August 26, 1994

Notes on the meeting:
"The Fuel Cell for the Next Generation Vehicle"
Vice President Gore's Automotive Technology Symposium #2
White House Conference Center
Washington, DC
July 27, 1994

Joan Ogden and Margaret Steinbugler

We were invited to attend and present a poster paper for the Vice President's second automotive technology symposium, which was focused on the fuel cell as a key option for meeting the goals of the Partnership for a New Generation of Vehicles.[1] The meeting lasted from 8:45 am until 4:30 pm and consisted mainly of a series of short presentations and discussions.[2] In addition, 6 poster papers were presented, including ours, which was entitled, "Fuels for Fuel Cell Vehicles." Opportunities to discuss the poster papers were limited to the registration period before the meeting began and the breaks.

The meeting was attended by about 125 people in all. Chrysler, GM, Ford, Exxon, Texaco, Los Alamos National Lab, Argonne National Lab, Idaho National Engineering Lab, Livermore National Lab, Oak Ridge National Lab, H-Power, Ballard, International Fuel Cells, Allied-Signal, Arthur D. Little, Directed Technologies, DuPont, Society of Automotive Engineers, Texas A & M University, Georgetown University, University of Florida, Princeton University, and the Institute for Transportation Studies of UC/Davis were among the organizations represented. Below are brief summaries and highlights from the meeting's presentations; parenthetical comments in italics are the contributions of several reviewers of this memo.

Dr. Mary L. Good, Undersecretary of Commerce

The meeting was chaired by Dr. Mary L. Good, who discussed the implementation plan for Goal 3 (three times the fuel efficiency of current vehicles in 10 years) of the Partnership for a New Generation of Vehicles (PNGV) and coordination between the US

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[1]The program for the PNGV is described in the report "PNGV Program Plan," US Dept. of Commerce, Washington, DC, July 1994, which was made available at this symposium. Symposium No. 2 was focused specifically on the fuel cell vehicle as a major option for meeting Goal No. 3 for the PNGV, namely to develop in a decade's time production-ready prototypes of automobiles with three times the fuel efficiency of today's cars of comparable performance, while costing no more to own and drive than today's cars and meeting the customers' needs for quality, performance, and utility.

[2]For the list of presentations and speakers see the attached Tentative Agenda.

Q. Iran Thomas (Department of Energy): With all the talk about light-weight vehicles there must be some discussion of safety. People must be convinced that light cars are safe.

A. Good: It is a program requirement that cars have the same safety parameters as current cars.

Comment: Pena mentioned collision avoidance technology.

Q. Larry DuBois (Advanced Research Projects Agency): A lot of fuel infrastructure change is required for alternatives - how much effort is going into infrastructure development?

A. Will discuss later in meeting.

Q. Glenn Rambach (Lawrence Livermore National Laboratory): What about technologies that may not be ready in 10 years, but look good in the 15-20 year time frame?

A. Good: Too early to say right now, can't pick long-term technology now. But won't abandon longer term technology. Mentioned NASA doing system model for Goal 3 to look at trade-offs.

Q. Dan Sperling: Observed that there seemed to be no fuel supply people involved; but noted that he knew of one oil company funding a university research project on gasoline reforming.

A. Two fuel representatives spoke up: Pat Grimes, formerly of Exxon, and a representative of Texaco. The Texaco representative noted that the fuel industry would rather move in small steps than in large jumps. He brought up internal combustion engine hybrid vehicles and, for fuel cell vehicles, fuel processing via partial oxidation, which permits more flexibility in fuel choice than steam reforming.

Al Gore - Vice President

Talked about the importance of the PNGV program to himself and the President. Noted that the Big 3 are becoming more nimble; reminded group that 15 years ago people would not have believed that US cars could improve as much as they have. This is an example of how large bureaucratic organizations can change for survival; he holds up the Big 3's improvement as an example to government workers when discussing reinventing government. Noted that commitment is vital to achieve any goal. Reminded group of Apollo project: they did not have the necessary rockets, computers, or materials at the time of the announcement in 1961, but they had the commitment.

Francois Castaing - USCAR, Chrysler VP of Engineering

Mentioned that fuel cells have been controversial; controversy and debate are good as long as we follow the rules of science and discuss facts, not opinions. Noted that fuel cells are but one way to achieve the goal of 3x fuel efficiency in 10 years. We need to discuss not only science, but also applying science to mass produced items. Need also to address safety issues, reliability, and start up time. We must be committed to changing the pace of innovation.

