Beyond

THE INTERNAL COMBUSTION ENGINE

The Promise of Methanol Fuel Cell Vehicles

AMERICAN METHANOL INSTITUTE

ABOUT THE AMERICAN METHANOL INSTITUTE

As the voice of the methanol industry, AMI works with auto manufacturers and government agencies to accelerate the introduction of electric fuel cell vehicles powered by methanol. AMI helps inform elected officials and the public about the energy security, greenhouse gas and other environmental benefits of methanol fuel cell technology. Leading portable power equipment, telecommunications, and consumer electronics companies, with AMI s support, expect to introduce garden and camping equipment, cellular telephones and other methanol-powered fuel cell products in the near future.

AMI encourages the development of new markets for methanol s use, such as its vital role in reducing the discharge of nitrogen into the sensitive Chesapeake Bay from the Blue Plains wastewater treatment facility which serves the nation s capital. The Institute is encouraging the development of methanol-from-landfill gas technology, finding a productive use for methane gas emissions that would otherwise be vented or flared to the atmosphere contributing to global warming.

ACKNOWLEDGMENTS

This report benefited greatly from the support and guidance of the AMI Board of Directors, led by the chairman of AMI s Market Development Committee, William R. Bell (Synetix). The AMI Board of Directors includes Wayne Wright (Methanex Corporation); Roger Seward (Lyondell Methanol Company); Burton Joyce (Terra Industries); Bob Gengelbach (Celanese); Mohammed Al-Bat hi (Sabic Americas, Inc.); Rampersad Motilal (Methanol Holdings Trinidad Ltd.); Jim Prentice (Enron Clean Fuels); and John Lynn (AMI President and CEO).

AMI s Market Development Committee provided considerable assistance with the preparation of this report, including Mark Allard (Methanex Corporation); Tim Clifford (AMPCO); Raymond Lewis; Doug MacMillan (Terra Nitrogen); Glyn Short; Ed Swinderman (Lyondell Petrochemical Company); Steve Skasko (Saturn Methanol Company); Michael Walsh; Peter Ward (California Energy Commission); John White (V. John White and Associates); Bob Wright (Methanex Corporation); and Paul Wuebben (South Coast Air Quality Management District).

A number of external reviewers offered their expert comments on draft versions of this report. These reviewers included Debby Harris (Ballard Automotive); Johannes Ebner (DaimlerChrysler); James Larkins (Georgetown University); Jason Mark (Union of Concerned Scientists); Stefan Unnasch (A.D. Little); Peter Iwanowicz (American Lung Association of New York State); and Dr. Shannon Baxter (California Air Resources Board). It is understood that none of the persons listed above bear responsibility for the report s findings and recommendations.

Beyond

THE INTERNAL COMBUSTION ENGINE

The Promise of Methanol Fuel Cell Vehicles

PREPARED FOR THE AMERICAN METHANOL INSTITUTE BY BREAKTHROUGH TECHNOLOGIES INSTITUTE

CONTENTS

EXECUTIVE SUMMARY 3

BEYOND THE INTERNAL COMBUSTION ENGINE 6

WHAT IS A FUEL CELL? 8

WHO IS DEVELOPING METHANOL FUEL CELL VEHICLES? 12

WHAT ARE THE SAFETY AND HEALTH IMPACTS OF METHANOL USE? 18

WHY IS METHANOL NOT THE SAME AS MTBE? 20

HOW WILL METHANOL FUEL CELL VEHICLES REDUCE URBAN AIR POLLUTION? 22

HOW WILL METHANOL FUEL CELL VEHICLES ADDRESS THE GREENHOUSE EFFECT? 24

HOW WILL METHANOL FUEL CELL USE ADDRESS WATER POLLUTION? 26

WHERE WILL I BUY METHANOL FUEL? 28

HOW MUCH WILL I PAY FOR METHANOL FUEL? 30

HOW MUCH METHANOL WILL BE NEEDED TO SERVE THE MARKET? 32

IS THERE ENOUGH NATURAL GAS? 34

WILL METHANOL BE MADE FROM FLARED NATURAL GAS? 36

WILL RENEWABLE FEEDSTOCKS BE USED FOR METHANOL PRODUCTION? 38

ARE THERE OTHER POTENTIAL METHANOL FEEDSTOCK SOURCES? 40

WHAT ARE THE STRATEGIC IMPLICATIONS OF A WORLD METHANOL MARKET? 42

AREN'T GASOLINE FUEL CELLS AND GASOLINE/BATTERY HYBRIDS BETTER? 44

HOW DO WE ENCOURAGE THE INTRODUCTION OF MFCVs? 46

BIBLIOGRAPHY 50

EXECUTIVE SUMMARY

"WITHIN THE WIDELY DISCUSSED QUESTION OF WHETHER HYDROGEN OR METHANOL IS THE RIGHT FUEL FOR FUEL CELLS WE BET ON METHANOL FOR THE PASSENGER CARS... MOREOVER, TODAY'S DISTRIBUTION SYSTEM CAN BE ADJUSTED IN A COST EFFECTIVE WAY TO ACCOMMODATE METHANOL, INCLUDING THE FUTURE OPTION OF PRODUCTION FROM RENEWABLES."

DR. FERDINAND PANIK, SENIOR VICE PRESIDENT FUEL CELL PROGRAMS FOR DAIMLERCHRYSLER, AND PRESIDENT OF XCELLSIS

September 2000

Methanol a convenient liquid fuel made from natural gas or renewable resources is a leading candidate to provide the hydrogen necessary to power fuel cell vehicles (FCVs). In the last few years, much progress has been made in bringing methanol fuel cell technology closer to the marketplace. Also known as wood alcohol, methanol has been in commerce for over 350 years since 1648. Methanol s widespread global use has focused primarily on its value as a building block for thousands of consumer products from plastics and paints, to construction materials and windshield washer fluid. The American Methanol Institute (AMI) has prepared this report to highlight the ongoing advances in methanol s use with emerging fuel cell technology, address economic and environmental issues surrounding the use of methanol fuels, and explore likely paths to achieving a successful market introduction of methanol fuel cell vehicles (MFCVs).

IMPORTANT FINDINGS

- The world s major automakers are racing to introduce FCVs to the market. Many demonstrations, advancements and breakthroughs have been achieved with methanol fuel cells.

- Automotive industry leaders conclude that within two decades, between 7 and 20 percent of new cars sold in the world will be powered by fuel cells. We can envision a global fleet of 40 million FCVs on the road by 2020.

- With fuel cell technology now moving out of the laboratory, the research emphasis has shifted to reducing costs in preparation for mass production. A few years ago, the

THE WORLD METHANOL INDUSTRY HAS A SIGNIFICANT IMPACT ON THE GLOBAL ECONOMY, GENERATING OVER $12 BILLION IN ANNUAL ECONOMIC ACTIVITY WHILE CREATING OVER 100,000 DIRECT AND INDIRECT JOBS.

fuel cell stack only one part of the whole fuel cell power system cost a prohibitive $5,000 per kilowatt, the equivalent of buying an engine for $250,000. The entire fuel cell system cost (fuel cell stack, methanol reformer and associated controls) is now down to $300 per kW, and developers are targeting full power system costs in the range of $50 per kW with high-volume production. A 50-kW fuel cell system for a vehicle would cost, therefore, about $2,500, comparable to the cost for today s internal combustion engine (ICE).

- Methanol is one of the safest and most environmentally sound fuels available. In the United States, there are over 180,000 vehicle fires each year in which gasoline is the first material to ignite. According to the Environmental Protection Agency (EPA), a switch to methanol could reduce the incidence of these fires by 90 percent, saving 720 lives, preventing nearly 3,900 serious injuries, and reducing property losses by millions of dollars.

- While methanol is used as a feedstock in the production of the gasoline additive methyl tertiary butyl ether (MTBE); methanol and MTBE are two different chemicals with entirely different effects on groundwater and drinking water. Both methanol and MTBE are highly soluble in water and poorly adsorb to subsurface soil, the similarity in the behavior of the two compounds in the environment ends there. Ubiquitous in nature, methanol is easily and quickly degraded in the environment by a diverse range of microorganisms under most environmental conditions that use methanol as a source of carbon and energy. Compared to gasoline, the environmental impacts of methanol are much more benign.

- Due to its high rate of biodegradation, more than 100 wastewater treatment plants in the United States add methanol to accelerate the removal of nitrates in the final stages of sewage treatment before the wastewater is discharged into sensitive oceans and rivers.

- Full fuel-cycle carbon dioxide emissions and other greenhouse gases from a MFCV will be less than half of those for today s gasoline internal combustion vehicle. With an estimated global fleet of 40 million MFCVs by 2020, we expect the total well-to-wheel CO_2 emissions from a MFCV to be 243.5 equivalent grams per mile, versus 461.9 equivalent grams per mile for a gasoline ICE car. Assuming that each car is driven 12,000 miles per year, the annual equivalent CO_2 emission reductions from the global fleet of MFCVs would reach a staggering 104 million metric tons.

- It will cost less than $500 million to adapt 10 percent of the refueling stations in California, New York, Massachusetts, Germany, and Japan to methanol operation. Even converting 25 percent of the stations in these target areas would only amount to $1.2 billion.

- In 2000, worldwide methanol production capacity stands at 12.5 billion gallons (37.5 million tons) per year, with a utilization rate of just under 80 percent. The world methanol industry has a significant impact on the global economy, generating over $12 billion in annual economic activity while creating over 100,000 direct and indirect jobs.

- Under initial market penetration assumptions, estimates reveal that by the year 2010, automakers will have introduced nearly 500,000 MFCVs. If each vehicle travels 12,000 miles annually, using 436 gallons of methanol (achieving 55 miles-per-gasoline equivalent gallon), overall demand would reach 218 million gallons of methanol per annum, or less than 2 percent of current world capacity.

- Today, methanol is being produced from otherwise flared or vented natural gas in many other parts of the world. If only 10 percent of the natural gas flared each year was made available for the methanol fuel market; it would be enough to power 9.5 million FCVs annually.

- Technology to produce methanol from renewable feedstocks such as wood, municipal solid waste, agricultural feedstocks and sewage has been widely demonstrated.

ESSENTIAL RECOMMENDATIONS

Establish incentives for the purchase and operation of FCVs. Legislation has been introduced in the U.S. Congress to provide a 25¢ per gasoline-equivalent gallon tax credit for the use of methanol and other natural gas-based fuels. This legislation provides short-term incentives that will be critical in helping to build the market for fuel cell vehicles so that economies of scale can be achieved to reduce vehicle costs.

Use Corporate Average Fuel Economy Credits. The Alternative Motor Fuels Act of 1988 established a Corporate Average Fuel Economy (CAFE) program for vehicles fueled with alcohol or natural gas. By accumulating significant CAFE credits from the sale of MFCVs, automakers can offset the lower mileage ratings from larger vehicles (like SUVs and minivans) that are generally more profitable than smaller, higher mileage vehicles.

Develop specifications for methanol fuel for FCVs. In 1999, representatives of the oil, automotive and methanol industries formed the Methanol Specification Council to develop readily accepted specifications for the safe and effective use of methanol in MFCVs.

Provide credit for MFCVs in regulatory policies encouraging the use of electric vehicles. The State of California requires that 10 percent of the vehicles sold in Model Year 2003 must be zero emission vehicles (ZEVs). MFCVs qualify for the highest level of partial ZEV credits. Direct methanol fuel cell (DMFC) vehicles fully qualify as ZEVs.

Establish a mechanism to monetize the value of CO_2 emission reductions. Successful emission trading systems have been established to buy and sell emission reductions achieved by stationary facilities for several pollutants. An emission trading system should be established for CO_2 emissions, which would provide a mechanism for the inclusion of emission reductions such as those from MFCVs.

Support the fuel cell work of the Partnership for a New Generation of Vehicles (PNGV). This public/private partnership has identified fuel cell vehicles as one of its technology options for developing highly efficient vehicles.

Encourage the use of aggressive marketing campaigns for FCVs. Automakers have come to realize the significant consumer enthusiasm for clean, advanced technology vehicles. The market introduction of MFCVs will create even broader opportunities for educating consumers to the benefits and availability of this technology.

Increase funding for research in DMFC technologies. DMFCs hold great promise for reducing size, weight, cost, emissions and improving energy efficiency for a broad array of applications. The efforts of national laboratory, university and private researchers should be directed to accelerating the pace of development of this important technology.

BEYOND THE INTERNAL COMBUSTION ENGINE

"I BELIEVE FUEL CELL VEHICLES FINALLY WILL END THE HUNDRED-YEAR REIGN OF THE INTERNAL COMBUSTION ENGINE AS THE DOMINANT SOURCE OF POWER FOR PERSONAL TRANSPORTATION. IT'S GOING TO BE A WINNING SITUATION ALL THE WAY AROUND — CONSUMERS WILL GET AN EFFICIENT POWER SOURCE, COMMUNITIES WILL GET ZERO EMISSIONS, AND AUTOMAKERS WILL GET ANOTHER MAJOR BUSINESS OPPORTUNITY — A GROWTH OPPORTUNITY."

WILLIAM C. FORD, JR., FORD CHAIRMAN
International Auto Show, January 2000

Fuel cell technology has proven itself as a greener alternative to internal combustion engines, there is no doubt about that. Now there is an intense international competition to commercialize fuel cell vehicles, and a race to make the technology affordable and appealing to the consuming public. The FCV driving experience will be much quieter and require much less maintenance. Imagine no oil changes for your car, no noise from the explosive ignition of fuel within an engine block, greatly reduced maintenance repairs such as valve jobs, ring jobs, starter replacements, timing adjustments and timing belt replacements. Fewer moving parts means greater reliability and longer vehicle life, saving the operator time and expense.

Every major auto company in the world is developing fuel cells, in the lab and increasingly on the road. Fleet testing began in 2000 under the California Fuel Cell Partnership. Since a fuel cell engine also acts as a portable generator, companies that commercialize FCVs will also help revolutionize the way the world thinks about energy.

Dr. Ferdinand Panik, DaimlerChrysler s senior vice president, Fuel Cell Programs and president of XCELLSIS, claims that by 2020, a conservative prediction holds that at least 7 percent of new cars sold in the world will be FCVs. His optimistic estimate is a 20 percent market share. In 1999, global sales of automobiles topped 56 million vehicles. Taking Dr. Panik s estimate, by 2020, 4.2 million to 12 million new fuel cell cars will be sold each year, based on new car sales of 60 million units per year. Ford Motor Company Chairman, William C. Ford, Jr., has apparently gone a step further, stating that the fuel cell could become the predominant automotive power source in 25 years.

Fuel cells have undergone astonishingly rapid development in the past several years, driven by the world s leading

METHANOL (CH_3OH) *— a convenient liquid fuel made from natural gas or renewable resources — is a leading candidate to provide the hydrogen necessary to power fuel cell vehicles, the next generation of automotive technology. The commercialization of methanol-powered fuel cells will offer practical, affordable, long-range electric vehicles with zero or near-zero emissions while retaining the convenience of an economical liquid fuel. By 2004 or sooner, fuel cells operating on methanol will power a variety of vehicles in the United States and worldwide.*

industrial giants, high-tech startups, universities, national laboratories and government agencies. In fact, fuel cells already provide clean, reliable, stationary electric power in hospitals, hotels, schools and computer centers in the United States, Europe and Japan. A host of smaller applications for fuel cells as battery replacements in consumer electronics like cellular phones and laptop computers will enter the marketplace in the next few years. Other promising markets include displacing highly-polluting, small two-cycle engines sold each year in nearly 8 million pieces of portable power equipment such as lawn mowers, chainsaws and leaf blowers. Perhaps the first large consumer introduction will be for residential power, allowing homeowners to back up or even bypass the electric utility grid. These are exciting and promising markets for fuel cells. However, since the vehicle market will be a dominant influence, this report focuses on the automotive sector.

AMI has prepared this second report to highlight the ongoing advances in methanol fuel cell technology, address economic and environmental questions about the use of methanol fuels and explore likely paths to achieving the promise of methanol fuel cell vehicles.

WHAT IS A FUEL CELL?

"WE BELIEVE [FUEL CELL] TECHNOLOGY HAS THE POSSIBILITY OF BECOMING MAIN STREET TECHNOLOGY, NOT NICHE TECHNOLOGY."

FIROZ RASUL, CHAIRMAN AND CEO
OF BALLARD POWER SYSTEMS
The Detroit News, November 30, 1999

A fuel cell reverses the process of electrolysis in which an electric current breaks down water into its constituent oxygen and hydrogen gases. In 1839, British scientist Sir William Robert Grove s discovery that hydrogen and oxygen gas can be recombined to produce water and electric current gave birth to the fuel cell.

