Journal of Scientific & Industrial Research
Vol. 62, January-February 2003, pp 97-105

# The Methanol Story: A Sustainable Fuel for the Future

Roberta J Nichols

Ford Motor Company, 8645 N Territorial Road, Plymouth, Michigan MI 48170-5043

Development of vehicles that could operate on alternative fuels began in earnest as a response to the oil shocks of the 1970s. Of the various choices, methanol appeared to be the best candidate for long-term, widespread replacement of petroleum-based fuels. Initial support by the government was based on the desire for energy security, but the potential for improvement in air quality became an important driver as well. Experimental fleets of dedicated methanol vehicles did well in the field, but the lack of refueling infrastructure led to the development of the flexible fuel vehicle (FFV), a vehicle that could operate on either gasoline or methanol with only one fuel system on board. Legislation was put in place to encourage the auto industry to begin production, which started in 1993 for the M85 FFV at Ford. By the end of the decade, however, full production volumes had been transferred to the E85 FFV (gasoline or ethanol). The technical, economic and political reasons for this shift are emphasised and are discussed below, including visions for the future, and the direct methanol fuel cell.

## Introduction

On a global basis, petroleum fuels are the predominant source of energy for transportation vehicles and they will remain like this for a long time. But petroleum supplies are finite and pressure on that supply will increase as transportation growth accelerates in the developing countries, particularly in Asia. In recognition of this eventual need for change, Ford Motor Company decided in 1980 that it was not too soon to begin the difficult transition to new sources of energy.

Many factors need to be considered when making this kind of major change, such as the potential size of the energy resource base, the effect on the environment, the impact of the economy, and acceptance by the consumer. Life-cycle analysis of the system, i.e., the resource and its use, has come to be recognized as essential for making intelligent decisions about a sustainable energy future. Also, when designing engines and fuel systems, there are many fuel properties and combustion characteristics affecting efficiency and performance, as well as emissions, which must be considered[1]. Many of the inherent properties of the alternative fuels choices are quite different from gasoline and diesel fuel.

The volumetric energy density of the fuel is an important parameter since it directly affects the size of the fuel storage system of the vehicle. Unfortunately, all of the alternative fuels are less energy dense per volume compared to gasoline (Table 1). It is noticed that diesel fuel is the only fuel better than gasoline, which accounts for 12 per cent of the higher fuel economy (mpg) associated with the diesel-powered vehicle. (The compression-ignition (CI) engine is still more energy efficient than the spark-ignition (SI) engine, however). Since the public has been trained to think in terms of miles per gallon (mpg), it is hard for them to understand that most of the alternative fuels are more energy efficient than gasoline; i.e., the vehicle goes more miles per energy unit. In some cases, it just consumes more gallons to

Table 1— Energy densities compared to gasoline

| Natural gas | Volume ratio |
|---|---|
| CNG | 4.8-5.9 |
| LNG | 1.57 |
| Propane (LPG) | 1.29 |
| Hydrogen (LH2) | 3.93 |
| Reformulated gasoline | 1.01 |
| No. 2 diesel | 0.88 |
| Methanol | |
| M100 | 2.03 |
| M85 | 1.76 |
| Ethanol | 1.53 |

get the same amount of energy. Fuels also should be taxed on an energy basis as not every gallon contains the same amount of energy.

Liquid fuels have a better volumetric energy density than gaseous fuels. They also are the most compatible fuels with existing distribution systems and engines, i.e., they require the least departure from the technologies in place today for both the vehicle and the refueling infrastructure. The racing community has known for years that the alcohol fuels have performance and safety advantages compared to gasoline, with methanol having a slight edge in power compared to ethanol because of the higher octane-value.