Rob Chapman - Chairman, PNGV Technical Task Force, Dept. of Commerce

Management of PNGV is to include multiple idea paths:
-partnering with USCAR
-USCAR consortia
-creative track
-supplier participation

There is also a review and public participation process:
-program plan
-NSF/SAE/PNGV workshops
-DOT/NAE/PNGV Peer Review
-VP PNGV Engineering Conference

Focus on Goals:
1. Design and manufacturing
2. Near term improvement
3. Three times fuel efficiency

Discussed energy distribution through vehicle drivetrain. He argued that fuel cells alone will not deliver a three-fold fuel efficiency improvement. According to his figures, combining existing state of the art technology for internal combustion engine vehicles will get you about 40 mpg; the fuel cell will get to about 80 mpg, but with no comfort margin. We will also need:
-mass reduction
-braking energy recovery
-accessory load reduction
-improved drivetrain efficiency *(motors at wheels)*

Discussed the idea that as new technologies are being developed there is a period during which the old technology performs better than the new, and people question why the new technology is worth pursing; but the new technology holds the promise for performance exceeding conventional technology, though it takes time to achieve it. New technologies being pursued now include:

-Methanol PEM and hydrogen PEM
-Direct fuel injected diesel and sparked stratified charge engines
-gas turbine alternators or other hybrids (combustion engines/generators plus storage)

He called these "deadly parallel" paths, in that those that fail to show promise will lose out to the better paths.

Dr. Ron York - PNGV Program Manager, GM

Goal 3 is to develop a vehicle with three times the fuel efficiency of the current Chrysler Concorde, Ford Taurus, or Chevrolet Lumina sedan. Does the fuel cell fit in? GM's understanding of the market is that people want the desirable characteristics of clean cars, as long as they don't have to compromise on anything else. Besides three-fold fuel efficiency improvement, there are other goals:
-same cost as today's car
-maintain performance, size, utility
-meet or exceed safety and emissions requirements
-the vehicle should be 80% recyclable *(or remanufacturable?)*

Program calls for a concept vehicle in 6 years and a production prototype in 10 years.

To meet Goal 3 we must meet some sub-goals:

1. Reduce energy demand by 50% by:
   -reducing mass by 20-40%
   -reducing aerodynamic drag by 30%
   -reducing rolling resistance by 30%
   -reducing accessory loads by 30%

2. Improve conversion and delivery of input energy to tire patch on the road by:
   -improving fuel conversion efficiency to 40-55% thermal efficiency *(present is 10±2%)*
   -reducing power train and transmission losses by one-third

3. Recovery of 50-70% of braking energy *(driving patterns may change with the use of electric vehicles; available braking energy may be less than we expect)*
   -achieve 95% mechanical/electrical conversion
   -achieve >90% round trip efficiency in high-power storage system
   -implement a systems energy management strategy

He remarked that with respect to controls, this future vehicle will be more like an aerospace product than a current car. The ranges given for these improvements define a design space within which the three-fold goal is achieved.

He mentioned that GM's fuel cell targets are 50% efficiency at maximum power and 55% efficiency at average power with a power density of 0.2-0.4 kW/kg.

Another figure of interest mentioned was that each additional pound of engine, fuel cell, or fuel storage weight requires an additional half pound of structural weight. *(Or the removal of one pound of seats, glass, control knobs, etc.)*

Dr. A. John Appleby - Texas A & M University

Reviewed how fuel cells work; some interesting figures cited were that the membrane and electrode assembly, the heart of the fuel cell, weighs only about 600 gr/m^2 and delivers about 4 kW/m^2 *(some would consider this a conservatively low number)*, but the whole system weighs 45 kg/m^2. Other components are heavy and need to be made lighter - bipolar plates, gas manifolding, etc.

He mentioned that the natural gas reformer for IFC's 200 kW stationary power plant would be a nice size for a vehicle gas station. Projections by IFC are for their PC25 phosphoric acid fuel cell power plant with natural gas reformer to cost $3000/kW in 1995 and $1500/kW in 2000. The cumulative production of PAFCs by United Technology/IFC is only 36 MW.

Platinum loadings that resulted in power per gram Pt in the Watts per gram range are now measured in kW/gram. Texas A&M's Center for Electrochemical Systems and Hydrogen Research (CESHR) has been experimenting with low Pt loadings. In 1991 with $150,000 from NASA they achieved 0.15 gr/ft^2 (0.16 mg/cm^2) in the lab; in 1994 with funding from a private, non-US industry they achieved 0.05 gr/ft^2 (0.054 mg/cm^2). Typical cell performance is about 0.5 $amps/cm^2$ at 0.7 volts with these very low Pt loadings, corresponding to a power per gram ratio of about 3.2 kW/gr Pt. Work yet to be done is:

-life testing
-further cost reduction, especially the membrane (it now costs about $8/gram; he feels it needs to be reduced an order of magnitude; Teflon costs about $9/pound or only about $0.02/gr)
-operation on methanol reformate
-product water removal

CESHR's target, which Dr. Appleby feels is achievable by around 2000, is to develop a 20 kW stack that weighs 14.7 kg, measures 50 cm x 12 cm x 30 cm and includes only 3.1 grams Pt total (0.05 gr/cm^2 at the cathode and 0.025 at the anode). This target represents power densities of 1.36 kW/kg and 1.1 kW/liter and power per platinum ratio of 6.45 kW/gram.