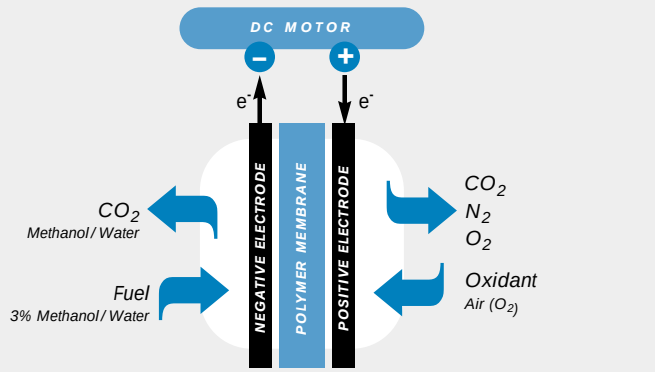
While there are several types of fuel cells, the proton exchange membrane or PEM fuel cell is the leading contender for vehicle applications. The PEM is a thin wafer-like material that allows hydrogen ions to pass through it. The membrane is coated on both sides with highly dispersed metal alloy particles (mostly platinum) that are active catalysts. Hydrogen is fed to the anode side of the fuel cell where the catalyst encourages the hydrogen atoms to release electrons and become hydrogen ions (protons) (see Figure 1).

The electrons travel in the form of an electric current that can be utilized before it returns to the cathode side of the fuel cell where oxygen has been fed. At the same time, the protons diffuse through the membrane to the cathode, where the hydrogen atom is recombined and reacted with oxygen to produce water, thus completing the overall process.

To produce a practical fuel cell, each thin wafer is stacked with others into an assembly that is carefully designed to allow for hydrogen to be supplied to the anode sides and oxygen to the cathode sides of each cell. The entire fuel cell unit also must manage spare heat produced by the process, and remove oxygen-depleted air and excess water. All fuel cells need hydrogen in some form. On vehicles, hydrogen can be stored as a cryogenic liquid or as a pressurized gas. But liquefying hydrogen to -253…C is expensive and highly energy-intensive, and storing this fuel on a vehicle is a difficult engineering task. Storing hydrogen as a

gas requires significant energy expenditure for compression, stringent safety precautions, and bulky, heavy storage tanks. Natural gas (methane or CH_4) is used as a hydrogen source in some fuel cell designs for large, stationary electricity generating stations. But it, too, presents many of the weight and space limitations of cryogenic liquefaction or compression when considering mobile applications.

FIGURE 1 • SCHEMATIC OF THE DIRECT METHANOL FUEL CELL



Source: Jet Propulsion Laboratory

Methanol emerges as an ideal hydrogen carrier for vehicles because it is liquid at room temperature and ambient pressure. Methanol is a simple molecule consisting of a single carbon atom linked to three hydrogen atoms and one oxygen-hydrogen bond. Releasing the hydrogen bonds in a methanol molecule is easier to accomplish than with other liquid fuels. Moreover, methanol fuel contains no sulfur, which is a fuel-cell contaminant, has no carbon-to-carbon atomic bonds which are hard to break, and has the highest possible hydrogen-to-carbon ratio. In fact, a gallon of methanol fuel contains even more hydrogen than the same volume of cryogenic liquid hydrogen.

Operating at relatively low temperatures, a methanol steam reformer easily splits the methanol molecule to produce the hydrogen needed by the stack, which then generates electricity to power the vehicle. The presence of the reformer in this design has advantages and disadvantages. An advantage is that the reformer rapidly and efficiently delivers hydrogen to the fuel cell from a liquid fuel that is easy to distribute and store on the vehicle. The disadvantage is that the reformer may produce trace emissions as it burns some of the methanol and hydrogen to provide the necessary heat of reaction. Moreover, the reformer adds weight, complexity and cost to the overall system.

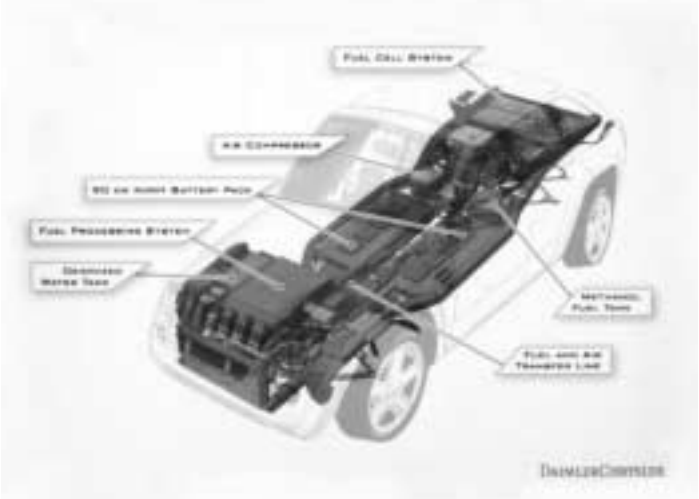
Gasoline also can be used as a hydrogen source in a PEM fuel cell; however, the commercial development of this technology is less advanced than the methanol steam reformer PEM. It will require a very low- or no-sulfur fuel, with low aromatics that is not yet commercially available. The process by which this very low-sulfur, gasoline-like hydrocarbon fuel is broken down to feed into the fuel cell is referred to as partial oxidation (POX). POX systems operate at much higher temperatures than steam-reforming and are less fuel-efficient. POX systems may have the advantage of being fuel flexible, that is, capable of operating on a variety of fuels such as gasoline, methanol, ethanol or natural gas. A POX system designed as a multi-fuel processor will produce high levels of carbon monoxide (CO), requiring the use of a large-scale gas clean up system adding to the overall system s complexity, weight and cost. A methanol-fueled POX system would be far simpler, operating at a lower temperature and producing less CO. While the hydrocarbon POX system is still being developed in the laboratory, the methanol steam reformer PEM fuel cell has demonstrated its potential in on-the-road prototype vehicles, and is likely to be on board the first commercial fuel cell vehicles.

Researchers at NASA s Jet Propulsion Laboratory in Pasadena, CA; the University of Southern California; the California Institute of Technology; Los Alamos National Laboratory, and other institutions are developing direct methanol fuel cell (DMFC) technology. No reformer is needed in this fuel cell methanol is injected directly to the cell s anode. There, the liquid methanol reacts to form electricity and carbon dioxide. Companies such as DaimlerChrysler, Ballard Power Systems, Giner Inc., Motorola, Manhattan Scientifics, and Energy Ventures, Inc. (EVI) have completed preliminary stages of research, development and demonstration of DMFC technology.

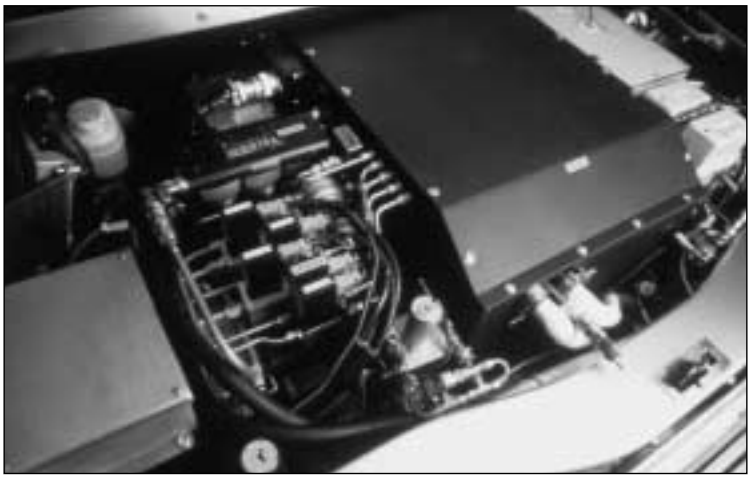
Much progress has been made with miniature fuel cells for a range of small consumer applications such as cellular phones and laptop computers and portable power equip-

ment such as lawnmowers and leaf blowers. Commercialization of miniature fuel cells is predicted to take place in 2001 or 2002. Motorola researchers have developed a miniature fuel cell that could power a wireless phone for more than a month and keep a laptop running for 20 hours. The fuel cell runs on less than one ounce of liquid methanol stored in small plastic canisters similar to those used for fountain pens. The mini-cells measure about one inch square and less than one-tenth of an inch in thickness, and will likely be comparable in cost to traditional rechargeable batteries. The benefits of increased energy density (power for several days rather than several hours), and eliminated time spent recharging portable electronic devices will be extremely attractive to the consumer. Motorola and other companies manufacturing small fuel cells can be expected to conduct intense education and outreach to help raise awareness and drive consumer demand for methanol fuel cells, which will spill over into numerous market applications.

FIGURE 2 • JEEP COMMANDER 2 FUEL CELL SYSTEM



The DMFC vehicle will eliminate emissions of nitrogen oxide (NO_x) and hydrocarbons, making it a true zero emission vehicle, under standards set by the California Air Resources Board (CARB). The DMFC offers other significant benefits due to its inherent simplicity. Eliminating the need to include a steam reformer and its associated controls will reduce vehicle weight and costs and thereby further improve fuel economy. The great potential of the DMFC is yet another good reason for early FCVs to be designed for methanol, eliminating the need for a second fuel transition.



The challenges facing PEM fuel cell developers are threefold: 1) Reduce the cost to build the electrode plates; 2) Reduce the amount of expensive platinum used as a catalyst; and 3) Design a cheap and effective membrane. Enormous progress has been made in each area. A few years ago, the fuel cell stack only one part of the fuel cell power system (see Figure 2) cost a prohibitive $5,000 per kilowatt (kW). The entire fuel cell system cost (fuel cell stack, reformer and associated controls) has now been reduced to $300 per kW (based on mass production economies), and developers are targeting full power system costs in the range of $50 per kW with high-volume production. A 50-kW power system for a vehicle would cost about $2,500, similar to the cost for today s internal combustion engine (ICE). The key to reducing the price of a fuel cell system is to reduce the costs of the subsystems.

Ballard Power Systems has led the way, reducing plate costs from $100 per plate to about $1. According to a report by Arthur D. Little, 99.99 percent pure materials (high purity specialized graphite) used for the bipolar plates may cost as little as $1.75 to $2 per pound, drastically reducing overall costs. Working with Johnson Matthey, Ballard Power Systems has curbed its platinum usage to roughly the cost of catalyst used in the catalytic converters

found in today s cars. The major manufacturer of membranes, DuPont, has announced that future membranes will cost no more than $10 per square-foot when large production volumes are achieved, stating that the price could drop to nearly $5 per square-foot.

Many of the challenges facing reformer developers are being met with equal zeal. From a cold start, reformers need to produce hydrogen quickly. Tremendous progress has been made in this area. For example, a few years ago Johnson Matthey s HotSpot methanol reformer achieved start-up times of 20 seconds for 50 percent hydrogen production, and full production in only 50 seconds. This fuel processor system was also highly efficient, releasing 89 percent of the hydrogen contained in the methanol fuel. Additional progress has been made since. XCELLSIS engineers have reduced the weight and volume of the complete methanol reformer system, increasing process efficiency.

WHO IS DEVELOPING METHANOL FUEL CELL VEHICLES?

"FUEL CELL VEHICLES WILL PROBABLY OVERTAKE GASOLINE-POWERED CARS IN THE NEXT 20 TO 30 YEARS."

TAKEO FUKUI, MANAGING DIRECTOR OF RESEARCH AND DEVELOPMENT, HONDA MOTOR CO.
Bloomberg News, June 5, 1999

Many automotive manufacturers are racing to be the first to bring a fuel cell vehicle to the marketplace. Automakers and component suppliers are spending billions of dollars to drive fuel cell technology toward commercialization. Some are concentrating on using pure hydrogen, while others are trying to find ways to use gasoline-like hydrocarbons. The non-hydrogen fuel choice that is the most advanced technically, has the most potential, and likely will be used in the first commercial vehicles is methanol, either reformed into hydrogen on-board the vehicle or used directly in the fuel cell.

MFCVs offer virtually all the environmental benefits of battery electric vehicles (EVs), while retaining the performance and range of today s internal combustion engine (ICE), and the convenience of filling up with a liquid fuel without the energy security risks of further dependence on foreign sources of crude oil. The energy efficiency of fuel cells also makes them an attractive alternative for automakers. Several studies have modeled the potential energy efficiency of FCVs. Argonne National Laboratory estimates that MFCVs will achieve a fuel economy 2.1 to 2.6 times greater than an ICE car. The Pembina Institute for Appropriate Technology assumes that MFCVs will achieve efficiencies of 1.76 times that of a gasoline ICE. For purposes of this report, we will rely on the fuel economy estimate of 1.74 times that of a gasoline ICE prepared by (S+T)2 for the Methanex Corporation (found at *www.methanex.com*).

The U.S. Environmental Protection Agency s (EPA) 1999 assessment of automobile fuel efficiency shows that overall fuel economy for passenger vehicles (the average for cars and light-duty trucks combined) was 23.8 mpg, the

lowest since 1980 and six-tenths of a mile-per-gallon lower than in 1998. The fuel economy for the entire U.S. fleet of new vehicles has been declining in recent years as light trucks and SUVs gain a greater market share. In its Reference Case, the U.S. Energy Information Administration s (EIA) Annual Energy Outlook 2000 projects that new fuel economy will grow to 31.4 mpg by 2010. We can therefore assume that the fuel economy of the gasoline ICE will improve to 32 mpg by 2010. Assuming a MFCV fuel economy of 1.74 times that of a gasoline ICE in 2010, the MFCV will achieve over 55 mpg gasoline gallon equivalent.

Innovative changes in vehicle design and materials to reduce vehicle weight and improve aerodynamics will benefit FCVs as well as conventional vehicles. For this reason the public/private Partnership for a New Generation of Vehicles (PNGV) anticipates that a fuel cell vehicle comparable to today s Ford Taurus or Chevrolet Lumina will achieve nearly 80 miles per gasoline-equivalent gallon.

The MFCV also will offer some unexpected benefits in terms of portable power. With 75,000 watts plus of electric power, a MFCV will be a portable energy plant providing 10 to 15 times more output than portable gasoline generators, that retail for $1,000 to $1,400 and have rated capacities of 5,000 to 6,500 watts (or more than $200 per kW). Vehicles equipped with DC/AC inverters may provide abundant power for camping, construction sites and other activities. Companies such as Freightliner, BMW and International Fuel Cells are working on using fuel cells as auxiliary power units (APUs) in trucks and cars. This technology allows automakers to offer vehicles with additional features. For instance, the air conditioning system can be run while the car is parked and the engine switched off to produce no emissions. Tractor-trailer rigs could protect cargo while stopped for extended periods using the power generated from a fuel cell, rather than running the diesel engine. If hurricanes, ice storms, thunder-storms or tornadoes have downed power lines, it would even be possible to run many homes from a properly equipped fuel cell car.

The automotive industry is now moving fuel cell technology from the laboratory to the street, by introducing a list of prototype vehicles. Table 1 lists the demonstrations to date from the major automobile manufacturers.

TABLE 1 • PROTOTYPE FUEL CELL VEHICLE INTRODUCTION

AUTOMAKER/VEHICLE TYPE	YEAR SHOWN	FUEL TYPE
BMW		
Series 7 Sedan	In development	hydrogen
DAIMLERCHRYSLER		
NECAR (van)	1993	gaseous hydrogen
NECAR 2 (mini-van)	1995	gaseous hydrogen
NECAR 3 (A-class)	1997	liquid methanol
NECAR 4 (A-class)	1999	liquid hydrogen
Jeep Commander 2 (SUV)	2000	methanol
NECAR 5 (A-class)	2000	liquid methanol
FORD MOTOR COMPANY		
P2000 HFC (sedan)	1999	hydrogen
TH!NK FC5	2000	methanol
GENERAL MOTORS/OPEL		
Zafira (mini-van)	1998	methanol
Precept	2000	hydrogen
HONDA		
FCX-V1	1999	hydrogen
FCX-V2	1999	methanol
MAZDA		
Demio (compact car)	1997	hydrogen (stored in a metal hydride)
NISSAN		
R'nessa (SUV)	1999	methanol
RENAULT		
FEVER (station wagon)	1997	liquid hydrogen
Laguna Estate	1998	liquid hydrogen
TOYOTA		
RAV 4 FCEV (SUV)	1996	hydrogen (stored in a metal hydride)
RAV 4 FCEV (SUV)	1997	methanol

In 1997, DaimlerChrysler displayed a prototype MFCV the compact NECAR 3, that featured a 50-kW methanol-powered fuel cell that ran the car and all standard features for passenger comfort. Earlier versions the NECAR 1 and

NECAR 2 were fueled by gaseous hydrogen stored in bulky high-pressure cylinders, as is Daimler s fuel cell-powered transit bus called the NEBUS. Daimler used vans for its first two FCVs, while the space-saving features of liquid methanol fuel allowed the automaker to produce the NECAR 3 as its smallest passenger car. The NECAR 4, demonstrated in late 1999, uses liquefied hydrogen at -253¡C. The NECAR 4 s fuel cell equipment is located in the floor, leaving passenger and cargo space intact or unaffected. The car goes 280 miles before refueling, travels up to 90 miles-per-hour and emits water vapor as exhaust.

