III.2 FUELS FOR PEM FUEL CELLS: CHOICES AND ISSUES

The technical characteristics, economic feasibility and infrastructure requirements of PEM fuel cell electric engines and vehicles are impacted greatly by the fuel chosen, with large differences between these impacts for the fuels that are presently being considered for transportation applications: Hydrogen, methanol, and gasoline or related petroleum distillate fuels. The choice of fuel thus is one of the most important decisions in any program to develop and, eventually, commercialize automotive fuel cell technology.

Given the issues and uncertainties associated with each of these fuels, it is not surprising that the developers of automotive fuel cell systems have arrived at different choices, or that several of them appear prepared to reconsider their current choice if called for by important developments regarding the major technical, economic and availability questions surrounding the choice of fuel.

To better understand the choices and their actual or potential impacts on prospective availability, operating characteristics and competitiveness of FCEVs, the Panel included fuels-related questions in its investigations. Key considerations driving fuel choice, and the findings from the Panel's discussions with automobile manufacturers engaged in fuel cell engine development, oil companies, and representatives of the methanol industry are summarized below.

A. HYDROGEN

As discussed in the preceding sections, hydrogen has excellent electrochemical reactivity at PEM fuel cell anodes, and hydrogen-air fuel cell technology has attained levels of power density and efficiency adequate for automobile propulsion. If hydrogen were to become a practical, generally available and affordable fuel in the foreseeable future, this could reduce the complexity and cost and thus enhance the success prospects of automotive fuel cells.

Despite the fundamental attraction and widespread advocacy of hydrogen as a primary fuel for automotive fuel cells, the car makers engaged in development of fuel cell engines and FCEVs are not presently considering hydrogen. Indeed, Toyota, Daimler-Benz, Ford and other leading developers have shifted their initial emphasis from hydrogen to methanol. In the timeframe of their programs, they do not see a resolution of the two major issues surrounding hydrogen: Storage of adequate amounts onboard automobiles, and general availability of hydrogen at acceptable costs. The Panel's examination of these issues is summarized in the following.

On-Board Storage

Storage of hydrogen as a gas compressed to 5000 psi requires a 10-fold larger volume than gasoline for the same amount of energy. While the anticipated high fuel efficiency of fuel cell engines would reduce the hydrogen storage problem somewhat, even an advanced vehicle with a fuel efficiency of 70 miles per gallon of gasoline energy equivalent would require 7 cubic feet (200 liters) of compressed hydrogen for a 350 mile range.

As studies by Ford[1] have shown, tanks for storage of this amount of hydrogen cannot be accommodated in a car without seriously compromising the space allocated to passengers and cargo. Even larger vehicles such as the Daimler-Benz NeCar 2 van and the various hydrogen-air fuel cell buses being demonstrated can only accommodate the required hydrogen tank volume on the roof which is not considered an acceptable solution for personal automobiles.

The volume problem is much reduced if hydrogen is stored as a liquid or bound chemically to a metal alloy. Both approaches have been explored, but they introduce new issues. Because of the equipment and electricity required, liquefaction adds to the cost of gaseous hydrogen (already a major issue, as discussed below), and it reduces overall energy efficiency significantly. Storage of liquid hydrogen also is expensive because of the need for high-performance insulation, heat exchangers, and safety measures. None of the current efforts to develop fuel cells for automobile propulsion appear to include liquid hydrogen storage.

Storing hydrogen as a metal alloy hydride has been under investigation for more than 25 years with Government and private funding worldwide. This work has resulted in the discovery and development of alloys that have increased hydrogen storage capacity at pressures suitable for ambient temperature operation. However, the specific storage

[1] Conceptual Vehicle Design Report: Pure Fuel Cell Powertrain Vehicle, Report No. DOE/CE/50389-501, February 1997; Battery-Augmented Fuel Cell Powertrain Vehicle, Report No. DOE/CE/50389-503.

capacity (e.g., in kg hydrogen per kg of alloy) is still inadequate, and the specific cost of presently available alloys (in $/kg of hydrogen storage capacity) is too high for automotive applications[2]. Toyota claims to have developed a new alloy with adequate storage capacity but its cost is considered too high, leading Toyota to shift most of their development effort to methanol.