Pandit Patil - Director, Office of Advanced Vehicle Technologies, USDOE

Declared "the race is on" to develop fuel cell technology for vehicles; European countries and Japan are involved. For the US he listed the Big 3 teams:

GM	Chrysler/Pentastar	Ford
Allison	Allied Signal Aerospace	IFC
Ballard	Allied Signal Automotive	H-Power
Dow	Allied Signal Engineering	Tecogen
DuPont		Directed Technologies
LANL		Air Products
		Airco
		Praxair
		Electrolyzer

He showed a slide illustrating the progress Ballard has made with its PEM fuel cell in the last three years:

1991 Ballard stack	1994 Ballard stack	
5 kW continuous	10 kW continuous	(0.22 kW/kg)
7.5 kW peak	15 kW peak	(0.33 kW/kg)
100 lbs.	100 lbs.	
11"x11"x22"	"same envelope"	(0.23 kW/liter continuous, 0.35 kW/liter peak)

In Europe, developers of fuel cells for vehicles include: Siemens, DeNora, Ansaldo, Vickers, and Dornier. Daimler-Benz and Ballard are an example of the partnerships emerging between automakers and fuel cell developers. Others are BMW/Siemens and Renault/Volvo/DeNora. There is growing government support in Europe for fuel cell research with $64 million/year coming from the European Community for transportation fuel cell research.

Siemens has developed a PEM stack that delivers 34 kW continuous power, 50 kW peak (650 amps at 52 volts), on hydrogen/oxygen. Cell active area is 1.3 ft^2 (1208 cm^2) with 72 cells. The efficiency is reportedly 59% at rated load and 69% at 20% load.

Daimler-Benz has invested $60 million so far in fuel cell research for transportation and has plans for a production prototype within 5 years.

Japan's fuel cell R & D program is supported by
-the new Sunshine (solar and renewable energy) project, 1993-2020, $11 billion for all technologies

-the Clean Energy Network project (use of H_2 and methanol as energy carriers), $2 billion
-$30 million/year additional estimated total transportation fuel cell funding

Companies involved include automakers, fuel cell developers, and engine makers: Honda, Toyota, Fuji, Mitsubishi, Mazda.

Fuji has a 4 kW PEM stack with 0.65 ft^2 (600 cm^2) with performance comparable to a Ballard stack, dimensions 0.6 m x 0.6 m x 1.1 m (0.01 kW/liter). This includes controls. Finally, Dr. Patil mentioned that a Japanese firm (Asahi) may be working on developing a membrane specifically for automotive fuel cell use (unlike the DuPont membrane, which was developed for the chlor-alkali industry).

In response to a question on how far current densities could be improved, **Dr. Appleby** noted that at Texas A&M they get just a little less at atmospheric pressure than the state-of-the-art Ballard stack gets under pressurized operation. He mentioned again the disparity between the weight of the membrane electrode assembly at 600 gr/m^2 and the whole fuel cell weighing 45 kg/m^2.

Ira Kuhn - Directed Technologies

Of the two approaches to fuel cell power plants taken by the Big 3 (methanol onboard by GM, hydrogen onboard by Ford and Chrysler) he discussed mostly onboard hydrogen storage and infrastructure.

After evaluating 5 hydrogen storage technologies (compressed gas at 5000 psi, cryogenic liquid, rechargeable metal hydrides, adsorption on an activated matrix, and reactive chemical hydrides) on the basis of weight, volume, fuel extraction complexity, system cost, fuel cost, dormancy, and safety, he concluded that compressed hydrogen was the near term winner. He looked at supplying enough hydrogen to provide a Ford Taurus with a 342 mile range on the Federal Urban Driving Schedule (FUDS). While the weight of the compressed gas hydrogen storage system is only 1.5 times larger than that of the gasoline system, its volume is still a problem. For a 342 mile range, gasoline storage volume is only 2.5 ft^3 while the hydrogen storage volume is 13 ft^3. These figures apply to carrying 15 pounds of hydrogen occupying 10.5 ft^3 in one cylinder at 24" x 48" or in two cylinders, each carrying 7.5 pounds at 5.25 ft^3 (16.5" x 48").

To supply the hydrogen he looked at several options including hydrogen derived from natural gas and garage scale electrolysis and compression with off-peak electric power.