DaimlerChrysler introduced the NECAR 5 in November 2000, a MFCV that is expected to serve as the pre-production prototype. The company characterizes the present status of the fuel cell drive as fit for practical use. NECAR 5 is the first vehicle in which the entire fuel cell system with methanol reformer has been accommodated within the underbody of the Mercedes-Benz A-Class compact car. The vehicle uses a Ballard *Mark 900* fuel cell, and can carry five passengers and their luggage, to over 90 miles per hour.

DaimlerChrysler has not set sales targets for the car, but is expected to introduce a few thousand units in 2004, with production increasing to between 50,000 and 100,000 units annually by the end of the decade. Generally, it is believed that with production volumes of greater than 100,000 vehicles each year, FCVs will become cost-competitive with traditional internal combustion cars.

In 1998, DaimlerChrysler unveiled a fuel cell concept vehicle based on the Jeep Commander, with the original goal of having a fuel cell/battery hybrid engine that utilized gasoline as its fuel. Since then, DaimlerChrysler has put gasoline reformer technology on the back burner and is pursuing methanol and direct-hydrogen systems more vigorously. The company unveiled a working methanol hybrid fuel cell system in the Jeep Commander 2 in October 2000. The Jeep Commander 2, the first fully-functional fuel cell vehicle from the Chrysler Group, supplements it s peak power output with an onboard battery pack.

Also in November 2000, DaimlerChrysler, along with Ballard Power Systems, demonstrated a DMFC prototype one-person vehicle. The small three-kilowatt system is the result of an ongoing collaboration between the research groups of DaimlerChrysler and Ballard.

Mazda Motor Corporation is joining DaimlerChrysler Japan Holding Ltd. and Nippon Mitsubishi Oil Co., Ltd., in a government-supported project to demonstrate MFCVs. Daimler and Mazda will provide one car each for test runs, and Nippon Mitsubishi will provide the fuel needed for the tests. The project will cost more than 1 billion yen (US $9.3 million) and is expected to receive between 200 and 300 million yen (between US$1.8 and $2.8 million) in support from Japan's Ministry of International Trade and Industry.

Early in 2000, Ford unveiled the TH!NK FC5, a family-size sedan powered by XCELLSIS s latest methanol reformer fuel cell electric powertrain. Ballard s *Mark 900* fuel cell stack powering the FC5 is designed for manufacturing in automotive production volumes and is significantly more powerful than any previous PEM fuel cell, generating 75-kW of power. It occupies half the space of Ballard's previous fuel cell, the *Mark 700*, and weighs about 30 percent less. Based on the 2000 Ford Focus, the TH!NK FC5 s fuel cell powertrain is located beneath the vehicle floor, so it doesn t compromise passenger and cargo space.

Prior to the TH!NK FC5, Ford introduced the P2000 FCV operating on hydrogen. Ford is also developing the P2000 SUV concept, a vehicle that features a fuel cell

THE CALIFORNIA FUEL CELL PARTNERSHIP

The California Fuel Cell Partnership (CFCP) includes auto manufacturers DaimlerChrysler, Ford Motor Co., Honda, Hyundai, Nissan, Volkswagen, General Motors and Toyota; energy providers BP, Shell, Texaco and Methanex (as an associate member); fuel cell companies Ballard Power Systems and International Fuel Cells; and governmental agencies CARB, California Energy Commission (CEC), South Coast Air Quality Management District (SCAQMD), DOE and the U.S. Department of Transportation (DOT). The Partnership will place nearly 70 fuel cell passenger cars and buses on the road between 2000 and 2003. In addition to testing the fuel cell vehicles, the Partnership will identify fuel infrastructure issues and prepare the California market for this new technology. CFCP will focus on the use of hydrogen and methanol in its fleet of fuel cell demonstration vehicles.

engine with a methanol reformer. In October 2000, Ford debuted the world s first production-prototype direct-hydrogen fuel cell vehicle the Ford Focus FCV. The automaker plans to put up to 50 fuel cell vehicles on the road between 2000 and 2003.

While Toyota remains fuel neutral, the company has showcased a prototype MFCV based on the popular RAV4 SUV, with a range of 500 kilometers (310 miles). Toyota s fuel cell RAV4 employs a 25-kW fuel cell that works in conjunction with a downsized electric vehicle battery pack. The batteries are constantly recharged from the fuel cell. Regenerative braking provides additional electric power to charge the batteries. Toyota s design draws extra power from the batteries to supplement the fuel cell during acceleration. The batteries also enhance the vehicle by providing instant power, avoiding the short warm-up that prototype fuel cell reformers require to reach maximum power output. Due to its high fuel economy, Toyota believes that once in production, the fuel cost to the consumer will be half that of conventional gasoline vehicles, and it is likely this estimated cost will decline even further with improved design and manufacturing experience.

Through its German subsidiary, Opel, General Motors Corp. (GMC) introduced a methanol fuel cell-powered car in 1998, based on the Zafira. The car is a four-seater, with a 50-kW electric motor. GMC is focusing much of its fuel cell research and development at Opel s Global Alternative Propulsion Center in Germany. In March of 2000, Opel unveiled the latest version of the Zafira, running on hydrogen. Powered by its seventh-generation fuel cell system, the Zafira now achieves full power nearly 12-times faster in freezing conditions than its predecessor. Opel also announced that the Zafira was chosen to be the marathon pace vehicle at the 2000 Olympics in Sydney, Australia.

In November 2000, General Motors displayed the HydroGen1, its latest road-going hydrogen-powered fuel cell vehicle. The HydroGen1 is a five-seat concept vehicle, based on Opel s Zafira compact van. Its hydrogen-fueled fuel cell unit powers a 75-horsepower electric motor that attains speeds of nearly 90 miles per hour and a range of about 250 miles per tank of hydrogen.

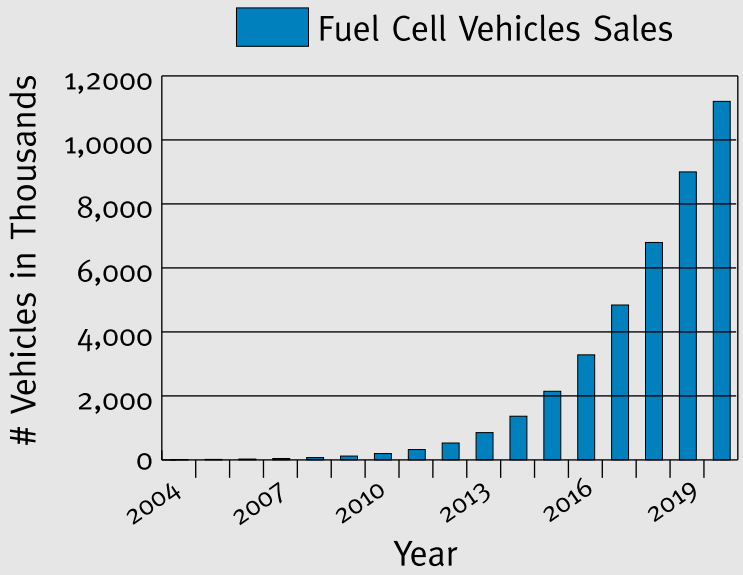
GMC announced plans to begin high-volume production of fuel cell vehicles before 2010, initially planning to use gaseous hydrogen in its fuel cell vehicles. To speed up the innovation process, GMC has teamed up with Toyota Motor Corporation and Giner, Inc., a research and development firm with extensive experience in developing direct methanol and other fuel cell technologies.

Germany s Volkswagen has developed a MFCV in partnership with Johnson Matthey (United Kingdom), Volvo (Sweden), and the Energy Research Foundation Netherlands ECN, supported by the European Union. In November 2000, Volkswagen showed its fuel cell vehicle, the Bora HyMotion, based on the popular Jetta. The HyMotion runs on liquified hydrogen.

Honda has introduced two fuel cell cars the FCX-V1 and FCX-V2. The V2 has a 60-kW PEM fuel cell and a methanol reformer, both built by Honda. The automaker plans to build 300 fuel cell-powered vehicles a year beginning in 2003 for sale in Japan and the United States.

Nissan is testing a fuel cell/battery hybrid vehicle first

TABLE 2 • PROJECTED GROWTH IN ANNUAL GLOBAL



shown in Japan in May 2000. The car, based on the Xterra SUV, features a PEM fuel cell using a methanol-reformer and lithium-ion batteries. The vehicle is able to switch between fuel cell power and battery power while in operation. Nissan and Suzuki have joined a government-sponsored project to develop DMFCs for vehicles that is expected to result in a prototype vehicle by 2003.

Georgetown University of Washington, DC has been a leader in the demonstration and development of methanol fuel cells for transit buses, supported by the U.S. Federal Transit Administration (FTA) and the Department of Energy (DOE). In 1994 and 1995, Georgetown rolled out three 30-foot buses that were the world s first fuel cell vehicles capable of operating on liquid fuels. In 1999, Georgetown unveiled a methanol-fueled, prototype 40-foot transit bus using a 100-kW phosphoric acid fuel cell from International Fuel Cells. Early in 2000, XCELLSIS built a 100-kW PEM fuel cell, powered by a Ballard fuel cell, for another full-size methanol-fueled bus. This is the largest liquid-fueled PEM fuel cell built to date, using a low-temperature steam reformer and a selective oxidizer (SelOx) to achieve acceptable levels of CO.

These are hybrid buses, using batteries to provide surge power and as storage for electricity created by regenerative braking. The use of methanol fuel gives them a range comparable to diesel buses, and they can be refueled as easily and quickly. The buses are expected to have virtually no emissions of nitrogen oxides (NO_x, an ozone precursor) and particulate matter (PM or soot), less than one-tenth the hydrocarbon emissions, and only 2 percent of the CO emissions of the cleanest compressed natural gas (CNG) buses on the road.

It is projected that the total number of vehicles worldwide will increase from 600 million today to 1 billion between the years 2015 and 2020. The introduction of large numbers of low-emission, energy-efficient MFCVs is not only needed, but well within reach. There have been several attempts to estimate the future market penetration of FCVs. The DOE has estimated that FCVs will account for 1.3 percent of the new car market in 2010, and 8.24 percent in 2020. The Japanese Institute of Energy Economics estimates that the share of new car sales for FCVs in Japan will increase rapidly from 0.1 percent in 2010 to 33.5 percent in 2020.

For purposes of this report, we will assume that in the first year of commercial sales (2004) 9,950 MFCVs will be sold (see Table 2), representing 0.02 percent of global sales of new cars (60,000,000 total). By 2010, market penetration increases to .33 percent or 197,765. By this time, the global fleet of MFCVs approaches one half million. In year 17 (2020), market penetration increases to 18.67 percent, or 11,204,268 million vehicles. At this time, the cumulative worldwide fleet of

WHAT ARE THE SAFETY AND HEALTH IMPACTS OF METHANOL FUEL USE?

"METHANOL IMPROVES THE PERFORMANCE OF THE CARS BECAUSE OF ITS HIGH OCTANE, BUT THAT'S NOT WHY WE USE IT. WE USE IT BECAUSE IT IS SAFER. IT GREATLY REDUCES THE RISK OF FIRE."

WILLIAM PHIL CASEY, TECHNICAL DIRECTOR OF THE INDY RACING LEAGUE

July 2000

Methanol has been the fuel of choice for the Indianapolis 500 since the mid-1960s, not only because it is environmentally sound and achieves high performance, but because it is also one of the safest fuels available.

Using methanol greatly reduces the risk of fire. In the United States, there are over 180,000 vehicle fires each year in which gasoline is the first material to ignite. A switch to methanol could reduce this to 18,000 vehicle fires, saving 720 lives, preventing nearly 3,900 serious injuries and eliminating property losses of millions of dollars a year (see Table 3). Pure methanol (M-100) is much harder to ignite than gasoline and burns at a much slower rate about 60 percent slower. Methanol also burns much cooler, releasing energy at one-fifth the rate of burning gasoline. Under bright daylight conditions methanol does burn with an invisible flame, however, fuel related fires typically combust some type of material from the vehicle that will impart color to the flame. Unlike gasoline fires, methanol fires can be extinguished simply and quickly by dousing them with water. For these reasons, methanol is a much safer fuel to use in a vehicle.

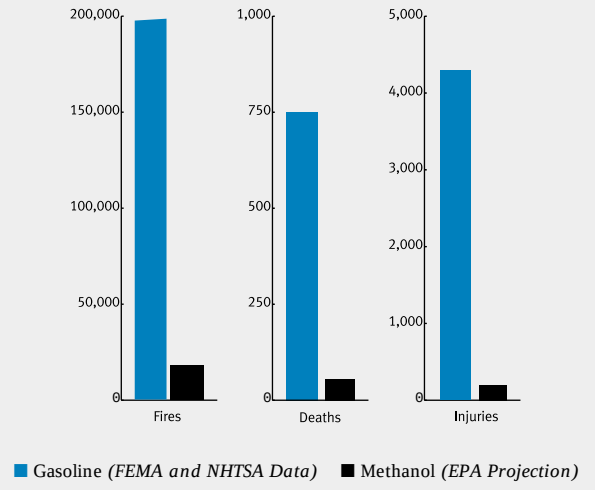
All motor fuels are poisonous and should be handled with care. Similar careful handling procedures used for gasoline and other fuels should be observed for methanol. There are three ways humans come in contact with fuels: by skin absorption, inhalation and ingestion. When in contact with skin, methanol will feel cool, and any affected areas should be washed thoroughly with soap and water. Since the EPA classifies gasoline vapors as a probable human carcinogen, long-term exposure to gasoline vapors is more hazardous than exposure to methanol vapors.

Methanol, like gasoline or diesel fuels, should never be

ingested. Deaths have been reported from intake of as little as 13 ml. of gasoline (less than one ounce). More often the untreated fatal range of ingestion is 120-300 ml. (4-10 ounces). Methanol is slightly more toxic than gasoline with a fatal dose range of 25-90 ml. (0.8-3 ounces).

According to key findings of a methanol hazard assessment by the Environ Corporation, there is no evidence to indicate, nor reason to believe, that it would be carcinogenic. These findings were supported by the 1999 study, Evaluation of the Fate and Transport of Methanol in the Environment, prepared by the environmental engineering firm Malcolm Pirnie, which found that methanol is less toxic to humans than gasoline, and is neither mutagenic nor carcinogenic.

TABLE 3 • FUEL-RELATED VEHICLE FIRES, DEATHS, INJURIES



Human bodies contain methanol naturally, and it is found in many parts of our diet, including fresh fruit, vegetables and fermented foods and beverages. The body even makes methanol from Aspartame-sweetened diet beverages. In fact, studies suggest that more methanol is generated from drinking a can of diet soda than from exposure to vapors from a half dozen fill-ups of a MFCV at a self-service pump. But make no mistake, methanol, like gasoline, can be toxic if ingested and should be handled

THE HEALTH EFFECTS INSTITUTE

The Health Effects Institute (HEI), an independent, nonprofit corporation, provides research findings on the health effects of a variety of pollutants. To determine whether exposure to methanol vapors could have adverse health impacts, HEI conducted several studies, using primates and their infant offspring, pregnant and non-pregnant rodents and humans. Each study proved that methanol inhalation has no detectable effect on the respective subject. In the human study, researchers exposed 12 young male volunteers to either filtered air or methanol vapors (192 parts-per-million) for 75 minutes. This concentration of methanol is estimated to approach the highest concentration that individuals might experience from normal use of methanol-fueled vehicles under a worst-case scenario. The volunteers underwent 20 commonly used tests of sensory, behavioral and reasoning performance before, during and after each exposure. They found that methanol had no detectable effect on the subject's performance for most tests. Performance was slightly impaired in two tests, but the effects observed were minor and within the range of test values for subjects exposed to air. HEI's primate studies concluded that exposure to methanol posed no risk for reproductive or developmental effects.