## Methanol vs Ethanol

These two alcohols actually complement each other. The performance and emissions of the two in an ICE are quite similar. Ethanol does not have a flame visibility issue like methanol (and methane and natural gas), because ethanol has two carbon molecules to form soot. This creates the yellow colour in a burn. But ethanol also has a more difficult cold start because of the much lower vapor pressure (2.3 psi compared to 4.6 psi for methanol). Both alcohols have a single boiling point and a high latent heat of vaporization, which adds to the cold start problem, particularly at temperatures much below 8 °C (45 °F). If the economics of the two alcohols were equivalent, ethanol would be the alcohol of choice for transportation use because the volumetric energy density is better, making on-board storage of the fuel, less of an issue for the packaging engineer. But the economics of methanol are more favorable, making it the better choice for replacement of petroleum-based fuels in the transportation sector where the consumer is very much aware of the cost of fuel at the pump. The good news is, the FFV can use either methanol or ethanol and, in fact, some of the early experimental cars ran well on a combination of all three fuels (methanol, ethanol, and/or gasoline), which made them really flexible!

## Methanol Economics And Potential Resource Base

The major sources of energy today are oil, natural gas and coal. Natural gas, seems to be more uniformly spread throughout the world, compared to oil, making it less prone to supply disruptions. In fact, many of today's oil exploration projects result in the finding of new gas fields rather than oil. And there is an abundance of coal in the world; this supply could support our energy needs for several hundreds of years. However, the mining, processing, and burning of coal has undesirable environmental impacts, including the release of large amounts of carbon dioxide ($CO_2$), and it is difficult to use directly as a transportation fuel. The DOE clean coal program is conducting research to resolve some of these issues in order that this abundant resource can be part of a strategy for satisfaction of future energy needs. Coal could become a clean transportation fuel, with no sulphur content, by turning it into methanol through indirect liquefaction.

Overall, the potential resource base for methanol is huge, because it can be made from any organic material, including biomass. This is an important way to mitigate climate change issues because of the uptake of the carbon dioxide by plants, making the net $CO_2$ emission zero. It can also be made from waste, which becomes more important with every new landfill required. Because of the favorable economics, at present almost all methanol is produced from natural gas, although there is a coal-to-methanol plant in Tennessee. It is also a way of utilizing the gas in remote fields because tankers can ship the liquid methanol product a lot easier and with less cost than building a pipeline to transport the gas.

The natural gas-to-methanol process is about 70 per cent efficient in terms of energy. This is not as good as the oil-to-gasoline production efficiency, but good enough that in 1980 most analysts agreed that the economics of methanol could be competitive with gasoline in volume. The state of California, being the third largest energy user in the world, led the way with their interest in methanol as the best candidate for replacement of petroleum-based fuels. Ford Motor Company, as well as others in the auto industry, responded to this request for vehicles that operated on methanol.

## Ford Methanol Research Programs

In 1981, Ford delivered 40 dedicated methanol-fueled Escorts to Los Angeles (LA) County. Four refueling stations were installed throughout the county, including two in underground garages. The experience gained with these initial refueling stations added considerably to the knowledge base required for methanol-compatible infrastructure, as well as identifying the ventilation requirements for underground installations. The 200-mile driving range of the vehicle also made it clear that four stations were inadequate to cover the territorial driving requirements of LA County. But the drivers of the vehicles loved the performance, offering 20 per cent more power than their gasoline-powered cousins and a 15 per cent improvement in fuel efficiency[2].

These vehicles were calibrated to meet an advanced emission standard, including 0.4 $NO_X$. This $NO_X$ requirement had been an emission standard since 1975, but gasoline vehicles had not been able to achieve it. Based on the periodic, high mileage emission data acquired on three of these vehicles operating in the field, the first glimpse was had of the air quality improvement that could be obtained with methanol combustion. And the deterioration factor (DF) for the 0.4 $NO_X$ at 50,000 miles was 1.00.

