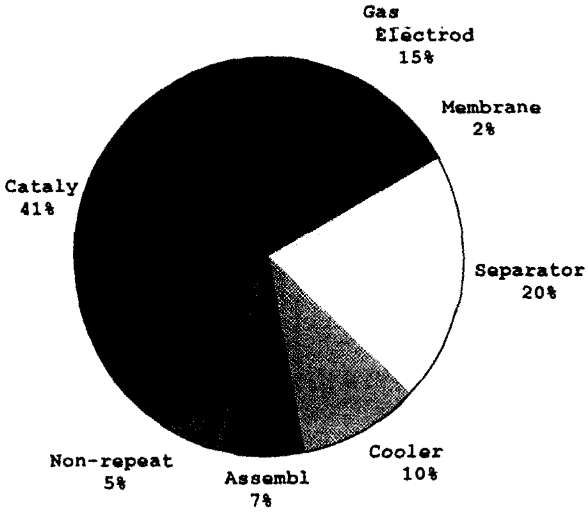


Figure 6. Cost breakdown for PEM fuel cell stack.

However, for stacks operating on reformate, comparable reductions in catalyst loading have not been achieved and therefore reformate tolerant stacks are likely to cost more, at least in the near term. Bipolar plates are another stack component currently produced at high cost by machining graphite plates. However, machined graphite is expensive and not amenable to high volume manufacturing. As alternatives, bipolar plates made from stainless steel or composite materials are currently under investigation. Stainless steel would certainly be amenable to high volume manufacturing, but possible long-term corrosion of the plate and ion contamination of the PEM from the stainless steel remain open issues. Composite bipolar plates, formed by either compression or injection molding, are also an attractive high volume, low cost manufacturing possibility (Marianowski, 1998).

14. FUEL CELL SUBSYSTEMS

The next significant challenges are the issues related to the fuel cell subsystems. Three major subsystems currently requiring improvements are the air supply, the thermal management and the water management subsystems. The most efficient operating pressure for current PEM fuel cell system is about 207 kPag. This requires an air supercharging mechanism at a cost of parasitic loads. Current superchargers used in fuel cell power systems have excessive parasitic loads, approaching 10 - 15 kW at a peak power of 50 kW net, and are heavy, big, and costly. Because pressure drops in most stacks are only on the order of several psi, significant energy is still contained in the cathode exhaust gas. To recover this energy and reduce the total parasitic load of the supercharger, expanders are being developed as part of the air supply subsystem. However, none of the current supercharger/expander designs are on track to meet the weight, volume, and cost goals required for automotive applications. At present, the air supply subsystem remains a critical development item for successful automotive application of fuel cells.

Thermal management subsystem also requires innovation and improvement. Two major difficulties facing thermal management are: (1) the large radiator and fan required for removing the low temperature waste heat from the stack; and (2) development of nonconducting coolants capable of operating at sub-freezing temperatures. Due to the low stack temperature of 80 – 90 °C for 3 atm operation, the radiator size for a 60 kW net power system is projected to be 1.5 times larger than a compatible internal combustion engine vehicle.

Current fuel cell stack designs require the use of de-ionized water for the stack coolant. If the ionic conductivity of the coolant is too high, shunting currents can occur which lowers the stack efficiency. Because de-ionized water is very corrosive to current aluminum radiators, a separate liquid-liquid heat exchanger is used. De-ionized water flows through the stack and one side of this heat exchanger, while glycol coolant flows between the radiator and the other side of the heat exchanger. Use of this intermediate heat exchanger further exacerbates removal of stack waste heat by lowering the coolant temperature reaching the radiator by approximately 5 – 10 °C compared to the de-ionized water stack coolant loop. Development is only now beginning on alternative radiator designs, nonconductive coolants, and stack designs capable of using water/glycol coolants. Operation at sub-freezing temperatures is an issue because pure water freezes at 0 °C. Interestingly, the membrane may not be a significant problem at sub-freezing temperatures. Laboratory data indicate that the membrane retains significant proton conductivity at temperatures below -20 °C. However, the presence of de-ionized water will require significant system level development to achieve current ICE performance at low temperatures.