WHY IS METHANOL NOT THE SAME AS MTBE?

METHANOL IS UBIQUITOUS IN NATURE SINCE IT IS PRODUCED BY MICROORGANISMS RESPONSIBLE FOR COMPLEX HYDROCARBON BIODEGRADATION. IN CONTRAST, MTBE IS A XENOBIOTIC OR MAN-MADE COMPOUND. AS A RESULT, METHANOL IS EASILY AND QUICKLY DEGRADED IN THE ENVIRONMENT BY A DIVERSE RANGE OF MICROORGANISMS UNDER MOST ENVIRONMENTAL CONDITIONS.

Methanol has been widely used as an industrial chemical since the nineteenth century. Currently, methanol is used as feedstock for the production of commonly used organic compounds including formaldehyde, acetic acid and MTBE. In addition, it is heavily used as a solvent in paint strippers, plastics, plywoods and in automobile windshield washer solutions. Since 1965, methanol has also been used as a fuel, most commonly as M-85, a blend consisting of 85 percent methanol and 15 percent unleaded gasoline. Programs to demonstrate the feasibility of using M-85 as an alternative to conventional gasoline have successfully taken place over the last 20 years, most notably in California. In 1990, requirements to ensure that new underground storage tanks were compatible with either gasoline or methanol were established by Congress.

Contrary to methanol s diverse applications over the decades, MTBE s use has been mostly limited to the fuel industry. MTBE was initially added to gasoline in low quantities to replace lead as an octane enhancer in the late 1970s. In the United States, the addition of MTBE to gasoline significantly increased following the Clean Air Act (CAA) Amendments of 1990, which mandated the use of reformulated and oxygenated gasoline in certain urban regions to reduce air pollution from motor vehicles. Since then, almost all of the MTBE produced has been used to oxygenate gasoline.

Because methanol is used during the production of MTBE, there has been some concern expressed regarding a potential similarity in the behavior of both compounds in subsurface environments. In particular, there has been an interest in understanding whether the two different compounds can be expected to have similar impacts if

released into groundwater and drinking water supplies.

The fate and transport characteristics of methanol and MTBE in the environment, as with any chemical compound, are a strong function of the compound s chemical and physical properties. Both methanol and MTBE are highly soluble in water relative to the aromatic (e.g., benzene) and aliphatic (e.g., iso-pentane) components of gasoline (see Table 4). In addition, both compounds poorly adsorb to subsurface soil particles. However, this is where the similarity in the behavior of these two compounds in the environment ends.

TABLE 4 • WATER SOLUBILITY OF HYDROCARBON COMPOUNDS

Benzene[2] — 18
Toluene[2] — 25
MTBE[3] — 4,700
Methanol[4] — 791,400

[1] Solubility (mg/L) at 20¡C
[2] From conventional gasoline containing 1 percent benzene and 5 percent toluene
[3] From reformulated gasoline containing 11.1 percent MTBE
[4] Methanol s solubility in water is 100 percent so its solubility is equal to the density of methanol.

In contrast to MTBE, which is a highly branched molecule with a tertiary carbon structure and a molecular weight of 78 grams per mole, methanol has a simple straight-chain structure and a molecular weight of 32 grams per mole. In addition, methanol is ubiquitous in nature since it is produced by microorganisms responsible for complex hydrocarbon biodegradation. In contrast, MTBE is a xenobiotic or man-made compound. As a result, methanol is easily and quickly degraded in the environment by a diverse range of microorganisms under most environmental conditions (i.e., in the presence and absence of oxygen), that use methanol as a source of carbon and energy. Furthermore, due to its high solubility in water, methanol molecules are readily available to microorganisms, and a wide distribution of methanol-degraders has been documented as occurring naturally in the environment.

While MTBE has been shown to degrade in laboratory and field studies under controlled conditions, there are no compelling indications to date that the biodegradation of MTBE is occurring at significant rates in subsurface environments. As a result, if MTBE is accidentally released into subsurface environments, it can be expected to move at the speed of groundwater with little to no retardation. Methanol, however, can be expected to dissolve quickly leading to its dilution in groundwater, followed by its rapid biodegradation by subsurface microbial communities.

While the health effects of MTBE are not yet well understood, those associated with methanol have been well studied. Methanol s 8-hour occupational Threshold Limit Value (TLM) of 200 ppm (parts-per-million) is slightly lower than that of conventional gasoline (TLM of 300 ppm). An adult refueling with methanol at a service station may be exposed to a maximum vapor concentration of 38 ppm for 4 minutes, corresponding to an oral intake of 3 mg of methanol. To put this in perspective, drinking one can of diet soda containing Aspartame (10 percent of which is converted to methanol in the body) corresponds to an oral intake of 20 mg of methanol.

MTBE s taste and odor threshold limits are extremely low (<40 ppb or parts-per-billion) occasionally necessitating stringent clean-up levels during water treatment that are based on consumer acceptance rather than potential health effects. On the other hand, the odor detectability of methanol is relatively high and has been shown to vary from 100 to 6,000 ppm.

It is interesting to note that methanol is used in cars, even when they are not operated on methanol fuels. Almost 400 million gallons of methanol are used annually in windshield washer fluid that may consist of up to 50 percent methanol by volume. Methanol s use in windshield washer fluid is favorable due to its antifreeze properties, and because it is quickly diluted during wet weather minimizing its environmental impact.

It is also important to note that over 100 wastewater treatment plants in the United States currently use methanol as a carbon source to remove nitrate from water during the anaerobic denitrification of sewage. Reducing nitrate levels from wastewater treatment plant effluent helps protect sensitive aquifers. For example, the Blue Plains Wastewater Treatment plant, which serves the Washington, DC metropolitan area, injects roughly 14 million gallons of methanol each year to reduce nitrates and protect the sensitive Chesapeake Bay watershed.

HOW WILL METHANOL FUEL CELLS REDUCE URBAN AIR POLLUTION?

"IF THEY WORK, METHANOL FUEL CELLS COULD BE A MAJOR BREAKTHROUGH IN ENERGY CONSUMPTION AND CONSERVATION. THE BRAVE NEW TECHNOLOGY COULD DRASTICALLY CUT AIR POLLUTION FROM AUTO EMISSIONS AND OTHER SOURCES."

MICHAEL PARRISH, ENVIRONMENTAL NEWS NETWORK
December 30, 1999

Air pollution is associated with large metropolitan areas where many vehicles, homes and industries are found. In the United States, the principal pollutants regulated by the CAA and its amendments are CO, NO_x, volatile organic compounds (unburned hydrocarbons or VOCs), and PM. According to the EPA, over 113 million Americans live in areas not meeting National Ambient Air Quality Standards (NAAQS).

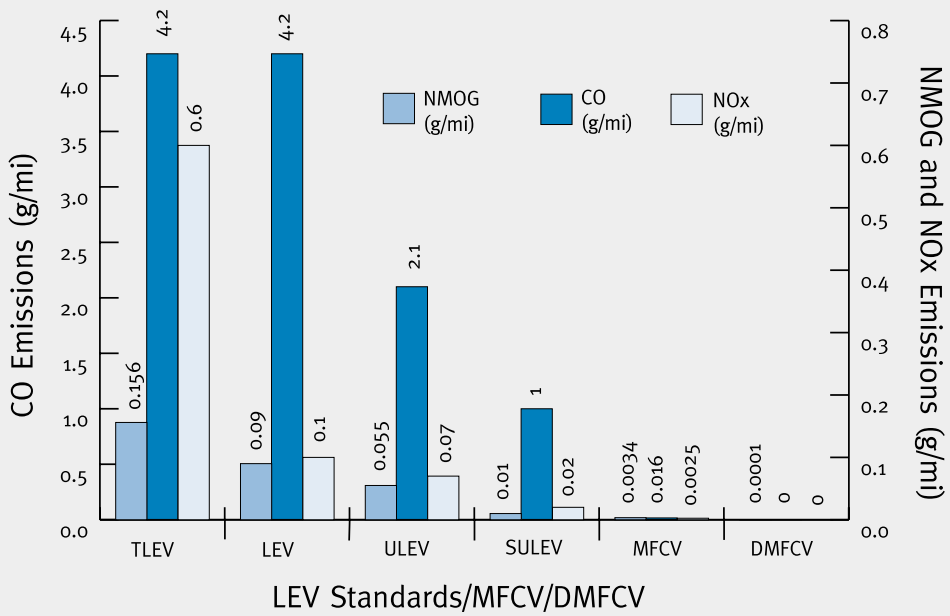
The MFC will all but eliminate these pollutants from vehicles (see Tables 5 & 6). A substantial benefit to air quality and the public health may be anticipated as a result. As can be seen in Table 5 by moving away from combustion, methanol fuel cell cars will emit a minuscule amount of the criteria pollutants described here.

Initial dynamometer emissions tests of NECAR 3 were extremely encouraging. Although the tests were conducted on a hot operating vehicle, and unfortunately too few for statistical extrapolation, they showed that the MFCV produced no NOx or CO emissions. Hydrocarbon emissions were 0.005 grams per mile, or one-half the Super Ultra Low Emission Vehicle (SULEV) limit set by the State of California.

The MFCV is an inherently clean vehicle. Even the cleanest gasoline ICE vehicle will not be as clean as a MFCV. The gasoline vehicle depends on elaborate control technologies and computerized diagnostics to maintain its level of emissions control. Since the MFCV relies on an electric drivetrain, it is feasible that the MFCV will not be required by states to have regular emissions testing.

In the absence of proper maintenance and sophisticated inspection or diagnostic procedures, the gasoline vehicle can enter a failure mode that may emit hundreds of times the legal limits of pollution. Over time, as the vehicle passes from one owner to another, it tends to be less well

TABLE 5 • URBAN SMOG FORMING EMISSIONS



Source: Evaluation of Fuel Cell Reformer Emissions, Acurex - CARB/SCAQMD, 1999; www.methanex.com

maintained, and its emissions increase. In contrast, the MFCV can pass from owner to owner and its pollution profile will remain very low: zero in some pollutant categories, close to zero in others.

Methanol has a much lower vapor pressure than gasoline with a Reid Vapor Pressure (RVP) of 4.63 pounds-per-square-inch (psi) as opposed to gasoline with an RVP of approximately 7-9 psi depending on exact composition. This implies that methanol will exhibit lower evaporative emissions when compared to gasoline. CARB recently commissioned a study by Arthur D. Little titled Refinement of Selected Fuel Cycle Emission Analyses. The draft final report found that methanol emissions from a bulk terminal with tank capacity of 50,000 barrels (bbl) and associated evaporative emissions controls would emit 0.0063 g of methanol per gallon of throughput. The report also concluded that NMOG (non-methane organic gases) emissions associated with methanol would be approximately 0.01 g/mile which is roughly equivalent to CEC's estimates of the NMOG emissions associated with a battery electric vehicle.

TABLE 6 • STEADY STATE TRANSIT BUS EMISSIONS

FUEL	POWER PLANT	HC	CO	NOX	PM
Diesel	DD Series 50*	0.10	0.90	4.70	0.04
CNG	DD Series 50	0.80	2.60	1.90	0.03
Diesel	Cummins C8.3	0.20	0.50	4.90	0.06
CNG	Cummins C8.3	0.10	1.00	2.60	0.01
Methanol	94 Fuji Fuel Cell	0.09	2.87	0.04	0.01
Methanol	98 IFC Fuel Cell**	<0.01	<0.02	n/a	n/a
96 Standards		1.30	15.50	5.00	0.05
98 Standards		1.30	15.50	4.00	0.05

*All emissions values in g/bhp-hr. * with converter ** IFC test results*

HOW WILL METHANOL FUEL CELL VEHICLES ADDRESS THE GREENHOUSE EFFECT?

"WE ARE CONVINCED THAT METHANOL IS A SUITABLE AND SAFE FUEL FOR THE FUEL CELL VEHICLES OF TOMORROW."

FINN KULAS, HEAD OF THE METHANOL DIVISION OF STATOIL
November 12, 1999

Global emissions of greenhouse gases (GHG) gases such as CO_2 and methane (CH_4) blamed for an increase in average world temperatures have been under increasing scrutiny during the last decade. In most industrialized nations, the transportation sector is a major source of GHG emissions.

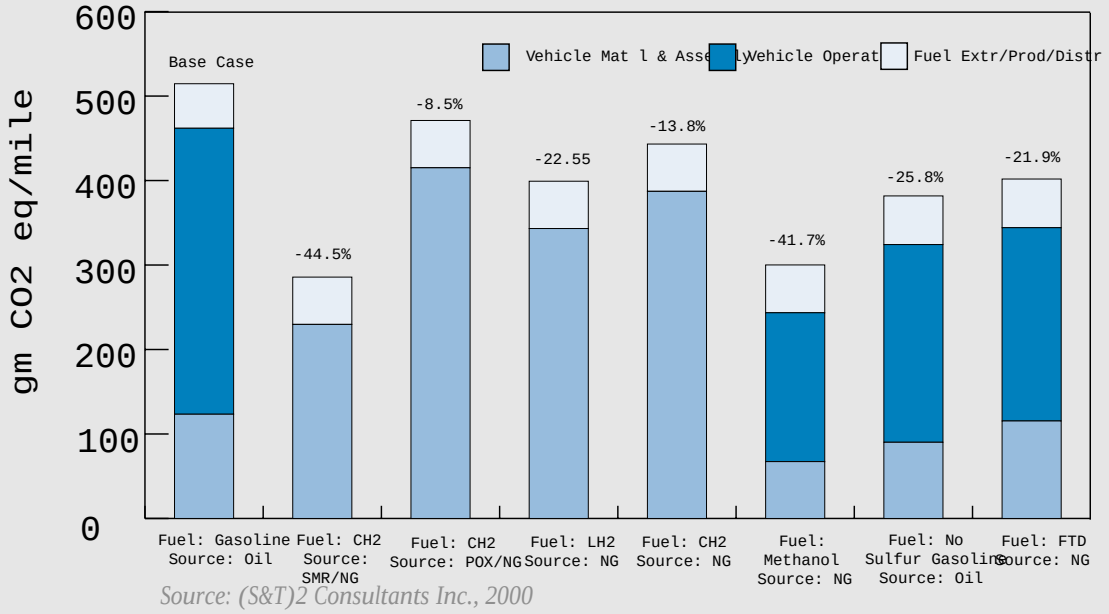
FCVs have the potential to substantially reduce GHGs in addition to virtually eliminating urban smog. The choice of fuel for the fuel cell can significantly impact the GHG benefit received. The study, Assessment of Emissions of Greenhouse Gases from Fuel Cell Vehicles, prepared by (S+T)2 Consultants for Methanex Corporation, found that decentralized steam reforming of natural gas to produce hydrogen at a service station provided the greatest CO_2 reductions (see Table 7). However, these plants are relatively large, expensive, may require skilled operators and may raise zoning concerns. And while there is an extensive natural gas distribution network in the United States, this is certainly not the case in many parts of the world. In countries without pipeline natural gas, methanol derived from natural gas offers the greatest CO_2 reductions. Of the liquid fuels considered for FCVs, methanol clearly provides the largest benefits for reducing GHG emissions, nearly twice that of low sulfur gasoline.

The methanol industry is very competitive, with increasing pressure to build larger, more efficient manufacturing plants. Existing methanol plants based on steam methanol reforming generally operate with an energy efficiency of nearly 65 percent. New plants using autothermal or combined reforming can achieve 70.3 percent (low heating value or LHV) to 72.1 percent (high heating value or HHV) efficiency. Future technology is expected to improve upon efficiency even further, with

expected energy efficiencies of 71.7 percent LHV and 73.5 percent HHV.

Looking ahead to 2020, we can envision a global fleet of 40 million MFCVs. We expect the total well-to-wheel CO_2 emissions from a MFCV to be 243.5 grams per equivalent mile, versus 461.9 grams per equivalent mile for a gasoline ICE car. Assuming that each car is driven 12,000 miles per year, the annual CO_2 emission reductions from the global fleet of MFCVs would reach a staggering 104 million metric tons.

TABLE 7 • WELL-TO-WHEEL GREENHOUSE GAS EMISSIONS



Source: (S&T)2 Consultants Inc., 2000

HOW WILL METHANOL FUEL CELL USE ADDRESS WATER POLLUTION?