Several years ago, researchers at Northeastern University claimed to have discovered a method for high density storage of hydrogen adsorbed or absorbed by carbon microfibers. However, to date all efforts to reproduce this encouraging finding appear to have failed.

These facts make clear that breakthroughs in hydrogen containment or storage materials would be needed to meet technical requirements and cost criteria for hydrogen storage onboard automobiles. While research on advanced storage materials continues, prospects for success are uncertain at best.

Hydrogen Availability and Cost

The other major issue arises from the uncertain — even unlikely — prospects for general availability of hydrogen at competitive costs. This issue has been studied repeatedly, with qualitatively similar conclusions. A recent study by the Argonne National Laboratory[3] developed detailed capital cost estimates for the production and distribution infrastructures for six fuels (RFG, diesel fuel, DME, methanol, ethanol, and hydrogen) . Infrastructure costs were estimated for 2015 (limited penetration, requiring daily production and distribution of hydrogen with the energy equivalent of 70,000 barrels of gasoline) and 2030 (wide penetration; daily production of 1.6 million barrels of gasoline equivalent).

For hydrogen, the estimated production facilities capital costs were $10 billion (2015) and 230-400 billion (2030); the costs of the required distribution facilities were $7.7 and 175 billion. With the assumption that vehicles are driven an average of 14,000 miles/year at a fuel efficiency of 80 mpg (gasoline energy equivalent), the Panel

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[2] For example, a typical alloy storing hydrogen at 1.5% of its weight would add over 50 kg and very likely over $200 per gallon of gasoline energy equivalent in H_2 storage capacity, not counting the weight and cost of the insulated pressure tank.

[3] K. Stork et al., "Assessment of Capital Requirements for Alternative Fuels Infrastructures," Argonne National Laboratory Report No. ANL/ESD/TM-140.

estimates that these costs correspond to per-vehicle infrastructure costs of $3,500 to 5,000; at a more likely 60 mpg, per-vehicle infrastructure costs become $4,700 to $6,700.

At an ROI of 15%, the infrastructure investments alone would contribute between $3.00 and $4.30 to the cost of hydrogen with the energy equivalent of one gallon of gasoline; to this would have to be added the costs of the precursor natural gas and of operating the production and distribution facilities.

Another recent study, performed by Directed Technologies, Inc.[4], analyzed various hydrogen production schemes with capacities to serve between 5000 and 500,000 fuel cell vehicles and concluded that "5000 psi compressed hydrogen could be delivered to fuel cell vehicles at costs that would be competitive with gasoline per mile driven." The basis of his statement is a comparison of a gasoline vehicle operating at 24.5 mpg on taxed gasoline with a fuel cell vehicle achieving around 80 mpg (gasoline energy equivalent) on untaxed hydrogen. If the comparison were made between hydrogen and gasoline on the same basis (80 mpg, tax free), hydrogen would cost 2-3 times more per mile driven than gasoline even under most favorable assumptions.

The lowest estimate[5] of capital costs for a large-scale hydrogen production and distribution infrastructure is $100 billion for a system with one million barrels per day gasoline energy equivalent. At $100,000 per barrel/day of capacity, ADL's highly optimistic estimate is only one third of the ANL number ($405 to 575 billion for 1.6 million barrels/day, or about $250,000 to 360,000 per barrel/day).

Even the lowest of the estimated investments needed for a general hydrogen supply infrastructure are unlikely to occur, however, until the competitiveness of hydrogen with other automotive fuel cell fuels has become plausible and major prospective manufacturers of fuel cell electric vehicles have focused their development programs and product plans on hydrogen as the primary fuel.