The LA County fleet accumulated more than three million miles, with many of the vehicles going of the road after running for more than 100,000 miles. The success of this early fleet led California to ask for more of these vehicles. In 1983, 582 vehicles were built on the production line at the Escort assembly plant, in Wayne, Michigan. Most of these vehicles (501) went to California, with the remainder sent to small fleets in New Zealand, Sweden, Norway, United Kingdom, and Canada. Two were even purchased by Toyota in Japan. The price premium for this methanol Escort was $2,200.00 compared to the gasoline version, and most of that was in the engine ($1,900.00). The compression ratio was 11.8:1, which accounted for most of the increase in power and efficiency. The fuel tank was increased in size so that the vehicle had a nominal driving range of 230 miles. This fleet accumulated more than 35 million miles and a few of them are still on the road.

With the additional vehicles going to local, county, and state government fleets, California installed another eighteen stations in strategic locations throughout the state. But it was clear that this number of stations was totally inadequate for the drivers of these vehicles to feel comfortable. They had to constantly monitor the fuel gauge and carefully plan their routes. In 1982, Ford began development of the flexible fuel vehicle since it appeared to be a reasonable solution to the lack of refueling infrastructure. These vehicles have higher performance when operating on methanol, but transparent operation on gasoline. Thus the technology was viewed as a way to introduce large volumes of methanol-capable vehicles into the market while the methanol-refueling infrastructure could grow to meet local demand.

Between 1985 and 1992, 705 experimental FFVs were built and delivered to the field, primarily to demonstration fleets in California and Canada. The vehicle models included the 1.6L Escort, the 3.0L Taurus, and the 5.0L Crown Victoria LTD. There were even a few 5.0L Econoline vans. This broad spectrum of vehicles showed that the technology was applicable to any size engine/vehicle. As the size of the vehicle fleet grew in California the number of stations increased, so that by 1990 there were about 50. This was still far from adequate for completely normal operation on methanol, but nonetheless encouraging. In September of 1989 the price at the pump for methanol, on a gasoline energy equivalent basis, was between that of unleaded regular and premium gasoline. The customer seemed willing to pay this for the added performance and the knowledge that there was an air quality benefit, which had become the near-term driver for introduction of methanol rather than the initial, longer-term energy issues.

## Air Quality Impact Of Methanol

Ozone, or photochemical smog, is formed in the lower atmosphere when sunlight reacts with hydrocarbons (HC) and nitrogen oxide. It is generally regarded as the most serious non-attainment problem. The vehicle contribution to hydrocarbons comes from two sources: the tailpipe and evaporative emissions. One of the approaches to lowering the motor vehicle contribution to ozone formation is to change the character of the tailpipe emissions. This is one of the ways in which methanol vehicles make a contribution to improvement in air quality. It is not the level of the HC tailpipe emission per se that is lower; it is the composition of the emission that is different. Hydrocarbon compounds have varying levels of reactivity in the atmosphere, as shown in Table 2. Fuels that produce less reactive exhaust emissions when burned, will generate less ozone. As can be seen, methanol is quite low on the reactivity scale compared to some of the more complex hydrocarbons associated with gasoline. The ozone reduction associated with the use of methanol is also dependent on proper control of the formaldehyde emission. Fortunately the technologies that control HC emissions, in general, are the same kind of controls

Table 2— Photochemical reactivity of organic compounds: Rate constants for reaction with hydroxyl (OH) radical

| Compound | $K^{-4} \times 10^{-1}$ (ppm/min) |
|---|---|
| Trans-2-butene | 10.5 |
| 1,2,4 Trimethyl benzene | 4.9 |
| M-Xylene | 3.4 |
| Propionaldehyde | 2.2 |
| Acetaldehyde | 2.2 |
| Propene | 2.1 |
| Formaldehyde | 2.1 |
| Ethylene | 0.45 |
| *N*-butane | 0.35 |
| Propane | 0.25 |
| Methanol | 0.148 |
| Ethane | 0.045 |
| Acetylene | 0.022 |
| Carbon monoxide | 0.021 |
| Methane | 0.0012 |

that control formaldehyde; in both cases, almost all of the emission is produced in the first two minutes of operation after a cold start [3]. Beginning in May 1993, the California Air Resources Board (CARB) included an emission standard for formaldehyde of 0.15 mg/min, which was approximately the formaldehyde emission level of the typical gasoline vehicle. The emission standard also included a reactivity factor for the various alternative fuels. For methanol, it was about half that of gasoline.