"OUR STUDY ON THE FATE AND TRANSPORT OF METHANOL IN THE ENVIRONMENT SHOWED THAT, RELATIVE TO GASOLINE AND ITS CONSTITUENTS LIKE BENZENE, METHANOL WILL LIKELY HAVE FAR FEWER ADVERSE IMPACTS ON THE ENVIRONMENT."

DR. MICHAEL C. KAVANAUGH, P.E., VICE PRESIDENT OF MALCOLM PIRNIE

January 29, 1999

The MFCV, in addition to lowering harmful emissions into the atmosphere, will also prove to be a major advancement toward improved protection of water quality on land and in the ocean.

Methanol is intrinsically less damaging to the environment. No one would argue that the accidental release of methanol into the environment would be a good thing, but it would cause much less damage than similar oil or gasoline spills. Methanol is easily biodegradable in aerobic and anaerobic environments. Methanol is used in the final stage of municipal sewage treatment processes before the wastewater is discharged into sensitive oceans and rivers. This denitrification process prevents nitrates from building up in streams and rivers. Nutrient loading in lakes, streams, rivers and oceans can lead to excessive algae and plant growth that subsequently kill fish and place unnecessary pressure on aquatic and marine ecosystems. Currently, more than 100 sewage treatment plants in the United States use methanol for wastewater treatment.

According to the study, Evaluation of the Fate and Transport of Methanol in the Environment, prepared by Malcolm Pirnie, researchers reviewed the chemical and physical properties of methanol and then examined the fate of methanol in the environment under several potential release scenarios, such as surface water spills or leaks from underground storage tanks. It concluded that a large methanol spill into surface water would have some immediate effects on the biota in the direct vicinity of the spill. However, in contrast to a crude oil spill, as methanol rapidly dissipates into the environment, it reaches low concentration levels where biodegradation will occur quickly. Methanol is significantly less toxic to marine life than crude oil or gasoline, and many of the effects of short-

term exposure are temporary and reversible. The Office of Pollution Prevention and Toxics (OPPT) indicated that methanol is essentially non-toxic to the four aquatic fish species that were tested. The study found that in the event of a spill, methanol concentrations will be benign to surrounding organisms in most cases and will be likely to biodegrade easily under a wide range of geochemical conditions.

Under another scenario, if methanol were to leak from an underground storage tank, rapid biodegradation is expected to occur under both aerobic and anaerobic subsurface conditions. Hazards from gasoline leaks are greater than those of methanol, because gasoline and many of its toxic constituents, such as benzene, biodegrade more slowly and will persist longer in the environment. The use of double-walled containment tanks and leak detection monitors greatly reduce the likelihood of methanol spills. Table 8 compares the estimated half-lives of methanol, benzene and MTBE in the environment and clearly shows the more rapid biodegradation of methanol in soil and water.

TABLE 8 • ENVIRONMENTAL HALF-LIVES

ENVIRONMENTAL MEDIUM	METHANOL	BENZENE	MTBE
Soil[1]	1–7 days	5–16 days	28–180 days
Air[2]	3–30 days	2–20 days	1–11 days
Surface Water[3]	1–7 days	5–16 days	28–180 days
Groundwater[4]	1-7 days	10–730 days	56–359 days

[1] *Based on unacclimated grab sample of aerobic/water suspension from groundwater aquifers.*
[2] *Based on photo-oxidation half-life.*
[3] *Based on unacclimated aqueous aerobic biodegradation.*
[4] *Based on unacclimated grab sample or aerobic/water suspension from groundwater aquifers.*

WHERE WILL I BUY METHANOL FUEL?

> "OUR PREFERRED FUEL IS NOW METHANOL. IT IS EASIER TO TRANSPORT AND WE ARE TALKING ABOUT INSTALLING THE INFRA-STRUCTURE WITH ALL THE MAJOR FUEL SUPPLIERS."
>
> KLAUS-DIETER VOEHRINGER, DAIMLERCHRYSLER
> *Financial Times, September 20, 1999*

Consumers have come to expect near universal availability of fuel for their automobiles. In the United States, nearly $100 billion in undepreciated capital is invested in the infrastructure to produce, refine, distribute and retail market motor fuels. Each year more than $10 billion is spent to maintain and upgrade this network of 200,000 retail gasoline stations and 30,000 diesel stations. Cars with methanol fuel cells would do little to change the regular routine of consumers at the filling station. A driver would simply stop at a pump and fill up with methanol rather than gasoline.

The existing wholesale methanol distribution infrastructure is relatively smaller, but well established and capable of delivering product to markets worldwide. Methanol distribution to the transportation sector would involve utilizing the existing gasoline distribution system by adding methanol-fueling capacity to retail gasoline outlets. The global distribution system includes significant maritime movements on vessels as large as 45,000 tons, and Methanex, the world leader in methanol production and marketing, has a new 100,000 dead weight ton (dwt) vessel, the Millennium Explorer. For delivery to inland locations, an extensive barge, rail car, and tanker truck network already exists to feed most locations in the United States, Europe and Japan. A major expansion of the system would be required if methanol fuel demand increased significantly.

In the late 1980s and early 1990s, the state of California built a network of nearly 100 public and private methanol refueling stations to service the public, publicly-owned and private fleets. The private and state-owned fleets comprised nearly 15,000 methanol-powered alternative fuel vehicles (AFVs). Additional methanol pumps were placed at energy stations across the country and in Canada. Based on calcula-

tions performed in Methanol Refueling Station Costs, a study prepared by EA Engineering, a nationwide methanol fueling retail system could be installed at 10 percent of the gasoline stations in the United States for less than $1 billion. This amounts to a fraction of the $13 billion spent by the oil industry to introduce reformulated gasoline (RFG) at stations throughout the country, or the $1.4 billion spent each year to upgrade the retail gasoline network.

Converting an existing double-walled gasoline underground storage tank to methanol use, and installing new piping and a dispenser is the lowest cost option for retail station conversion. An existing gasoline or diesel tank can be cleaned and a methanol dispensing system added for slightly less than $20,000. The capital cost for adding methanol capacity to an existing gasoline station by installing a new 10,000-gallon, double-walled, underground storage tank, piping and dispenser is about $62,400. Adding an aboveground storage tank, used by fleet operators and rural retail stations, costs roughly $54,500.

Fuel cell vehicle introduction will most likely focus initially on California with its requirement for the sale of zero-emission vehicles (ZEVs) by 2003 (and possibly New York, and Massachusetts which have or are adopting similar ZEV programs), as well as Germany and Japan. These highly populated areas are strong candidates because they tend to have higher levels of air pollution, and at the same time offer maximum scale efficiencies for the first wave of a methanol-fueling infrastructure. More customers for each fuel pump means lower cost in the crucial early phases of MFCV introduction. By simultaneously introducing their MFCVs in Germany and Japan as well as in the United States, global automotive companies will achieve higher production runs that will help lower costs.

As shown in Table 9, the cost of enabling 10 percent of the stations in target areas to dispense methanol would be less than $500 million. Converting even 25 percent of the stations in target areas would cost approximately $1.2 billion. Assuming that retailing stations are required to dispense methanol throughout the United States, Europe, Japan and Canada, the cost to convert 10 percent of the stations approaches $1.4 billion, and the cost to convert 25 percent of the stations is roughly $4.7 billion.

The participation of the oil industry would help facilitate the establishment of a methanol-fueling network. Although the costs of installing methanol storage and pumping facilities are relatively low, the costs for real estate, buildings and developing brand name recognition can be much higher. Today s drivers want the convenient availability they enjoy with gasoline. In 1998, Ford announced a strategic alliance with ExxonMobil Corporation to develop cleaner fuel and engine systems, including technology for fuel reformers. DaimlerChrysler entered into a similar alliance with Shell Oil to cooperate on fuel cell and reformer technology, and to evaluate Shell s catalytic POX technology that transforms conventional fuel into hydrogen-rich gas. DaimlerChrysler and Ford are working with oil companies including BP, ExxonMobil and Texaco to develop the filling-station infrastructure for FCVs. The DaimlerChrysler/Ford partnership is currently urging oil companies to consider installing liquid methanol pumps and tanks in their service stations. In addition, oil companies, automakers and the methanol industry are collaborating in the Methanol Specification Council, formed in 1999 to develop worldwide specifications for methanol fuel for use in FCVs.

In September 2000, DaimlerChrylser, British Petroleum (BP), BASF, Methanex Corporation, Statoil and XCELLSIS entered into a cooperative agreement to evaluate what would be needed to facilitate the introduction and commercialization of MFCVs. The goals are to establish a joint position after examining any health, safety, environmental

TABLE 9 • INSTALLATION COST* TO INFRASTRUCTURE

REGION	EXISTING STATIONS	25% OF STATIONS	50% OF STATIONS
California	11,700	59	146
New York	6,504	33	81
Massachusetts	2,600	13	33
Germany	17,632	88	220
Japan	59,990	300	750
SUBTOTAL	98,426	$493	$1,230
Canada	13,782	69	172
Remaining U. S.	167,088	835	2,089
Remaining Europe	100,212	501	1,253
TOTAL	281,082	$1,405	$4,744

** Assumes installation costs of $50,000 per station.* *Amounts in Millions*

HOW MUCH WILL I PAY FOR METHANOL FUEL?

"THE DIFFICULTY HERE IS THAT FUEL CELLS USE NOT HYDROCARBONS BUT HYDROGEN. AND HYDROGEN, BEING AN EXPLOSIVE GAS WITH A RIDICULOUSLY LOW BOILING POINT, IS HARD TO HANDLE ROUTINELY. YET, IT IS FAIRLY EASY TO MAKE IT 'ON THE FLY' FROM METHANOL. AND IT IS THIS CHEMICAL (WHICH IS A LIQUID AT ROOM TEMPERATURE) THAT DRIVERS WILL EVENTUALLY PUT IN THEIR TANKS."

"FUEL CELLS HIT THE ROAD"
The Economist, April 24, 1999

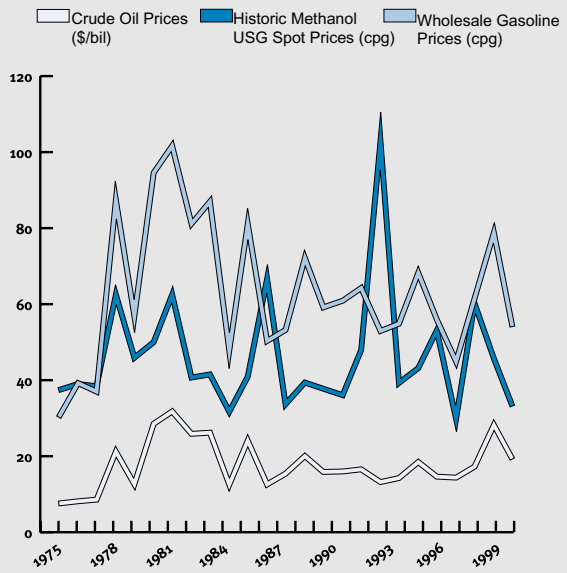
The future fuel cost of operating a MFCV cannot be determined precisely, but a relative sense can be inferred from past data. Historical price data can be used to calculate what it would cost to operate a MFCV, in comparison to a standard ICE vehicle getting 27.5 mpg using gasoline.

Since 1975, the average wholesale spot price for methanol has been 46 cents-per-gallon on a non-inflation adjusted basis. The cost structure of the methanol industry has been decreasing in real terms due to economies of scale achieved through the construction of larger, more efficient plants and the distribution of methanol in much larger seagoing vessels. New technologies such as jumbo methanol plants on a scale of 10,000 tons-per-day (the equivalent of 1.2 billion gallons per year), are extremely efficient and capable of producing at a forecasted bulk methanol price of approximately 30 cents-per-gallon that includes full capital cost recovery and a reasonable return for investors.

Table 10 compares methanol and gasoline pricing in the United States from 1975 to 2000. Methanol, like gasoline, has experienced pricing highs and lows, but it is clear from the data that on average, methanol is substantially cheaper per gallon than gasoline. To determine the potential pump price of methanol, assume the average cost to bring a gallon of methanol to the retail station includes the following: 10 cents for regional transportation and distribution, 4 cents for local distribution and 5 cents for the station owner, or an overall pre-tax cost of 19 cents. Then add 9.15 cents in federal tax, and 9 cents in state tax (for California). Based on the wholesale spot price of 30-45 cents-per-gallon for methanol, and the addition of other costs, the pump price may fall between 67-82 cents-per-gallon. While methanol

contains just one-half the energy of gasoline, because the fuel cell car has a fuel economy of 1.74-times greater than a gasoline ICE, the actual cost to the consumer to fuel a MFCV will be between 77-94 cents per gasoline-equivalent-gallon. At this price, methanol will be able to compete quite well with gasoline, and provide a significant return on investment to retailers converting pumps to methanol operation.

TABLE 10 • METHANOL AND GASOLINE PRICING



HOW MUCH METHANOL WILL BE NEEDED TO SERVE THE MARKET?

"IT IS ESTIMATED THAT THERE IS SUFFICIENT EXCESS CAPACITY FROM EXISTING METHANOL PLANTS AROUND THE WORLD TO SUPPORT A PRODUCTION RATE OF SEVERAL MILLION METHANOL-BASED FUEL CELL VEHICLES ANNUALLY. PERHAPS MORE IMPORTANTLY, IT LOOKS AS IF IT WOULD BE RELATIVELY INEXPENSIVE TO EXPAND PRODUCTION FOR METHANOL IN THE FUTURE."

ROBERT K. WINTERS, BEAR STEARNS

April 2000

In 2000, worldwide methanol production capacity stands at 12.5 billion gallons (37.5 million tons), with a utilization rate of just under 80 percent. The industry generates over $12 billion in annual economic activity, while creating over 100,000 direct and indirect jobs. Methanol and its derivatives are widely used in manufacturing products such as fiberboard used in home construction, Spandex fibers used in clothing, numerous plastics, windshield washer fluid and cleaner-burning gasoline. Typical plant sizes a decade ago were capable of producing 600,000 tons of methanol a year. Plants now coming on line can produce 1 million tons-per-year and planned jumbo plants may produce up to 3.5 billion tons-per-year within a decade. Methanol supply will not be limited, because the sources of methanol production are large, diverse, and in the long term, renewable.

Given the estimates of fuel cell vehicle market penetrations from Table 2, several assumptions about methanol fuel demand can be made. Under initial penetration assumptions, estimates reveal that by the year 2010, automakers will have introduced nearly 500,000 MFCVs. If each vehicle travels 12,000 miles annually, using 436 gallons of methanol (achieving 55 miles-per-gasoline-equivalent-gallon), overall demand would be 218 million gallons of methanol per annum, or less than 2 percent of current world capacity.

By 2020, the estimated global fleet of fuel cell vehicles jumps to 40 million vehicles, consuming 17.4 billion gallons of methanol exceeding current world capacity and requiring significant capital investment in new methanol production. Because large-scale methanol plants can be built within 24 to 30 months, adding the necessary capacity to meet this new demand in the 20-year time horizon can be accomplished easily.

Meeting the demand for the use of methanol as a transportation fuel will support plants using the most advanced technologies plants with greater than 70 percent energy efficiency and capable of capturing 10 percent more of the energy in methane than predecessor plants just 10 years older. Adding new production capacity will push the industry standard toward this new technology norm. Large new mega-methanol plants generating roughly 10,000 tons-per-day of methanol (enough to power about 2.6 million MFCVs annually) will benefit from economies of scale and are expected to cost less than $1 billion. Energy efficiency improvements will lower production costs still further.

Companies such as Methanex and Synetix have worked together closely to develop a new syngas generation technology for methanol production. The process is aimed at large-scale syngas production, and while it offers benefits for plant sizes of 1 million tons of methanol per year, the scalability of the equipment delivers significant advantages over competing technologies at plant scales of 2 million tons-per-year or larger. The Foster Wheeler Corporation has developed the Starchem methanol production process. This approach produces low purity methanol on a very large scale at low cost from remote and stranded gas resources, through integration of enriched air production, catalytic partial oxidation, methanol synthesis and purge-gas hydrogen recovery.

IS THERE ENOUGH NATURAL GAS?

THERE ARE VAST QUANTITIES OF INCONVENIENTLY LOCATED NATURAL GAS WORLDWIDE THAT MAKE DISTRIBUTION TO LOCAL ENERGY MARKETS UNECONOMICAL. HOWEVER, BY CONVERTING THE NATURAL GAS TO METHANOL, IT BECOMES POSSIBLE TO ACCESS THESE LARGE RESERVES FOR USE IN THE TRANSPORTATION SECTOR.