Smaller, local or regional hydrogen supply infrastructures may present less of a barrier to investments. The current interest in smaller-scale hydrogen production and distribution systems is fostered by two developments: technically successful demonstrations of hydrogen-powered PEM fuel cell buses, and the development of

[4] "Hydrogen Infrastructure Study Summary," Directed Technologies, Inc., Contract No. DE-AC02-94CE50389, July 1997.
[5] Presentation of Arthur D. Little at the Vice President's Automotive Technology Symposium No. 6, July 1997.

relatively small hydrogen generators derived from the steam reforming- or partial oxidation-based fuel processors used for power generation or intended for automotive engine applications of fuel cells, respectively. Some developers (e.g., Ballard and Daimler Benz) believe that fuel cell buses could eventually become a fleet vehicle market for hydrogen that would be supplied by limited local or regional manufacturing and distribution facilities. Support for this belief comes from the developers of smaller-scale hydrogen production technology (e.g., IFC, ADL, Hydrogen Burner) and producers of industrial hydrogen (e.g. Air Products) who claim that cost of this hydrogen could be low enough for automotive applications, for example, in the order of $2.50-3.00 per kg, or about $2.25-2.75 (tax-free) per energy equivalent of one gallon of gasoline.

However, there is still considerable uncertainty regarding the capital cost of such units, and existing hydrogen fuel cost projections do not seem to take into account all the factors — such as fail-safe compression, distribution, dispensing and storage of high-pressure hydrogen — that will contribute to the cost of onboard hydrogen. Whether these issues can be satisfactorily resolved for fleet applications is unclear at present. It seems clear, however, that local or regional populations of hydrogen-based fuel cell electric vehicles would be difficult to aggregate into the minimum market size (e.g., >100,000 units/year) needed to sustain mass manufacturing and achieve competitive costs of fuel cell-powered automobiles.

In summary, difficult technical and cost issues surround the choice of hydrogen as the primary fuel for fuel cell-powered, mass-marketed automobiles. The present concentration of the major developers of automotive fuel cells on methanol and gasoline is a clear indication that they consider resolution of these issues within the foreseeable future less likely than their success in developing fuels cell engines that can use carbonaceous fuels with acceptable efficiency and cost.

B. METHANOL

Methanol has been considered for fuel cell power generation for a number of years because it can be processed into a hydrogen-rich fuel gas fairly easily and efficiently by steam or autothermal reforming. Processing of methanol onboard a vehicle presents a number of difficult challenges as discussed in Section II.1.B. Nevertheless, much of the automotive fuel cell and fuel processor development worldwide is focusing on methanol, mostly for technical but also for longer-term strategic reasons.

At the long-term average price of about $0.80 per gallon of gasoline energy equivalent, methanol made from natural gas is more expensive than gasoline on tax free energy basis, but it is nevertheless quite affordable as a motor fuel, especially at the high fuel efficiencies expected for future FCEVs. The prospects for expanded supplies of relatively inexpensive methanol appear promising because methanol could become an increasingly important vector for transport of natural gas energy from many sources worldwide — including remote sources not accessible by gas pipeline[6] — to users across the world's oceans.

At present, however, world capacity for methanol production would be sufficient only for a fraction of just the U.S. fleet of personal automobiles, raising questions about the implementation and costs of the required methanol production and distribution infrastructures. To explore these questions, the Panel met with representatives of Methanex (the world's largest producer of methanol) and the methanol industry, to obtain information on the factors that govern methanol supply, and to determine the prospects for development of methanol supply and distribution infrastructures that could meet the fuel demand of mass produced FCEVs.

According to information from Methanex and, also, the American Methanol Institute, world production of methanol has grown to 26 million tons per year, mostly in response to growing demands for methanol-based chemicals and motor fuel additives such as MTBE and MTAE. Even at this level, the energy equivalent of world methanol production is only about 6% of U.S. gasoline consumption. Importantly, however, a modern methanol plant with a typical capacity of 1 million tons per year can be constructed and put on stream in less than 3 years at a cost of about $350 million or less than $700 per vehicle since the output of just one such plant would be sufficient to meet the needs of more than 500,000 methanol fuel cell vehicles. Methanex representatives stressed that their company is prepared to make the necessary investments if and as the

[6] Since large volumes of natural gas are still being flared or vented at oil production sites, conversion of that gas to transportable methanol would have a double benefit with respect to undesirable releases of greenhouse gases to the atmosphere: the venting of methane, a highly effective greenhouse gas, would be reduced or

demand from methanol-powered FCEVs develops. Methanol produced by such plants can compete in today's marketplace, and larger plants are expected to result in yet lower methanol production cost.