The methanol vehicle evaporative emission benefit is difficult to define. If the vehicle is dedicated to operation on methanol, the evaporative HC emission is definitely lower (and less reactive) because of the low vapor pressure of methanol. But, for the FFV, the vapor pressure can vary greatly since the mixture in the tank can vary from all gasoline to all methanol, and anything in between. When the 3.0L FFV Taurus went to production in 1993, four canisters were required to certify them for evaporative emission control across the full spectrum of fuel combinations.

## Fuel Specification

The methanol fuel specification evolved from M100 (100 per cent) to M85 (85 per cent methanol and 15 per cent gasoline) for several reasons. As stated earlier, the Reid vapor pressure of M100 is only 4.6 psi, which made cold starts quite difficult. The addition of 15 per cent gasoline brought the vapor pressure up to about 7 psi, thus making cold starts possible in most climates[4]. In fact, in cold weather regions, the user generally relies on a block heater even with gasoline.

The addition of 15 per cent gasoline to the methanol also addressed two other concerns associated with M100 combustion[5]. Without the complex hydrocarbons of the gasoline, the flame of methanol combustion is invisible in daylight, which was a concern in the case of a vehicle fire. With M85 and providing of the gasoline had at least 20 per cent aromatic content, there was sufficient yellow color, even in bright sunlight, so that one could say the fuel was burning.

The other issue was the flammability limits of M100. At normal ambient temperatures, the air-fuel mixture ratio of the gasoline vapor above the liquid in the tank is too rich to ignite. This is not true for the alcohols because of their low vapor pressures. The addition of 15 per cent gasoline moves the flammability limit temperatures to a more acceptable range of risk, close to that of the gasoline vehicle. This became an even more important consideration with the introduction of fuel injection, with electric fuel pumps located in the fuel tank.

The biggest challenge in the development of alcohol vehicle technology was getting all of the fuel system materials compatible with the higher chemical reactivity of the fuel. Methanol was even more of a challenge than ethanol but, fortunately, much of the early experience gained with ethanol vehicle production in Brazil was transferable to methanol. In particular, interaction with certain elastomers could cause unacceptable swelling, shrinking, disintegrating, etc. The alcohols were corrosive for certain metals, as well. The oil additive package had to be reformulated to account for the more acidic nature of the fuel in order to achieve acceptable engine durability.

The M85 fuel specification received extensive work through the professional societies and experience in the field. In house, before ever making the decision to move to production, the potential health effects of exposure to methanol had been thoroughly studied and no unacceptable risks were found. The studies of the U S Environmental Protection Agency (EPA) found this to be the case as well. Anti-siphoning devices were included in the vehicle fuel tank to prevent inadvertent intake of the methanol, which is toxic, but, then, so is gasoline. The risk with gasoline is mitigated by the fact that it usually causes vomiting if ingested, which is not the case with methanol. Interestingly enough, the antidote for methanol poisoning is ethanol, since the human metabolism preferentially processes the ethanol.

## Technology Status

The knowledge gained with the in-house research and the demonstration fleets in the field has brought the technology for methanol-fueled vehicles to a high level of reliability[6,7]. Otherwise, Ford could not have made the decision to take this technology to production. But there are also some areas where further work will be beneficial. For example, continuous evaluation and evolution of the fuel specification will be needed, just as it has occurred for gasoline over many years. The same is true for the oil specification. There is a need for better control of fuel contamination in the field. As the infrastructure expands, the distribution system needs to accommodate methanol transport via pipeline in order to reduce costs. Since the air quality and energy efficiency benefits of the dedicated methanol vehicle are even better than those of the FFV, research on the dedicated methanol vehicle should continue, in anticipation of the day when there is sufficient infrastructure in place for the average retail customer to feel comfortable with a dedicated vehicle.