According to the EIA, global gas reserves have more than doubled over the past 20 years, outpacing the 62 percent growth in oil reserves. *Oil and Gas Journal* estimates proven world gas reserves as of January 1, 2000, at 5,146 trillion cubic feet. Under current reserve-to-production ratios, proven natural gas reserves worldwide should last for 63.4 years, compared with 41 years for oil. However, demand is expected to increase and new gas fields are being discovered regularly. This makes prediction of recoverable reserves a moving target.

Domestic natural gas production in the lower 48 states from onshore sources is expected to continue increasing through 2020. Production from unconventional sources and offshore wells in the Gulf of Mexico also will contribute to increased natural gas supplies. In addition, natural gas imports from Canada are expected to increase. At the same time, natural gas consumption will expand considerably. In 1998, natural gas consumption in the United States was 21.4 trillion cubic feet. By 2020, this figure will increase to between 29.5 and 32.7 trillion cubic feet. Growth is seen in every sector, led by rising demand for electricity generation.

In 2020, 40 million fuel cell vehicles operating on methanol derived from natural gas would create an annual demand of nearly 17.4 billion gallons of methanol or natural gas demand of 1.53 TCF (about one percent of anticipated world annual natural gas consumption of 167 TCF).

There are vast quantities of inconveniently located natural gas worldwide that make distribution to local energy markets uneconomical. However, by converting the natural gas to methanol, it becomes possible to access these large reserves for use in the transportation sector. In the

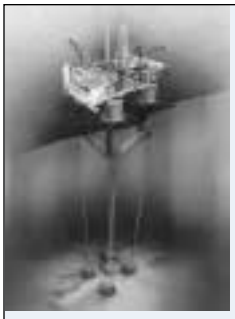
Western Hemisphere, Chile, Venezuela and Trinidad and Tobago are perfect examples of countries with large gas reserves and limited local markets. These countries have capitalized on methanol production technology and are shipping product around the world. Supplying methanol to a developing fuel cell market will be a logical next step.

Existing reserves are clearly plentiful and additional significant natural gas finds are likely. However, in the following sections we will review other potential feedstocks for methanol production that add to the already plentiful supply of raw materials.

WILL METHANOL BE MADE FROM FLARED NATURAL GAS?

> "MUCH OF THE WORLD'S ENDOWMENT OF IDENTIFIED, RECOVERABLE NATURAL GAS RESOURCES LIES IN REMOTE LOCATIONS OR IN SMALLER ACCUMULATIONS THAT MAKE TYPICAL APPROACHES FOR PROJECT DEVELOPMENT, SUCH AS DELIVERY VIA PIPELINE OR LNG TANKER, UNECONOMICAL."

ENERGY INFORMATION ADMINISTRATION
International Energy Outlook 2000, March 2000

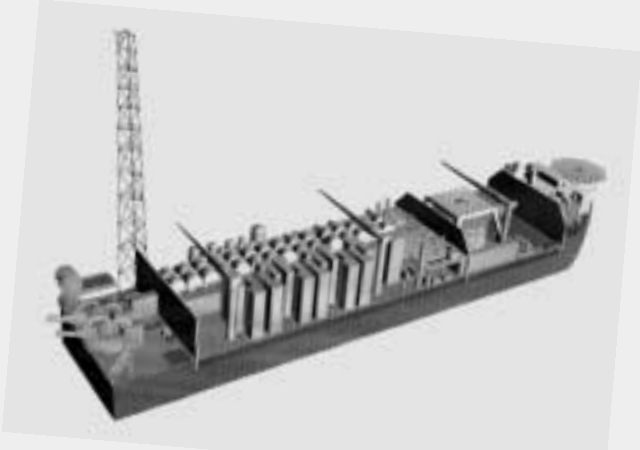


Both in the United States and around the world, great quantities of natural gas cannot be economically recovered. According to the EIA, 3,600 billion cubic-feet of natural gas is flared and vented each year worldwide. Of critical concern, natural gas is a more potent GHG than CO_2. One ton of natural gas emissions is equivalent to 21 tons of CO_2 emissions. Offshore natural gas offers a tremendous opportunity for methanol production because much of it cannot be economically connected to pipelines. If only 10 percent of flared gas was made available for the methanol fuel market, it would be enough to power 9.5 million FCVs.

More offshore natural gas will be discovered, and floating methanol production plants will provide a means of economically recovering this resource. Ocean-based facilities for producing methanol methanol floating production, storage and offloading systems (MFPSOs) are under development. One of the major developers of this production system is Kvaerner Process Technology, which by 2001 should begin to license the technology.

Synetix developed their LCM methanol production technology in the early 1990s specifically for offshore applications of MFPSOs. The first 54,000 ton-per-year development plant for capturing flared and vented natural gas began operating in Australia in 1994. The plant was built by BHP on land to test the novel concepts incorporated into the technology prior to Synetix taking it offshore. The principal features necessary for remote offshore operation include pressurized compact reforming technology; reduced demand for process water; steam venting and effluent processing; structured packing distillation; and full automation. During this research period, the plant also has been a commercial operation, producing about 164 tonnes of chemical grade methanol daily.

FIGURE 3 • METHANOL FLOATING PRODUCTION, STORAGE AND OFFLOADING SYSTEM (MFPSO)



Statoil operates one of the world s largest methanol plants in Tjeldbergodden, Norway, producing 830,000 tons annually. The plant uses gas from the Heidrun oil and gas field in the Norwegian Sea, making it possible to recover oil without flaring the natural gas.

Worldwide, 11 trillion cubic-feet of natural gas released during petroleum drilling are pumped back underground. If this methane could be captured for methanol production, it alone would power over 250 million FCVs annually.

Capturing gas prior to flaring has other benefits. It prevents the simple burning of a useful resource and the resulting pollution. It captures the potential energy of this fossil fuel for other useful market applications, such as fuel cells. The commercialization of methanol fuel cells could provide a boon to American oil and natural gas well operators, create additional jobs and foster incentives for use of methanol in nations such as Nigeria, where enough natural gas is flared each year to meet the country s commercial energy needs. The U.S. Overseas Private Investment Corporation (OPIC) has approved a $273 million loan to underwrite the construction of a methanol plant in Equatorial Guinea. The plant, operated by Atlantic Methanol Production Co. (Ampco), will produce 2,500 metric tons of methanol each day from natural gas. It will use 100 million cubic-feet a day of natural gas currently flared from oil fields in Equatorial Guinea s Alba production area.

The world s large integrated energy companies have lately placed a high priority on identifying strategies to monetize remote natural gas reserves by converting the gas to transportable liquid products such as liquefied natural gas (LNG), Fischer Tropsch (FT) liquids or methanol. While LNG plant costs have dropped significantly in recent years, overall investments, including the supply chain, are still on the order of $2 billion. While LNG plants are well suited for exploiting large natural gas fields near power markets (where LNG can be burned to produce electricity), methanol can compete at larger distances and would be the natural choice for smaller field monetisation.

A 5,000 tons-per-day improved methanol plant produces the equivalent of 18,500 barrels of FT liquids, at a capital cost of $21,600 per daily barrel of capacity. For FT plants producing 10,000 barrels a day, the capital cost would be the equivalent of $40,000 per daily barrel of capacity. Conventional mega-scale methanol plants can produce the cheapest transportable liquid fuel from remote gas..

WILL RENEWABLE FEEDSTOCKS BE USED FOR METHANOL PRODUCTION?

> "METHANOL, OR 'METHANOLIZED' HYDROGEN, IS AN IDEAL LIQUID STORAGE MEDIUM FOR HYDROGEN... METHANOL IS SIMILAR TO HYDROGEN IN THAT PETROLEUM IS NOT NEEDED TO PRODUCE IT. IT CAN, IN PRINCIPLE, BE PRODUCED FROM ANY CARBON SOURCE."
>
> DAIMLERCHRYSLER PRESS RELEASE
>
> *November 2000*

Most of the world s methanol is made by converting natural gas into an alcohol. But in the interest of reducing the United States dependence on foreign petroleum imports and reducing the U.S. trade deficit, methanol can be produced from domestic resources such as wood, municipal solid waste (MSW), agricultural feedstocks and sewage. All of these options are extremely attractive and feasible. The cultivation of dedicated wood biomass crops for methanol production may prove to be economical in the future.

Production of methanol from biomass may begin where the cost of producing the fuel is offset by other benefits. MSW disposal and sewage treatment both meet the criteria. Methane released from MSW landfills and sewage processing plants accounts for nearly 11 percent of all natural gas released by the United States into the atmosphere. Currently, the majority of the nations 4,800 landfills vent natural gas to the air. Since methane is a more potent GHG than CO_2, this is an intolerable situation. Landfills can be designed at the outset or even retrofitted to capture natural gas from the decomposing MSW, reducing this contribution to global warming. Currently, companies have tapped 140 U.S. landfills and are considering collecting natural gas at another 750, according to the EPA s Landfill Methane Outreach Program. In another process, gasification of MSW can be used to produce a high-quality syngas that is the basic building block for methanol production.

Methanol can also be made by gasifying dried sewage sludge. Such a facility is already being operated in Berlin by the SVZ subsidiary (Sekundarrohstoff-Verwertungszentrum) of Berliner Wasser Betriebe, Germany s largest water supply and sewage disposal company, where sewage sludge is blended with brown coal for methanol production. The

facility produces up to 75 megawatts of electricity, and has a methanol production capacity of over 33 million gallons-per-year. The facility is an important demonstration of the technical feasibility of methanol production as a commercially viable by-product of wastewater treatment.

Biomass processing tests will include local energy crops, municipal wastes, sewage sludge, landfill gas and waste wood. The University of California at Riverside s College of Engineering-Center for Environmental Research and Technology (CE-CERT), has constructed the world s first pilot-scale facility demonstrating the Hynol Process. Hynol is a method for converting biomass into a synthesis gas, which can be processed further into methanol. CE-CERT succeeded in operating the facility and gasifying biomass (wood chips) in December 1999 and January 2000, and will continue to develop and operate this facility throughout 2000 and beyond.

Methanol can be thought of as an ideal way to transport hydrogen to the fuel cell without suffering the economic and safety disadvantages of handling a volatile pressurized gas. Methanol can be produced from the same natural gas resources from which hydrogen is produced today. In fact, the first step in producing methanol is to make hydrogen. However, when large quantities of renewable hydrogen become practical to produce for the transportation market, it is unlikely that feedstock sources will be close to large metropolitan centers holding the highest demand. Finding a practical way to transport hydrogen through the existing liquid distribution system will greatly speed up its commercial acceptance. Developing MFCVs will help accomplish this important goal because methanol can be made from any source of renewable hydrogen by simply extracting CO_2 from the atmosphere and reacting it with hydrogen. Today, many methanol plants use their excess hydrogen by consuming waste CO_2 from other sources.

ARE THERE OTHER POTENTIAL METHANOL FEEDSTOCK SOURCES?

AN EVOLVING PICTURE SHOWS THAT WITH A LITTLE INGENUITY, AND EXAMINING ALL POTENTIAL RESOURCES, THERE ARE THOUSANDS OF YEARS OF FEEDSTOCKS FOR THE PRODUCTION OF METHANOL.

Natural gas is so abundant that it is likely to be an attractive methanol feedstock for decades. But for those who worry about the depletion of this resource, there are many other sources of methane on the planet. One of them, coalbed methane, is already in commercial production. Another, methane hydrate, is the subject of intense scientific interest but is developmentally further off. An evolving picture shows that with a little ingenuity, and examining all potential resources, there are thousands of years of feedstocks for the production of methanol.

Table 11 shows the number of years that various methanol feedstocks could potentially power 1 billion passenger vehicles. It does not take into account other uses of natural gas, but the overall picture is quite clear: this is an abundant resource. The following describes additional sources for the production of natural gas:

- Coalbed methane is natural gas that escapes from coal. It is vented naturally from the earth s crust, but also escapes into the atmosphere as a result of mining activity. Roughly 10 percent of anthropogenic methane in the atmosphere is due to coal mining. Harnessing coalbed methane for methanol fuel will help reduce coal mining-related emissions and also reduce the need to extract petroleum.

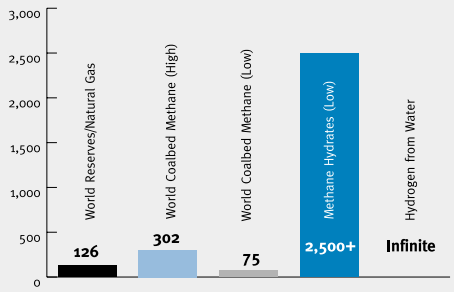
  Worldwide, total recoverable coalbed methane reserves are estimated at between 3,000 to 12,000 trillion cubic-feet. Used exclusively to make methanol, this would produce enough fuel to power 1 billion passenger vehicles for 75 to 300 years. Coalbed methane is a large resource in the United States and is currently in commercial production.

- Methane hydrate is another abundant source of natural gas, although currently not produced. Most of it is

offshore. It is a vast resource that defies easy quantification. World reserves of natural gas frozen in methane hydrate have been estimated at 100,000 to 5 million trillion cubic-feet, although one analysis calculated as much as 270 million trillion cubic-feet. The lower boundary estimate of 100,000 trillion cubic-feet would fuel a methanol fuel cell fleet of 1 billion vehicles for 2,500 years. These reserves answer the question of where natural gas can be found in the future should known and conventional reserves, many decades from now, face depletion.

TABLE 11 • WORLD METHANOL FEEDSTOCKS

CONVENTIONAL AND NONCONVENTIONAL
IN NUMBER OF YEARS OF FUEL FOR 1 BILLION VEHICLES



WHAT ARE THE STRATEGIC IMPLICATIONS OF A WORLD METHANOL MARKET?

"ENERGY-EFFICIENT CARS WILL DRAMATICALLY REDUCE OUR DEPENDENCE ON FOREIGN OIL. RIGHT NOW, MILLIONS OF AMERICANS ARE PAYING HIGHER GAS PRICES."

AL GORE, VICE PRESIDENT OF THE UNITED STATES
March 31, 2000

The global reliance on oil as a motor vehicle fuel brings energy security risks that can have serious economic implications. The United States continues to spend $60 billion each year on oil imports and another $30 billion per year to protect its interests in the Persian Gulf. Since the oil price shocks of the 1970s, the U.S. reliance on foreign oil has actually increased from 38 percent in 1973 to 56 percent today. The U.S. EIA estimated that foreign oil imports will account for 73 percent of total domestic energy consumption by 2020, at a cost of nearly $95 billion.

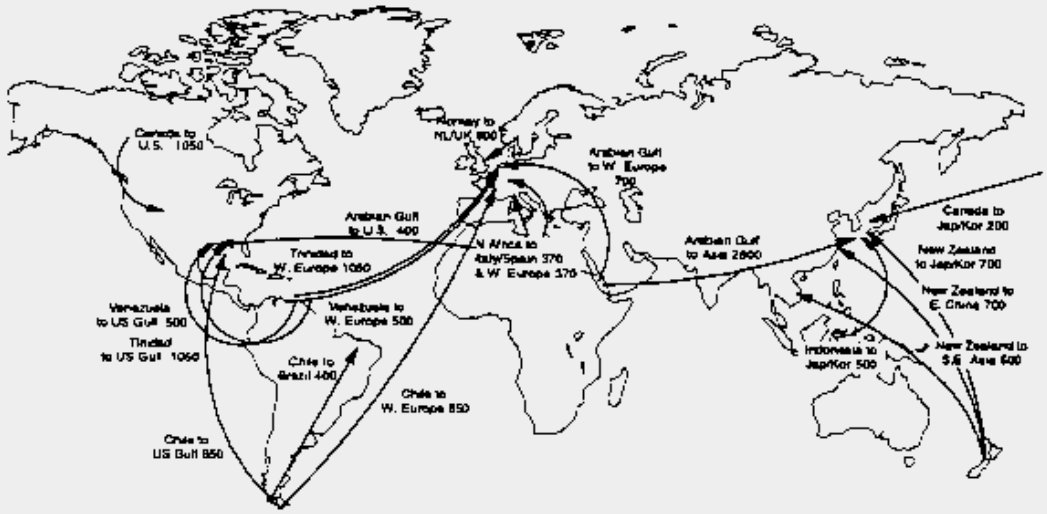
The early stages of fuel cell introduction will begin to shift world energy dependency away from oil and toward natural gas. The motivation of fuel markets should spur heightened interest to acquire nonconventional methanol feedstocks from the technologies discussed in the preceding sections. The benefits of these applications may be summarized as follows:

Better dispersion of energy resources. While the gasoline-powered automobile will be with us for decades, the rise of fuel cell vehicles will have significant worldwide energy implications. Energy-importing countries will benefit from increased competition to supply a wider variety of transportation fuels. According to the EIA, while the Middle East holds 65 percent of global oil reserves, this volatile region accounts for only 34 percent of natural gas reserves.