The establishment of a methanol distribution infrastructure is a more complex issue. With the exception of a limited distribution capability for M85 (a blend of 85% methanol and 15% gasoline) in parts of California, there is no infrastructure for methanol automotive fuel distribution at present, and the methanol industry is not in the business of owning and operating fueling stations. It is reasonable to assume, however, that alliances between the methanol industry and distributors and/or retailers of gasoline would develop apace with the emergence of an automotive fuel cell market for methanol. The investments required to establish limited and complete methanol distribution infrastructures has been estimated by Stork et al., (see footnote No. 14 on page III-56) as $360 million and $9 billion, respectively, which corresponds to costs of between $70 and $100 per vehicle. This study also generated estimates for methanol production, as follows: limited infrastructure (70,000 bbl/day capacity) investments for methanol production about $3.2 billion ($640 per car), full infrastructure (1.6 billion bbl/day) $84 billion ($720 per car). These numbers are somewhat but not materially higher than the production plant investments mentioned by Methanex (see above).

The Panel also discussed the choice of methanol with leading developers of PEM fuel cell electric engines as follows.

<u>Automotive Fuel Cell Engine Developers</u>

1. Daimler Benz

By most accounts, DB is the leading automotive fuel cell engine developer, is focusing on methanol for automobile fuel cell electric engines although hydrogen is still being pursued for bus fleet applications (see above). This choice was made in part because a methanol steam reformer is considered more efficient and less difficult to reduce to an automotive component than a fuel processor for gasoline. Another factor contributing to Daimler Benz' selection is the expectation that the higher hydrogen content of natural gas (the current and prospective source of methanol) will more than

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eliminated, and a significant amount of oil/gasoline would be displaced by methanol made from natural gas that otherwise would have been burned without performing useful work.

compensate for the greater inefficiencies in methanol production, with the net result that, for the complete fuel supply-fuel cell engine system, carbon dioxide emissions will be lower for methanol than for gasoline.

To assure adequate availability of fuel for future methanol fuel cell-powered cars, Daimler Benz is pursuing alliances with potential large scale suppliers and distributors of methanol. Should this initiative prove unsuccessful, Daimler Benz is prepared to shift their technical focus to gasoline, with some slippage of their development and commercialization schedules. However, Daimler Benz believe that gasoline fuel cells would only be an intermediate step to systems using methanol and, in the long term, hydrogen.

2. General Motors

GM's in-house fuel processor development program to date has emphasized methanol but gasoline is being pursued in parallel to keep open the possibility of technical breakthroughs and to guard against fuel cost and availability risks. For the reasons given above, GM does not consider any of the fuels being worked on entirely suitable, and the need for substantial investments in a supply infrastructure is anticipated not only for methanol but for gasoline as well since a gasoline-type fuel would need to be tailored for fuel cells, most likely at the refinery (see below). GM believes that the feasibility of automotive fuel cells will benefit significantly from a move toward new petroleum distillate fuels with the highest possible hydrogen content and a chemical reactivity facilitating processing into a hydrogen-rich fuel gas. GM is openly seeking alliances with oil companies to jointly pursue fuel strategies and the development of fuel processing technologies.

3. Japanese Automobile Manufacturers

Japanese car makers engaged in fuel cell development are focusing on methanol, for the same reasons as Daimler Benz: less difficulty in processing, a somewhat higher fuel efficiency of the fuel cell power plant, and reduced transportation energy system emissions of carbon dioxide. The expectation of lower greenhouse gas emissions appears to be an especially important argument in Japan for fuel cells in general and for methanol in particular. Finally, shifting transportation energy to methanol and, therefore, natural gas is in line with an energy security strategy that seeks reduced dependence on imported oil by broadening the transportation fuel base.