## Market Development

The most difficult aspect of any new technology is introduction into the market. This is especially true when trying to introduce a new vehicle fuel. Because there is an extensive infrastructure in place for petroleum-based fuels, it is hard to compete with their economics and the user is quite satisfied with their performance. The supply disruptions of the 1970s, however, prompted in-depth analyses of the long-term outlook for energy supplies for the future, and the conclusion at Ford was that if one wanted to remain in the personal mobility business, one needed to look at alternatives. For the reasons stated earlier, methanol appeared to be one of the best alternatives. Thus, in 1980-1981, the corporation actively sought a partnership with most of the major oil companies to develop methanol. There definitely was interest, especially if the oil company owned large coal reserves, but the country was going through a difficult recession at the time and cost was a huge issue. A large capital investment would be required to put the necessary refueling infrastructure in place.

At the time, about five per cent of the refueling stations had diesel fuel, primarily because of the truck stops. This appeared to be sufficient for diesel passenger cars to be bought by the retail consumer. Since a methanol-fueled vehicle would require more frequent refueling because of its lower energy density per gallon, it was estimated by one major oil company that 10 per cent of the refueling stations would need a methanol pump for introduction of the dedicated methanol vehicle. In 1980 the cost of this was estimated to be about $600 million. And when these facilities were first in place, there was lot of "real estate" devoted to methanol pumps and storage tanks with very little activity since it would take some time for methanol vehicle populations to grow.

The flexible fuel vehicle appeared to solve this "chicken and egg" problem: It could bridge the gap between refueling stations during the transition period by operating on gasoline in those areas where no methanol stations existed. The rationale was that the methanol stations would gradually appear when there were sufficient vehicles in the field to warrant the capital investment required and the activity at the pump justified its existence. If the cost of operation on methanol was competitive with gasoline, it was felt the customer would learn to choose that fuel based on the measurable, higher performance it provided, as well as the environmental benefits.

In January of 1985 at a National Science Foundation (NSF) workshop on methanol, the concept of giving a methanol-capable vehicle a Corporate Average Fuel Economy (CAFE) benefit was introduced and the subsequent enthusiasm for this idea by all concerned led to the introduction of the Danforth Bill. This legislation did not make it all the way through the legislative process before that session of Congress adjourned, but it had received lot of attention and refinement. In recognition of the fact that CAFE was legislated to reduce our use of petroleum, the Danforth Bill was expanded to give a CAFE benefit for the production of other non-petroleum vehicles, including ethanol, which ended the opposition by the ethanol community to the legislation. In fact, the bill was reintroduced in the next session of Congress by Senator Rockefeller of West Virginia (where methanol from coal could revive a depressed industry) and Senator Daschle of South Dakota (which is one of the farm states supporting ethanol production). Now known as the Alternative Motor Fuel Act (AMFA), it was signed into law by President Reagan in October of 1988. This became an incentive for the auto industry to invest the capital and engineering effort required to move to production of methanol-capable vehicles. In 1989, Ford began the transfer of the FFV technology from research to production engineering, with a target of 1993 for first production. The 3.0L Taurus was selected as a suitable vehicle, with a pilot production program (small quantity) slated for 1991 in order to add to the knowledge base acquired from the demonstration programs already in place. In keeping with this cautious approach, the 1993 production volume was limited to 2800 vehicles, with Job #1 on November 2, 1992, and gradually increasing volumes in 1994 and 1995.

Some of the other car companies were responding to this new market as well. Chrysler set the stage for everyone by offering their flexible fuel vehicle for sale without a price premium compared to the gasoline version, even though the production costs were somewhat higher. Based on the ethanol vehicle production experience in Brazil, however, this additional cost would tend to disappear as production volumes became larger.

The May 1996, Taurus was a new model and FFV production went to high volumes. This Taurus FFV was fully developed for ethanol (E85) as well. Plans were in place to move to other vehicle lines, such as the Ranger pick-up truck with both M85 and E85 versions. (The production engineers did not develop the same vehicle for both fuels because the certification and validation process would have been a nightmare in terms of possible combinations of fuel). From a technical point of view, the flexible fuel vehicles were a huge success.