Less dependency on energy. Since FCVs are more efficient, less energy will be required by the transportation sector.

Stable energy pricing. Price-regulating entities, such as the Organization of Petroleum Exporting Countries (OPEC), will find it increasingly difficult to control the price of crude oil as the number of energy producers increases and no single fuel is allowed to dominate and dictate energy supply.

FIGURE 4 • WORLD METHANOL TRADE FLOW (1,000 METRIC TONS)



Fewer strategic crises. As energy production and diversification increases, the probability decreases that tight markets will turn a local crisis in one country into an international energy shortage.

Greater capacity for domestic self-reliance. The development of renewable methanol feedstocks will offer many countries far more opportunities for self-reliance than can be discerned from current maps of the geographic distribution of natural gas resources.

AREN'T GASOLINE FUEL CELLS AND GASOLINE/BATTERY HYBRIDS BETTER?

"THERE IS NO REASON TO CRAM YESTERDAY'S FUEL INTO TOMORROW'S TECHNOLOGY. THE EXCITEMENT ABOUT FUEL CELLS LIES IN THEIR ABILITY TO PROVIDE A ZERO-EMISSIONS FUTURE; BURDENING THEM WITH GASOLINE'S POLLUTION UNDERMINES THIS PROMISE. AND HYDROGEN AND METHANOL FUEL CELLS ARE CLOSER TO COMMERCIAL PRODUCTION THAN GASOLINE ONES. FUEL CELLS THAT RUN ON CLEAN FUELS PUT US IN THE FAST LANE TO ENDING SMOGGY SKIES AND OIL DEPENDENCE. WHY TAKE A DETOUR THROUGH GASOLINE?"

JASON MARK, UNION OF CONCERNED SCIENTISTS
August 20, 2000

MFCVs are one of the great environmental bargains in history. For less than $2 per person, a state or nation the size of California, with 30 million people, could put methanol-fueling pumps into 10 percent of gasoline stations. From there, further development of the fuel distribution system would cost even less. The principal obstacle to fuel cell vehicle deployment is establishing this initial refueling infrastructure.

While this distribution hurdle should be manageable, it has been assumed that vehicles should be designed based on existing petroleum products such as gasoline and diesel. The two leading developments in this area are the gasoline FCV and the gasoline/diesel-battery hybrid vehicle.

The gasoline FCV is a decade behind other technologies in terms of development and several years behind efforts to commercialize steam-reformed MFCVs. Today s gasoline has several components that make it more difficult to reform into a hydrogen stream. Aromatic and sulfur levels make reforming gasoline a daunting engineering challenge. Researchers have been developing technology for the POX of gasoline providing a multi-fuel capability, able to run on methanol, ethanol, gasoline or natural gas. At this time, there are no FCVs operating on gasoline, although NUVERA has announced plans to ship multi-fuel processors to several automakers for on-board vehicle tests.

It is likely that a specially designed fuel from the refinery will be preferred for use in a gasoline FCV. This means that additional infrastructure costs would have to be incurred to accommodate this designer gasoline.

If gasoline were to be used, sulfur levels would need to be reduced to much lower levels, and this would have associated refinery upgrade costs. The EPA has been

pushing the oil industry to reduce the sulfur content of gasoline from an average of 300 ppm down to 40 ppm or less. Estimates on the cost to produce this cleaner gasoline range from two to nine cents-per-gallon more at the pump. The EPA s proposal to reduce sulfur in gasoline would increase the cost of making gasoline by more than $7 billion a year, much more than the cost of converting the infrastructure to accommodate methanol. For FCVs, a gasoline-like fuel would require a sulfur content close to zero or vehicles would need an onboard sulfur extraction technology. Currently, no such fuel exists.

Even if gasoline FCV technology is developed, there are still a number of reasons why methanol should be the fuel of choice for fuel cells:

- Gasoline reforming using POX requires much higher temperatures than methanol steam reforming: 800…C vs. 250—300…C.
- Gasoline POX technology requires greater CO clean-up (which is required for efficient performance of the fuel cell) that adds greater weight, complexity and cost.
- Gasoline is not practical to use in a direct PEM fuel cell, locking the industry into continual use of reformers. Reformed methanol will lead the way to DMFC vehicles.
- Gasoline reformer development because of its complexity could delay the commercialization of FCVs.
- Gasoline reformer-based FCVs do not break the world dependence on crude oil.

Another technological development has created the hybrid vehicle. The gasoline/diesel-battery hybrid vehicle is a development born out of the limitations of battery technology. Battery-powered electric vehicles are heavy, due to the weight of the battery pack, and have severe range limitations. Even the most advanced batteries have a range of about 100 miles in real world conditions, much less than what consumers demand from a vehicle.

On the hybrid vehicle, a small gasoline or diesel engine is provided to give extra range. There are a variety of designs, but they all have the common feature of allowing a battery pack to be recharged during operation. Moreover, they allow the gasoline engine to be optimized to control emissions to very low levels. For example, Toyota s hybrid battery-gasoline vehicle will reduce emissions of NO_x and VOCs significantly. Mileage per gallon may double if vehicle weight penalties are not too high, resulting in CO_2 emissions reductions of up to 50 percent.

MFCVs should achieve even lower levels of emissions for criteria pollutants, especially in the longer term when the DMFC is likely to take the very low pollution levels of the steam reformer fuel cell to zero in most emission categories.

All in all, a $2 per capita one-time cost in developed countries for methanol fueled infrastructure development seems a sensible investment when compared to these alternatives. It seems unreasonable to advocate continued reliance on petroleum products that are likely to cost the consumer more in annual fuel costs (based on historical pricing) and have higher environmental impacts. The wisest investment for the public, considering the environment, energy security and consumer satisfaction, is the MFCV.

HOW DO WE ENCOURAGE THE INTRODUCTION OF MFCVs?

"WHILE OUR NATION HAS MADE IMPORTANT TECHNOLOGICAL STRIDES TOWARD THE USE OF ALTERNATIVE FUELS, THREE PRINCIPAL MARKET BARRIERS REMAIN... ONE, THE INCREMENTAL COST OF ALTERNATIVE FUEL VEHICLES; TWO, THE COST OF ALTERNATIVE FUEL; AND, THREE, THE LACK OF REFUELING STATIONS IN OUR NATION. OUR BILL TAKES ON THIS THREE-PART PROBLEM WITH A THREE-PRONGED ATTACK USING INCENTIVES AND NO FEDERAL MANDATES. USING TAX INCENTIVES, OUR LEGISLATION PROMOTES THE PURCHASING OF ALTERNATIVE FUEL VEHICLES, PROMOTES THE USE OF ALTERNATIVE FUELS, AND PROMOTES THE BUILDING OF AN INFRASTRUCTURE OF ALTERNATIVE FUELING STATIONS THROUGHOUT THE NATION."

SENATOR ORRIN HATCH (R-UTAH)

Capitol Hill, May 18, 2000

Establish or extend incentives for the purchase and operation of FCVs and installation of alternative fuel infrastructure. Legislation has been introduced in the U.S. Congress to provide a 25¢ per gasoline-equivalent gallon tax credit for the use of methanol and other natural gas-based fuels. In addition, the legislation would extend and enhance existing tax credits for consumers purchasing electric vehicles including those powered by fuel cells that currently are set to expire in 2004. The bill provides tax credits of between $4,250 for light-duty vehicles and $42,500 for heavy-duty vehicles and buses until 2008. The incentive is increased to $6,373 for light-duty vehicles with a range of at least 100 miles. Finally, the legislation extends until 2007 the current law providing a $100,000 deduction for the cost of clean-fuel vehicle refueling property. This legislation provides short-term incentives that will be critical in helping to build the market for FCVs so that economies of scale can be achieved to reduce vehicles costs, and in encouraging the retail fueling industry to add methanol pumps.

Use Corporate Average Fuel Economy Credits. The Alternative Motor Fuels Act of 1988 established a CAFE program for vehicles fueled with alcohol or natural gas. To qualify for this credit, vehicles must meet requirements for: energy efficiency (a dedicated MFCV would certainly qualify); driving range (a minimum of 200 miles); and capability of starting and operating exclusively on the alternative fuel. For dedicated alternative fuel vehicles, the fuel economy calculated for CAFE purposes is deemed to be 15 percent by volume. For example, a dedicated MFCV with a measured fuel economy of 55 miles-per-gasoline-equivalent-gallon, or 27.5 miles-per-gallon of methanol would receive a

TABLE 12 • EXAMPLES OF PARTIAL AND FULL ZEV ALLOWANCE VEHICLES AND ZEVs

VEHICLE TYPE*	PRIMARY ENERGY SOURCE	SECONDARY ENERGY SOURCE	ZERO EMISSION RANGE (MILES)	TOTAL ZEV ALLOWANCE
Gasoline ICE	Gasoline	N/A	0	0.2
Gasoline ICE/HEV	Gasoline	Electricity	0	0.3
CNG ICE	CNG	N/A	0	0.4
Gasoline ICE HEV, 20 mile ZE range	Grid Electricity	Gasoline	20	0.7
Methanol Reformer, FCV	FC Methanol	Electricity	0	0.7
Gasoline ICE HEV, 40 mile ZE range	Grid Electricity	Gasoline	40	0.8
Direct Methanol FCV,	FC Methanol	Electricity	Any	ZEV
Battery EV	Grid	Electricity	Any	ZEV
Stored Hydrogen FCV	Hydrogen		Any	ZEV

rating of 27.5/0.15 or 183 miles per gallon. This is a significant benefit to automakers, who are currently building hundreds of thousands of ethanol-flexible fuel vehicles simply to gain a CAFE credit that is a small fraction of that available for dedicated MFCVs.

Develop specifications for methanol fuel for FCVs. In 1999, the Methanol Specification Council was formed to develop specifications for methanol fuel. The Council Working Group includes representatives of the oil, automotive and methanol industries. The Working Group s current focus is to prepare a comparative risk assessment of the use of methanol in FCVs and the use of gasoline in ICEs to provide technical support for the Council in developing safe and acceptable methanol fuel specifications.

Provide credit for MFCVs in regulatory policies encouraging the use of electric vehicles. The State of California requires that 10 percent of the vehicles sold in Model Year 2003 must be ZEVs. Massachusetts has also adopted this program, and New York is proposing to do so as well. ZEVs have been assumed to be battery-powered electric vehicles, however, the performance limitations of battery electric vehicles (EVs) do not make them attractive to many consumers. The emissions from methanol steam reformer FCVs are a fraction of those required for ICEs to qualify as ultra-low emission vehicles or super ultra-low emission vehicles ULEVs and SULEVs, respectively. Further, MFCVs will come close to or meet the emissions levels attributed to the electric generating stations providing power to recharge battery electric ZEVs. As a result, MFCVs qualify for the highest level of partial ZEV credits (see Table 12). Automakers may use partial ZEV credit vehicles to meet up to 60 percent of their ZEV requirements. DMFC vehicles get the full ZEV credit and auto manufacturers will be able to apply that credit toward the 4 percent pure ZEV requirement.

Partial ZEV credits for gasoline-fueled vehicles should be sunsetted after 2005. CARB should limit the ability of gasoline-fueled vehicles to qualify for partial ZEV credits. Gasoline FCVs, or even hybrid vehicles, are not inherently clean, and will result in higher levels of emissions than those from MFCVs. Further, the use of gasoline in advanced technology vehicles will merely perpetuate our nation's dependence on imported oil. By establishing a sunset provision removing the ability of gasoline-fueled vehicles to qualify for partial ZEV credits after 2005, California can demonstrate its preference for inherently clean vehicles using alternative fuels.

Establish a mechanism to monetize the value of CO_2 emission reductions. Successful emission trading systems have been established to buy and sell emission reductions achieved by stationary facilities for pollutants such as NO_x(ranging from about $1,000 to $2,000 per ton) and VOCs (ranging from about $3,000 to $4,000 per ton). This market-based approach provides industry with an economic incentive to reduce emissions beyond a statutory requirement. The Kyoto Protocol called for the establishment of an emissions trading mechanism for CO_2. Given the substantial reductions of CO_2 expected from MFCVs, including a mechanism for the trading of emissions from these mobile sources would provide significant monetary incentives for automakers and consumers. Further, since MFCVs will

provide significant reductions in criteria pollutants (such as NOx and VOCs), extending current emissions trading systems to allow for participation from mobile sources also would be advantageous.

Encourage the development of strategic alliances. A number of strategic alliances already have been formed to support the introduction of fuel cell and AFVs. Methanex is working with Ballard, Ford is working with ExxonMobil, and General Motors is partnering with BP, as well as Giner, Inc. Broad-based strategic partnerships that involve the automotive, methanol, natural gas, and oil industries, along with government should be encouraged. These strategic partnerships can help overcome many of the initial hurdles to the introduction of MFCVs, particularly the establishment of a retail-fueling infrastructure.

Encourage the use of aggressive marketing campaigns for FCVs. Automakers have come to realize the significant consumer enthusiasm for clean, advanced technology vehicles. Ford, Toyota and Honda have recently launched significant advertising campaigns for hybrid vehicles that are being marketed for their environmental and energy efficiency benefits. The market introduction of MFCVs will create even broader opportunities by educating consumers to the benefits and availability of this technology.

Provide additional incentives for FCV consumers. States have the authority to allow single-occupant drivers of MFCVs and other AFVs to use high-occupancy vehicle (HOV) lanes. The adoption of these rules (now in place in Arizona, California, Georgia and Virginia) should be encouraged. Also, incentives such as the designation of preferential parking for operators of MFCVs in public facilities, including ride-and-drive lots and transit facilities, would be welcomed by consumers.

Elimination of discriminatory fuel taxation. Fuels should be taxed on their energy content, not by volume. Currently taxation policies in many jurisdictions discriminate against alternative fuels by taxing clean fuels with relatively lower energy content on a simple volume basis, which encourages the use of gasoline. Many state governments penalize methanol fuel by taxing it as if it were gasoline. California is truly a fuel neutral state, with very little differential in taxation on an energy-equivalent basis. South Dakota policy favors the development of an alcohol market.

Encourage the use of CMAQ funds for methanol fueling station construction. Funding levels for the federal Congestion Mitigation and Air Quality (CMAQ) Improvement Program exceed $1 billion per year. States and municipalities should be encouraged to use this funding to help install methanol-fueling stations. The installation of fueling facilities serving government fleets is a logical first step.

Increase funding for research in DMFC technologies. The DMFC holds the greatest promise of reducing size, weight, cost, emissions and improving energy efficiency for a broad array of applications. Federal funding for DMFC development has been minimal and fragmented. The efforts of national laboratory, university, and private researchers should be directed to accelerating the pace of development of this important technology.

Notes

BIBLIOGRAPHY

This report summarizes information gathered from a wide variety of sources: interviews with, and critical review comments from industry and government officials; academic journals; academic and industrial conference papers; news articles in major print media sources; the business press; government publications; industry reports and news releases; and a variety of Internet materials made available by government, industry, environmental organizations, and other entities. The following citations are an extensive, but not exhaustive, list of resources used in compiling this report. Internet web sites are included.

Special Note on Web Sites: Many Universal Resource Locators (URLs) or web addresses that point to a specific document cannot be accessed directly after typing the address into a browser. Some web sites do not permit access directly to documents without first passing through a higher directory. Where this is so, we have divided the URL into two parts, the highest directory at which access can be gained to the web site and then the subsequent subdirectory information, which usually will require the researcher to select and click on the correct options.

Abbott, Jim (1997). "Floating Methanol Production Offshore: The Technology Challenges and the Opportunities," March 18-20, 1997, World Petrochemical Conference, Houston, TX.

Agbim, Arinze (1999). "The Availability of Remote and Stranded Natural Gas Feedstock for the future Production of Methanol", 1999 World Methanol Conference, San Diego, CA. Washington, DC: The World Bank Group.

Alson, Jeffrey (1990). "The Methanol Debate: Clearing the Air," in Methanol as an Alternative Fuel Choice: An Assessment, ed. Wilfrid L. Kohl, Washington, DC: John Hopkins University, pp. 393-410.

American Methanol Institute (1997). "Direct Methanol Fuel Cell Debuts at EVS 14," Dec. 13 news release, Washington, DC.