C. GASOLINE

Gasoline, of course, meets the cost and logistic criteria as an automotive fuel cell fuel and is an efficient, liquid "hydrogen carrier" of high energy density. However, compared to methanol, gasoline requires a somewhat more complex and less efficient chemical processing system for its conversion into a hydrogen-rich fuel gas stream. This is primarily because of the substantially higher temperature needed to chemically activate gasoline in the primary processing reaction. To date, gasoline fuel processors have seen less development for automotive applications and are less advanced than methanol processors although this situation is changing in the United States.

The basic feasibility of processing gasoline into a hydrogen-rich "reformate" has been established in several laboratories, but it is not yet clear whether ordinary pump gasoline will be compatible in practice with automotive fuel cell engines. Pump gasoline contains varying amounts of sulfur (in form of organosulfur compounds) as well as additives to promote clean burning of fuel in IC engines. Sulfur-tolerant fuel processor catalysts have been demonstrated in laboratory and industrial operations but it is unclear at present whether the conditions used are transferable to automotive fuel processors. If sulfur — in the form of hydrogen sulfide because of the reducing conditions prevailing in the reformate — breaks through the primary processing reactor(s), the platinum catalyst of the PROX reactor is likely to become deactivated by sulfide formation. If hydrogen sulfide also breaks through the PROX reactor and enters the stack, the anode catalyst almost certainly will be deactivated for the same reason. At the temperature of the stack, sulfide formation will be largely reversible.

To protect the fuel cell engine from this possibility will require removal of sulfur somewhere in the fuel processor by a "guard" consisting, e.g., of a zinc oxide bed. Such a guard would require monitoring and periodic replacement, further complicating an already complex fuel processing system. Sulfur removal at the refinery is likely to be more cost effective once sufficient demand for a "near-zero" sulfur gasoline develops, but it is not yet clear to what extent sulfur would have to be taken out for assured gasoline compatibility with fuel cell engines.

Gasoline additives such as detergents, anti-oxidants and corrosion inhibitors also raise questions regarding their long-term compatibility with future fuel cell engines if their composition includes elements other than carbon, hydrogen and oxygen. Clearly, the solution to this potential issue is to not add these compounds in the first place, thus making the case for a "fuel cell-grade" hydrocarbon fuel as discussed further below.

When the Panel discussed fuels questions with its information sources, the prevailing view was that "cleaning up" gasoline for fuel cells on a large scale at the refinery was likely to be more efficient and economical than burdening the already complex gasoline fuel processor with the additional requirements to handle sulfur and gasoline additives. Consistent with this view, most organizations focusing on gasoline for fuel cells advocate that petroleum distillate compositions suitable for fuel cells be determined and, ultimately, produced at refineries[7] for distribution to stations serving fuel cell electric vehicles. These compositions do not need to meet IC engine requirements such as octane rating, Reid vapor pressure and boiling point range but only the criteria for chemical compatibility of the fuel with the fuel processor, and compatibility of the reformate with the stack.

For a "fuel cell-grade" fuel, additives are not required (indeed, they are undesirable), nor is there a need for presence of hydrocarbons with high vapor pressure. As a result, the best petroleum-derived liquid fuel for fuel cells might simply be a distillate cut with relatively low vapor pressure from which sulfur compounds are removed down to sufficiently low but as yet undefined levels at the refinery. The lower vapor pressure compared with pump gasoline should result in lower evaporative emissions and an increase in fire safety, and the savings from elimination of additives and octane rating enhancing refinery processes could offset the cost of sulfur removal at the refinery in part or entirely.

The currently most significant U.S. activities focusing on gasoline as fuel for automotive fuel cells are summarized in the following.

[7] As noted below under Oil Industry Involvement, this possibility is of interest also to oil companies.

PNGV/DOE Fuel Cell Programs

Interest in gasoline as a practical fuel for automotive fuel cells was stimulated in large measure by PNGV, the collaborative program of the three major U.S. automobile manufacturers and several Federal Government agencies led by DOE. Five years ago, the development of gasoline-powered fuel cells became one of the technical strategies to achieve a primary goal of PNGV: an advanced-technology, commercially competitive automobile capable of delivering 80 mpg.