15. PUBLIC PERCEPTION

Public perception is that hydrogen is an inherently dangerous fuel. However, a safety study conducted under Ford's DOE fuel cell contract determined that hydrogen used as a vehicle fuel should be no less safe than gasoline used in current ICE vehicles (Directed Technologies, 1997b). Nevertheless, the poor public perception will need to be changed through extensive public education and awareness programs designed to familiarize the public with the use of hydrogen as a vehicle fuel.

16. SUMMARY AND CONCLUSIONS

The growing concerns on environmental issues and the recent advances in PEM fuel cell technologies have allowed the fuel cell powered electric vehicle to be one of the most promising alternatives for the development of zero emission and fuel efficient vehicles. In an effort to overcome the shortcomings of the battery electric vehicles, such as weight, charging time, cycle life and driving range, most of the leading automotive manufacturers have been involved in the development of FCEVs. In the past few years, several drivable fuel cell prototype vehicles have been introduced and demonstrated the technical feasibility. Also, to accelerate the development of FCEV, various alliances between fuel cell developers, petroleum companies, automotive manufacturers and government agencies have been formed. As a result of such joint efforts, we will see a lot more of FCEVs on the road within the next several years.

However, there still remains a significant amount of challenges to be tackled before FCEV can be fully accepted by widespread consumers. Among others, the most significant challenge is the hydrogen supply infrastructure. An interim solution for this issue is to install a methanol or gasoline reformer on-board the FCEV. However, it introduces considerable complexity to the vehicle and poses significant technical challenges for vehicle application. However, a better solution for the infrastructure problem is to install a smaller scale stationary fuel processing facilities at the existing gas refueling stations. This will significantly reduce the amount of investment for hydrogen supply infrastructure.

ACKNOWLEDGMENTS–The author would like to thank Dr. Jim Adams of the ford who made significant contribution to this paper. Also, the author would like to thank Mr. Brad Bates and Mr. Ron Sims of the Ford for their valuable continued consultations.

REFERENCES

Adams, J., Yang, W. -C., Oglesby, K., and Osborne, K., (2000). The development of Ford's P2000 fuel cell vehicle, *SAE Paper 2000-01-1061.*

Directed Technologies, Inc. (1997). Hydrogen infrastructure report, prepared by for Ford under DOE Contract No. *DE-AC02-94CE50389*, July.

Directed Technologies, Inc. (1997b). Hydrogen vehicle safety report, prepared by for Ford under DOE Contract No. *DE-AC02-94CE50389*, May.

Directed Technologies, Inc. (1998). Detailed manufacturing cost estimates for polymer electrolyte membrane (PEM) fuel cells for light duty vehicles, prepared by for Ford under DOE Contract No. *DE-AC02-94CE50389*, August.

Geyer, H., Ahluwalia, R. and Kumar, R. (1996). Dynamic response of steam-reformed, methanol-fueled polymer electrolyte fuel cell systems, *Proceedings of 31st Intersociety Energy Conversion Engineering Conference*, IECEC 96, 1101-1106.

Marianowski, L. (1998). Development of a $10/kW bipolar plate separator plate, *Institute of Gas Technology,* U.S. DOE Fuel Cells for Transportation Program, Contractor's Annual Progress Report, FY, **1**, 44-46.

Lynn, D., Murray, H., McCormick, J. And Huff, J. (1983). Simulated performance of solid polymer electrolyte fuel-cell-powered Vehicles, *SAE Paper 830351.*

Nguyen, T. and White, R. (1993). A water and heat management model for proton-exchange-membrane fuel cells, *J. Electrochem. Soc.*, **140**, **8**, 2178-2186, August.

Ohl, G., Stein, J. And Smith, G. (1996). Fundamental factors in the design of a fast responding methanol to hydrogen steam reformer for transportation applications, *J. of Energy Resources Technology*, **118**, **2**, 112-119, June.

Storbart, R., and Bentley, J. (1998). Multi-fuel reformers for fuel cell powered vehicles, *FISITA F98T/P235.*

Swan, D. And Dickinson, B. (1995). Fuel cell dynamics in transit applications, *Proceedings of EVS-12*, 73-80.

Yang, W.-C., Bates, B., Fletcher, N., and Pow, R. (1998). Control challenges and methodologies in fuel cell vehicle development, *Proceedings of the 1998 International Congress on Transportation Electronics, 363-370, Convergence SAE Paper 98C054,* October.