On June 12, 1989, President Bush announced a major alternative fuel vehicle program by Executive Order, which included 500,000 methanol vehicles for 1996, 750,000 for 1997, and one million per year after that. There was a government commitment to place them in the federal fleets to make this a reality.

On June 18, 1989, reformulated gasoline was announced by one of the major oil companies. The composition of the gasoline was changed so that the photochemical reactivity of the HC emission from the vehicle would be lower. As discussed earlier, this lower reactivity results in less ozone formation in the lower atmosphere. This was a major step forward for gasoline; it also meant the air quality benefit of methanol compared to gasoline became smaller.

### Market Collapse

The air quality benefits of methanol had become the near-term and primary driver for the programs designed to encourage its use in the transportation sector. There was a brief renewal of interest in the long-term energy issues because of Desert Storm in 1991, but mostly people had returned to a state of complacency about future oil supplies. By the middle of the decade, energy security was no longer on the "radar screen" of the California Energy Commission (CEC). Gasoline was cheap, plentiful, and reformulated.

Access to the methanol refueling stations in California was through the use of a fueling card key. This enabled the CEC to keep track of the usage of methanol in the FFV compared to operation on gasoline. For several years, the level of usage was pretty high. Over 80 per cent of operation was on M85, but it gradually began to drop. Then, when one of the methanol marketeers took advantage of a temporary shortage in supply, there was a sharp increase in the price of the methanol and the amount of methanol being used really fell. The environmental groups were critical of the FFV vehicles because they ran on gasoline most of the time, but their production was providing a CAFE benefit for the car companies (the CAFE benefit was calculated, assuming methanol usage 50 per cent of the time).

Meanwhile, interest in the air quality benefits of natural gas had grown. The photochemical reactivity of methane is really low (Table 2) and, therefore, the largest reduction in the formation of ozone could be realized by its use in the transportation sector. There are several reasons, however, why natural gas usage in vehicles probably will be limited to fleet usage, and not the retail market, not the least of which is the cost of the refueling station. Nevertheless, the methanol program began to suffer from the "Fuel of the Year" syndrome. The state of California was demanding zero emission electric vehicles because they would provide the most improvement in air quality benefit. No one was staying focused on the long-term vision and analysis, which said methanol was the best candidate for replacement of petroleum-based fuels in the future.

As reformulated gasoline usage grew and spread throughout the country, the use of MTBE (methyl tertiary butyl ether) to meet the oxygenate and octane-requirements of gasoline grew. Eventually, the presence of MTBE in water supplies was discovered. The underground fuel storage tanks had been leaking for years but, in the case of gasoline, it was usually sitting on top of a bottom layer of water, since gasoline and water are not really miscible. MTBE is produced by combining methanol and isobutylene and is miscible with water, all of a sudden, these leaking tanks became a menace. In spite of the fact that none of the studies conducted showed that the MTBE was a health hazard *per se*, it was malodorous, in the water, and legislation to ban its use began to appear. Because methanol is used in the MTBE production process, methanol unfortunately became associated with and tainted by this negative view of MTBE.

The momentum of the FFV production programs at the car companies has continued, although present emphasis is on the E85 version. Ethanol has a large base of support in the farming community and, with its government subsidy of the cost, continues to slowly grow in use. In fact, General Motors recently announced it would begin production of their full-size pickup trucks, the Silverado and Sierra, to operate on either gasoline or E85. Ford has produced high volumes of E85 FFV Ranger trucks, in addition to the Taurus. The Explorer Sport comes in an E85 FFV version, the Escape program has plans to do so, and 4000 E85 FFV Focus vehicles were recently shipped to Sweden.