In support of that strategy, DOE/PNGV funded the gasoline (originally: alcohol) fuel processor development at Arthur D. Little discussed above, and they support R&D on an autothermal gasoline processor concept at the Argonne National Laboratory. More recently and as summarized in Appendix E, DOE awarded a number of contracts to advance gasoline fuel processor and PEM stack technologies to the point of their integration into breadboard-level gasoline fuel cell systems. Several multi-kW systems are to become available in about 3 years. Their development and evaluation will be important steps in assessing the feasibility of gasoline as a fuel for PEM automotive fuel cells.

Besides information on the performance and operating characteristics of gasoline-fueled systems, the DOE-funded efforts also should give better indications whether ordinary pump gasoline is compatible with existing and evolving fuel processor technologies as has been claimed by at least one developer, and to which extent deleterious constituents and/or impurities of commercial gasolines need to be removed ahead of the fuel processor. This information, in turn, should help create a better understanding of the technically and economically preferred measures to assure compatibility between gasoline fuel and PEM fuel cells, through an optimum combination of distillate fuel cleanup and modifications at the refinery with chemical cleanup on board of the FCEV.

Automotive Fuel Cell Power Plant and Vehicle Developers/Manufacturers

Several years ago, ADL and Chrysler committed to gasoline as the fuel of choice for automotive fuel cell power plants. Recently, IFC announced plans for development of a gasoline-fueled fuel cell power plant. All three organizations continue to be important participants in the PNGV and DOE programs (see above and Appendix C and

E), but they are also making or planning to make corporate investments in advancing gasoline-based fuel processor and fuel cell system technology. Their commitments and success during the next 3 years are likely to bear importantly on the prospects of gasoline as a practical fuel for PEM fuel cells. However, given the relatively early stage of gasoline fuel processor development and systems integration, and in view of the limited information available, the Panel found it difficult to judge the probability of success.

Oil Industry Involvement

Facing the possibility that fuel cell electric vehicles could emerge as an entirely new, major market either for gasoline or for a non-petroleum product such as methanol, the oil industry is becoming engaged in efforts to understand and influence the issues and decisions bearing on fuel choice. This engagement is not yet very visible, but the cooperation between GM/Delphi, Exxon and ARCO announced in May 1997 is an important indicator for the emerging interest of the oil industry in automotive fuel cells and the fuel(s) for them. As explained to the Panel, the purpose of this collaborative effort is to utilize the combined talents of the participants, to develop a knowledge base on the potential use of gasoline and/or other petroleum-derived fuels in automotive fuel cells, identify major barriers and pursue possible solutions.

The participants are focusing on gasoline but realize that the fuel cell application presents fuel requirements quite different from those for ICE engines. The collaborative effort will include GM/Delphi work on fuel processing as integral part of fuel cell engine development. The oil companies will identify distillate fuels suitable for fuel cells and investigate possible production processes on the bench-scale. One current joint effort is the development of a “well-to-wheels” comparison of various fuel and automotive engine alternatives in terms of efficiencies and emissions. This collaboration has the potential to contribute importantly to the identification— and thus set the stage for production development — of optimal fuels for PEM automotive fuel cells.

Summary and Outlook, Fuels

In summary, methanol and gasoline are the current focus of worldwide efforts to develop automotive PEM fuel cell electric engines; hydrogen is unlikely to play a role in the foreseeable future except perhaps in limited volume produced from natural gas locally for bus or similar vehicle fleets. Better processability, somewhat higher fuel cell engine efficiency, reduced carbon dioxide emissions and longer-term energy strategic advantages are claimed for methanol. The existence of the required production and distribution infrastructures is the obvious advantage of gasoline although it is not clear at present to which extent petroleum distillates need to be modified to meet the purity and processability requirements of “gasoline” fuel processors. The technical, economic and policy bases for a rational choice between methanol and gasoline are not likely to be available until current development efforts have proceeded considerably further and cooperative efforts between fuel cell engine developers and fuel suppliers have identified preferred fuel strategies for fuel cell electric engines and vehicles. These strategies may well turn out to be different for different regions.