American Methanol Institute (1997). "Methanol: The Clear Alternative," Washington, DC.

Antosh, Nelson (1997). "Direct Methanol Fuel Cell Praised," Houston Chronicle, 26 March, pp. C-1, C-4.

"Assessment of Emissions of Greenhouse Gases from Fuel Cell Vehicles," prepared by (S&T)2 Consultants Inc. for Methanex Corporation, June 2000, Delta, British Columbia, Canada.

Ballard Power Systems (1997). "Ballard, Ford, Daimler-Benz to Join Forces to Develop Fuel Cell Technology for Future Vehicles in Over $600 Million Transaction," news release 15 December, Burnaby, British Columbia, Canada.

Berggren, Mark A. (1997). "Mega-Methanol - Methane Madness vs. Money Maker," 1997 World Methanol Conference, 8-10 December. Houston, TX: Chemical Market Associates, Inc.

Blumenstein, Rebecca (1998). "Auto Industry Reaches Surprising Consensus: It Needs New Engines," Wall Street Journal, January 5, p. A-1.

Brown, Stuart F. (1998). "The Automakers' Big-Time Bet on Fuel Cells," Fortune, 30 March, p. 122ff.

Business Week (1997). "Gas to Oil: A Gusher for the Millennium?" 19 May, pp. 131-132.

California Energy Commission (1996). "Methanol Fueling System Installation and Maintenance Manual," California Energy Commission, Sacramento, CA.

Campbell, Colin J., (1998). "The End of Cheap Oil," Scientific American, March, pp. 78-83.

Clean Fuels Report (1997). "State Taxes on Motor Vehicle Fuels," November, pp. 60-61.

Coalbed Methane Association of Alabama (1995). "History of Coalbed Methane in Alabama," available http://coalbed.com/ subdirectory history.html.

ConVault (1998). "The Above Ground Solution to the Underground Problem," McLean, VA, ConVault Mid-Atlantic, Inc.

Crocco, James R. (1997). "The Ever-Changing World Methanol Outlook," 8 December, World Methanol Conference. Chemical Market Associates, Inc.

DaimlerChrysler (1998). "NECAR3: A Methanol Car Hits the Road."

Department of Energy (1998). "Fuel Cells for Transportation: Program Implementation Strategy," Office of Advanced Automotive Technologies, U.S. Dept. of Energy, Washington, DC.

Department of Transportation (1997). "Fuel Cell Bus," Office of Transportation Technology, U.S. Dept. of Energy, Washington, DC.

Dillon, William (1992). "Gas (Methane) Hydrates - A New Frontier," U.S. Geological Survey, Marine and Coastal Geology Program. Available http://marine.usgs.gov/fact-sheets.

Dobrynin, V.M., Y.P. Korotajev, and DV Plyuschev (1981). "Gas Hydrates: A Possible Energy Resource," in Long-Term Energy Resources, eds. R.F. Meyer and J.C. Olson. Boston: Pitman, pp. 727-729.

Dow Jones Newswires (2000). "U.S. OPIC OKs Largest African Investment for $450M Plant", 14 June 2000, Dow Jones & Company.

Economist (1997). "At Last, the Fuel Cell," 25 October, pp. 89-91.

Edwards, Neil, Suzanne R. Ellis, et al. (1998). "On-Board Hydrogen Generation for Transport Applications: The HotSpot Methanol Processor," Journal of Power Sources, forthcoming.

Ekhtera, M. Reza, G. Ali Mansoori, et al. (1997). "Supercritical Fluid Extraction for Remediation of Contaminated Soil," in Supercritical Fluids: Extraction and Pollution Prevention, eds. Martin A. Abraham and Aydin K. Sunol, Division of Industrial and Engineering Chemistry, Inc., 24-28 March, 211th National Meeting of the American Chemical Society, New Orleans, LA. ACS Symposium Series No. 670, pp. 280-298.

Ellington, Rex T., and Mark Meo (1991). "Calculating the Net Greenhouse Warming Effect of Renewable Energy Resources: Methanol from Biomass," Journal of Environmental Systems, v. 20, no. 4, pp. 287-301.

Energy Information Administration (2000). "International Energy Outlook 2000 - With Projections to 2020, page 59, "Gas-to-Liquids Technology: The Current Picture," Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Dept. of Energy, Washington, DC.

Energy Information Administration (1997). "International Energy Outlook 1997: Appendix A: World Total Energy Consumption Reference Case," Energy Information Administration, Office of Oil and Gas, U.S. Dept. of Energy, Washington, DC.
Available http://www.eia.doe.gov/oiaf/ieo97/appal.html.

ENVIRON (1996). "Hazard Assessment for Human and Environmental Health: Methanol," Arlington VA.March.

ENVIRON (1997). "Methanol Pharmacokinetics and Implications for Safe Exposure Levels," Arlington, VA. August.

Environmental Protection Agency (1997). "Motor Oil Facts," available http://www.epa.gov/grtlakes/seahome/house-waste/ in subdirectories /src/oilfact.htm.

Environmental Protection Agency. (1993). "Methanol Fuels and Fire Safety," Fact Sheet OMS-8, January, Office of Mobile Sources, U.S. EPA, Washington, DC.

Environmental Protection Agency (1993). "Methanol Basics," Fact Sheet OMS-7, January, EPA 400-F-982-009, Office of Mobile Sources, U.S. EPA, Washington, DC.

E-Sources (1998). "E-Sources Special Topic: Fuel Cells," available http://www.e-sources.com/ in subdirectory fuelcell.html.

"Evaluation of the Fate and Transport of Methanol in the Environment", prepared by Malcolm Pirnie, Inc. for the American Methanol Institute, January 1999.

Frost, J.C. (1997). "Fuel Cell System for Transport Applications Including On-Board HotSpot Reformer," 20-22 October, Commercializing Fuel Cell Vehicles 97, Frankfurt, Germany, Intertech Conferences, 1997. Reading, United Kingdom, Johnson Matthey.

Gamlin, Tim, Robert Schneider and Muhammad Islam (2000). "Strategies for Low Cost Methanol Production," 29-30 June 2000, EPTC 2000, Prague, Czech Republic, 2000. Kvaerner Process Technology, Kvaerner Engineering and Construction.

Georgetown University (1998). "Clean Quiet Transit Buses Are Here Today," Georgetown University Advanced Vehicle Development, Washington, DC.

Gottesfeld, Shimshon (1996). "Polymer Electrolyte Direct Methanol Fuel Cells: An Option for Transportation Applications," 17-19 September 1996, Commercializing Fuel Cell Vehicles. Los Alamos National Laboratory, Los Alamos, NM.

Grigsby, Brian (1999). "U.S. Methanol - Evolution for Some, Extinction for Others?" 1999 World Methanol Conference, San Diego, CA: CMAI.

Halpert, Gerald, Todd Marsh, et al. (1997). "The Direct Methanol Liquid-Feed Fuel Cell," Pasadena, CA: Jet Propulsion Laboratory, 15 January.

Halpert, Gerald (1996). "Key Issues for Direct Methanol Fuel Cells," 17-19 September 1996, Commercializing Fuel Cell Vehicles, Jet Propulsion Laboratory, Pasadena, CA.

Hydrogen-Gazette (1998). "Opel Presents Fuel Cell Vehicle," 20 March. Available www.HyWeb.de/gazette-e.

Hymass, Richard (1997). "The Impact of New Methanol Technology on Global Markets," 1997 World Methanol Conference, Tampa, FL. London, U.K.: Kvaerner Process Technology.

Hymass, Richard (1997). "Low Priced Methanol for the New Millennium," 1999 World Methanol Conference, San Diego, CA. London, U.K.: Kvaerner Process Technology.

Jet Propulsion Laboratory (1997). "New Fuel Cell Shows Promise for Zero-Emission Vehicles," 24 February, Public Information Office, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA.

Jordan, Jim (1999). "A Global Overview of Methanol," 1999 Dewitt Global Conference on MTBE/Oxygenates/Methanol, Houston, TX: Dewitt & Co. Inc.

Journal of Power Sources (1996). "Proceedings of the Fourth Grove Fuel Cell Symposium: Opportunities, Progress, and Challenges," London, UK, 19-22 September 1995," v. 61, nos. 1-2, July-August 1996.

Kelly, Ed (1999). "The U.S. Natural Gas Market Outlook", 1999 Dewitt Global Conference on MTBE/Oxygenates/Methanol, Houston, TX. Kingwood, TX: Cambridge Energy Research Associates.

Kinney, Patrick L., and Robert Kavet (1987). "The Health Effects of Methanol Vapor: The Health Effects Institute's Analysis," Cambridge, MA: Health Effects Institute.

Koch, G., and H. Siegrist (1997). "Denitrification with Methanol in Tertiary Filtration at Wastewater Treatment Plant Zurich-Werdholzli," in Water, Science, and Technology: A Journal of the International Association on Water Pollution Research, v. 36, no. 1, pp. 165-172.

Kopinsky, Don (1993). "The Evidence for Low-Dose Methanol Toxicity," Technical Report EPA-AA-EVRB-93-01, Ann Arbor, MI: U.S. EPA.

Kvaerner (1998). "Kvaerner Process - Technology Newsletter."

Larson, Eric D., and Ryan E. Katofsky (1992). "Production of Methanol and Hydrogen from Biomass," PU/CEES Report no. 271, July, Center for Energy and Environmental Studies, School of Engineering and Applied Science, Princeton University, Princeton, NJ.

Lewis, Raymond (1997). "Methanol Fuel Cell Development:

Promise for the Future," 1997 World Petrochemical Conference, Houston, TX. Chemical Market Associates, Inc.

Lewis, Raymond (1996). "New Technology for Direct Methanol Fuel Cells and the Infrastructure to Supply Them," 17-19 September 1996, Commercializing Fuel Cell Vehicles. Washington, DC: American Methanol Institute.

Liebner, Waldemar (1999). "Lurgi's Multi Purpose Gasification-Methanol Syngas from Solid, Liquid and Gaseous Feedstocks", 1999 World Methanol Conference, San Diego, CA. Frankfurt, Germany: Lurgi Ol-Chemie.

Machiele, Paul (1990). "Summary of the Fire Safety Impacts of Methanol as a Transportation Fuel," Government/Industry Exposition, May 1-4, Washington, DC; S.A.E. Paper 90113; Warrendale, PA: S.A.E. International.

Mark, Jason (1997). "Environmental and Infrastructure Trade-Offs for Fuel Cell Vehicles," SAE Technical Paper Series 972693, Future Transportation Technology Conference, August 6-8, San Diego, CA.

Mark, Jason (1996). "Zeroing Out Pollution: The Promise of Fuel Cell Vehicles," Union of Concerned Scientists, May.

Materials Transportation Bureau (1985). "The Transport of Methanol by Pipeline," U.S. Dept. of Transportation, Materials Transportation Bureau, Research and Special Programs Administration, Washington, DC.

"Methanol in Fuel Cell Vehicles: Human Toxicity and Risk Evaluation," prepared by Statoil, 12 December 1999.

Mitchell, William L. (1997). "Fuel-Flexible Fuel Processors for Transportation," 21 October 1997, Commercializing Fuel Cell Vehicles 1997, Cambridge, MA: Arthur D. Little.

Monastersky, Rich (1996). "The Mother Lode of Natural Gas: Methane Hydrates Stir Tales of Hope and Hazard" Science News, 9 November.

Morton, Lawrence, Norman Hunter, and Hyman Gesser (1990). "Methanol: A Fuel for Today and Tomorrow," Chemistry and Industry, 16 July, pp. 457-462.

Murray, Charles N., ed. (1998). "H2-Methanol-CO2 Cycle," Joint Research Center European Commission, available http://me-www.jrc.it/diox/methanol subdirectory methanol-co2-0.html.

National Renewable Energy Laboratory (1995). "Methanol from Biomass." U.S. Department of Energy, NREL/SP-420-5570-Rev.2. Washington, DC.

Nowell, Gregory P. (1994). "On the Road with Methanol: The Present and Future Benefits of Methanol Fuel," prepared for American Methanol Institute, Washington, DC, Mountain View, CA: Arcadis (formerly Acurex Environmental).

Oil and Gas Journal (1997). "U.S. Gas Resource Estimate Up 6% in Two Years," April 21, v. 95, no. 16, p. 23.

Oil and Gas Journal (1996). "Technology Spurs Growth of U.S. Coalbed Methane," v. 24, no. 1, January 1, pp. 56-63.

Oil and Gas Journal (1993). "Methanol Plant Design Choices Affect Operations, Costs, Other Equipment," March 29, pp. 53-57.

Prensky, Stephen (1995). "Hydrate Resources Estimation," available http://www.gsj.go.jp/dMG subdirectory/hydrate/hydrate.resources.html.

Rice, Dudley (1997). "Coalbed Methane - An Untapped Energy Resource and an Environmental Concern," Energy Resource Surveys Program, U.S. Geological Survey, Fact Sheet FS-019-97. Available http://energy.usgs.gov/ subdirectory /factsheets/coalbed/coalmeth.html.

San Jose Mercury News (1997). "Engine Evolution: Accelerating the Move Away from Fossil Fuels," 26 March.

Short, Glyn, and Laura Antonio (1997). "Methanol in Gasoline and Diesel Engines: Environmental Considerations," 1997 World Methanol Conference. Imperial Chemical Industries Americas Inc., Wilmington, DE.

Short, Glyn (1999). "A Methanol Maritime Spillage Scenario - What if the Exxon Valdez Had Carried Methanol?" 1999 World Methanol Conference, San Diego, California. Hockessin, DE.

Shu, Lijn, Jeremy C. Nesheim, et al. (1997). "An Feiv2O2 Diamond Core Structure for the Key Intermediate of Methane Monooxygenase," Science, 24 January, v. 275, pp. 515-517.

Sperling, Daniel (1997). "Rethinking the Car of the Future," Issues in Science and Technology, Winter 1996-

1997, pp. 29-34.

Sperling, Daniel (1997). "A New Agenda," Access, No. 11, Fall, pp. 2-9.

Stokes, Charles A. (1997). "Why the Global Warming Issue Is Important to the Methanol Industry," Stokes Consulting Group.

Stork, K., M. Singh, et al. (1997). "Assessment of Capital Requirements for Alternative Fuels Infrastructure Under the PNGV Program." Argonne National Laboratory.

Swift News (1997). "Methanol to Boost Natural Gas Demand," v. 11, no. 3, pp. 3-4.

Tanahashi, M. (1996). "Messoyahkha Gas Field: The First Commercial Hydrate Deposits?" available http://www.gsj.go.jp/dMG/hydrate/Messoyakha.html .

TeraMeth Industries (n.d.). "On-Site Methanol Production," Walnut Creek, Calif.

Toyota Motor Corp. (1997). "Toyota New Developments: The Fuel Cell Electric Vehicle," International Automobile Association, Frankfurt 1997.

Toyota Motor Corp. (1997). "Water: The Only Emission from the Power Source of the Future," available http://www.toyota.co.jp/e/green subdirectory cell.html.

Unnasch, Stefan and Louis Browning (2000). "Refinement of Selected Fuel-Cycle Emissions Analysis," February 2000, Mountain View, CA: A.D. Little. California Air Resources Board Contract No. 98-339

Unnasch, Stefan (2000). "Fuel Cell Energy Conversion Efficiency Analysis," prepared for the California Energy Commission and the Air Resources Board, May 2000, Mountain View, CA.

Williams, Robert H., E.D. Larson, R.E. Katofsky, and Jeff Chen (1995). "Methanol and Hydrogen from Biomass for Transportation: With Comparisons to Methanol and Hydrogen from Natural Gas and Coal," Center for Energy and Environmental Studies, Princeton University, June 27, U.S. EPA Symposium on Greenhouse Gas Emissions and Mitigation Research, Washington, DC.

Wilson, Kevin A. (1997). "The Fuel Cell Sell," Autoweek, 3 March 1997, pp. 12-14.

Woods, Theodore (1995). "Zero-Emission Vehicle Technology Assessment," prepared for New York State Energy Research and Development Authority, NYSERDA Report 95-11. McLean, VA: Booz-Allen and Hamilton, Inc.

For more information about the American Methanol Institute, call us at 1-888-275-0768, or drive by our web site at *www.methanol.org.*

AMERICAN METHANOL INSTITUTE

800 Connecticut Avenue, NW
Suite 620
Washington, DC 20006
Telephone 1-888-275-0768 • Facsimile 202-331-9055
email: Ami@methanol.org

www.methanol.org