A great deal of support for ethanol is derived from the fact that it is a biomass fuel, which addresses the climate change/greenhouse gas issue. Whether there is a positive net energy for production of ethanol from corn is, however, still being debated[6]. If biomass-derived ethanol is going to make a major contribution to our future energy needs, the feedstock will most likely be a non-food, dedicated crop, such as switchgrass or poplars, and crop and forest residues, as well as other waste materials[7]. Many people do not realize that methanol can be a biomass fuel also, probably without the need for a subsidy. Methanol is more easily produced from cellulosic or woody material than ethanol. In 1927, methanol was known as "wood alcohol" because it was produced via the destructive distillation of wood residues in the forest[8]. It was cheaper to transport the methanol than it was to transport the wood.

## Fuel Cell Vehicles

Fuel cells are being developed as a potential alternative to the internal combustion engine (ICE) in vehicles. The hydrogen fuel cell produces electrochemical energy by combining hydrogen and oxygen, thus forming water in the process. Hence the hydrogen fuel cell has zero emissions. This is the primary driver for the development of the FCV, not an improvement in efficiency compared to the ICE, although that possibility exists. While overall costs and performance are still issues for the FCV, substantial progress has been made with the potential for first production by the end of the decade. A limited number of demonstration vehicles probably will appear in the field by the middle of the decade.

The critical issue, other than cost, is how to provide the fuel cell with hydrogen. Two basic methods are under consideration: (i) the direct storage of hydrogen on board the vehicle, either as a compressed gas at high pressure (5,000 psi) or as a liquid in a cryogenic tank at very low temperatures; and (ii) the indirect storage of hydrogen by using an onboard fuel reformer that extracts the hydrogen from another fuel. For the latter method the two primary candidates are methanol and gasoline, both having the advantage of being liquids. The methanol reformer technology is the most advanced and has the advantage of working at a much lower temperature (260 °C) compared to any of the other hydrocarbon (gasoline, ethanol, methane, etc.) reformers (600-900 °C). The gasoline reformer has the advantage of not requiring a new infrastructure.

As discussed above, experience with the other alternative fuel vehicles has demonstrated that it is very difficult to bring new infrastructure and vehicles to the marketplace at the same time. Therefore the most pragmatic solution for the FCV would be the gasoline reformer, even though it is less efficient and more polluting than the methanol reformer. (The fuel cell only uses the hydrogen extracted from the gasoline, or methanol, so the remainder of the fuel has to be "recycled" in the most useful and environmentally-friendly way). As research on the gasoline reformer technology has progressed, it appears that a "special" gasoline, such as naphtha, might be required in order to achieve acceptable results. If this is the case, then one is faced with a special refueling pump after all, but the changes would not be as extensive as in the other two cases (methanol reformer or direct hydrogen storage). It does not appear, however, that the gasoline reformer technology will be sufficiently developed in time for the introduction of the FCV. In fact, as the research goes on, enthusiasm for the gasoline reformer is beginning to disappear.

Introduction of the FCV in the near term favours use of the methanol reformer. Like the dedicated methanol ICE vehicle, it is estimated that 10 per cent of the refueling stations should have methanol refueling pumps in order for the customer to feel comfortable with owning an FCV that uses methanol to store the hydrogen. This would require a major investment by the oil industry. Extensive material changes would be required in the existing gasoline distribution system, in order to accommodate the methanol. But the gasoline technology/system, including the pipeline, could be used, since methanol is a liquid. Also, a desirable synergy would exist, because of the hundreds of thousands of methanol-capable vehicles already in the field, with more in line. Eventually, this scenario would get us back to the high-performance, high-efficiency, dedicated methanol vehicle.

The most desirable solution for the FCV in terms of the most efficiency and least pollution is direct hydrogen storage. Unfortunately, this option would also require the most infrastructure changes with substantial associated costs. In order to avoid installation of a hydrogen pipeline system throughout the country, one scenario proposed is to use steam methane reformers in the refueling station to produce the hydrogen on-site. The methane would get there via the existing natural gas pipelines. While less costly than a whole new system, each site would cost about ten times more than installation of a methanol pump.

In the long run the direct methanol fuel cell (DMFC) shows a lot of promise. In this case, no reformer is needed. The methanol is injected directly into the cell, where the methanol reacts to form electrochemical energy and carbon dioxide. This technology is under development at many research laboratories[9], but it lags several years behind the methanol steam reformer FCV. Daimler-Benz, however, recently announced that they have a DMFC in a vehicle that can actually drive down the road. This is a major breakthrough for this technology, and greatly enhances the synergies of methanol as a transportation fuel.

## Requirements for Success

Obviously, there are no easy or straightforward solutions. All of the options have advantages and disadvantages. All of the reasons that made methanol the best candidate for the long-term, widespread replacement of petroleum-based fuels back in 1980, still exist. There is a large resource base; because it is a liquid, it is the least departure from the technology in place, making it the most orderly, least expensive transition; it is environmentally friendly, since it has air quality benefits and can be made from biomass; it is a high performance, high efficiency fuel, and transparent to the customer in the ICE; it is an excellent hydrogen carrier for the fuel cell; and the economics can be competitive with gasoline in volume. Based on past experience, however, successful introduction of methanol has some fundamental requirements. There must be an adequate number of refueling stations, the price of the fuel must be stable, and the fuel quality must be controlled. Most important of all, it is not likely that anything will happen unless the oil industry is a partner in the overall objectives and action plan.

## References

1 Nichols R J, Applications of alternative fuels, SAE Paper No. 821573 (1982).

2 Nichols R J et al., Ford's development of a methanol fueled escort, Proc Fifth Int Alcohol Fuel Tech Symp, Auckland, NZ, 2 (1982) 109-116.

3 Nichols R J et al., A view of flexible fuel vehicle aldehyde emissions, SAE Paper No. 881200 (1988).

4 Nichols R J et al., Cold start studies, Canadian Flexible Fuel Vehicle Program, Final Report, Ontario Ministry of Energy (March 31, 1987).

5 Anderson J E & Nichols R J, Fuel methanol additives: Issues and concerns, Proc Tenth Energy Tech Conf, Wash. D C (February 28-March 2, 1983).

6 Roberta Nichols, Utilization of fuel methanol in transportation vehicles: Implications for air quality, Proc Eleventh No Am Motor Veh Emissions Control Conf, Baltimore, M D (April 20-23, 1986).

7 California methanol program, evaluation report, Vol. 1: Light-duty vehicle programs, California Energy Commission (CEC), Trans Technol Fuels Office (1999).

8 Energy Independent (October 2001).

9 Review of the research strategy for biomass-derived transportation fuels, National Research Council Report, (National Academy Press) (September 1999).

10 Energy technology handbook (McGraw-Hill Book Co., New York) 1977, P2-120.

11 The promise of methanol fuel cell vehicles American Methanol Institute Report, Wash D C, 1998.

*Dr Roberta J Nichols retired from the Ford Motor Company in 1995. From 1979 to 1991 she headed the research and development effort for Ford's alternative fuels vehicles, resulting in production vehicles that operate on methanol, ethanol, propane, and natural gas. She has three patents on the Flexible Fuel Vehicle (FFV) to her credit. From 1991 to her retirement, she was part of the management team for the Electric Vehicle Program. Prior to joining Ford, she was a Member of the Technical Staff at The Aerospace Corporation in El Segundo, California for 19 years. She is a Fellow of the Society of Automotive Engineers and the Society of Women Engineers, a member of the National Academy of Engineering, a recipient of the Clean Air Award for Advancing Air Pollution Technology from the South Coast Air Quality Management District. Dr Nichols has served on various technical advisory committees and peer review panels, including study committees of the National Research Council. She is currently a member of HTAP (Hydrogen Technical Advisory Panel). She is the author or co-author of more than 60 technical articles on alternative fuels, IC engines, and new sources of energy. Dr Nichols received a BS in Physics from UCLA, and an MS in Environmental Engineering and a PhD in Engineering from USC.*