Two useful numbers: the cost of the power train for a Taurus/Lumina/Concorde size car is $3000-4000 or $4/pound. When asked about whether the increased demand for natural gas would drive its price up, he mentioned the "ceiling" price of natural gas is about

$5/million BTU due to the economic competitiveness of producing hydrogen via coal gasification above that price.

Dr. Chris Borroni-Bird - Chrysler

Began with a discussion of the need for conventions in reporting fuel cell results: should base efficiencies on lower, not higher, heating values, since this is standard in the internal combustion engine world. Need to know, when efficiencies are cited, whether they include parasitic power losses (can consume 10-15% of fuel cell power), onboard fuel processing (can consumer another 15-20% of fuel cell power). Outputs reported should be system outputs, not stack outputs. Rather than expressing efficiency in percent, it should be expressed as a fuel efficiency on the EPA combined urban/highway driving schedules. We also need a standard for power rating. Is maximum power the maximum peak power, or sustainable power, or the power available for transients? The air pressure used to define rated power should be reported.

He outlined some technical issues for fuel cell stack cost reduction:

1. Bipolar plates: currently one-third of the stack cost. The plates must be nonporous and conducting *(what conductivity is needed?)*. Graphite plates are expensive because to get the graphite nonporous it must be made slowly, and because it must be machined. Graphite also has poor shock resistance. Alternative materials are needed that have high conductivity, corrosion resistance, and can be molded rather than machined. Possibilities are niobium or gold plating a substrate material.

2. Platinum catalyst: now at 0.050 mg/cm^2 or $1-2/kW, but CO poisoning is more of a problem at very low Pt loadings. For a vehicle, a fuel cell needs a life of 100,000 miles or 5000 hours. Are low Pt loadings durable? Alloying with palladium might help. Also need to address automating the process of putting the catalyst on the electrode.

3. Membrane: even if the large-scale production cost gets down to $5/ft^2 ($54/m^2), that's still about $10/kW and is not acceptable. Membranes being used now were developed for the chlor-alkali industry, which demands lifetimes of up to 100,000 hours *(some would dispute that this long a life is required in chlor-alkali applications)*. Perhaps these membranes are "over engineered" and shorter lived substitutes could do just as well for less cost. Membrane thickness also must be considered - thinner is both lower cost and has better conductivity, but allows more hot spots.

Ancillaries are another consideration. 90% of the ancillary load may be the air compressor. A variable speed air compressor would improve this number a lot. It is also desirable to reduce the number of switches, solenoids, regulators, and other moving parts. Cooling is an important issue. Some fuel cells now use water as a coolant; this will probably not be possible in automotive applications with the potential for freezing. The coolant may have to be an antifreeze and will have to be kept separate from the humidification system. Water management continues to be a challenge.

Brad Bates - Ford

The internal combustion engine and its associated fuel tank and exhaust system occupy only 12 ft^3 (about 340 liters) and weigh only 650 lbs. (about 300 kg) - this is the challenge the fuel cell based system must meet. Ford's approach is to have a hybrid system - this accomplishes:
-reducing peak (FC) power needed
-easing transient needs
-improving utilization

There is a trade-off between fuel cell stack size and energy storage size. Suppose the power plant is to be 100 kW (he noted one uses only about 8-10 kW most of the time on the FUDS). Then suppose maximum steady state power will be driving 70 mph on a 6% grade. This requires about half of the peak power. To meet this requirement for 20 minutes with a 40 kW fuel cell requires 1-2 kWhr of energy storage; but to meet it with a 30 kW fuel cell requires 14 kWhr energy storage.[5]

He cautioned that if one operates the fuel cell near its full power it will lose its efficiency edge over gasoline and diesel engines because its efficiency drops off at high load. He also discussed briefly the trade-offs between subsystem volume and pressurized operation and between output power and pressurized operation; suggested that 30 psig was a good pressure.

Identified several issues still outstanding:

-Fuel choice
-System definition
    Stack performance
    Operating pressure and energy storage subsystem
-Cost, size, weight, reliability

[5]We haven't yet figured out where these numbers come from; perhaps there are some assumptions built in about the weight of the peaking device.

Gerald Skellenger - Technical Director, GM Hybrid Vehicle Program

Discussed "Fueling the Fuel Cell Vehicle." Mentioned GM's concept of the "similar performance vehicle," which means the car has enough battery power to meet the FUDS requirements while the fuel cell system (GM's concept includes a methanol reformer) warms up. Mentioned you need about 5 lbs. of compressed hydrogen to get 500 km range. *(One reviewer pointed out that a partial oxidation fuel processor has a response time of 3 seconds or less.)*

S. Swathirajan - GM

Discussed GM's methanol fueled PEM fuel cell system. Their fuel processing system includes a steam reformer, a two-stage converter (one stage for converting residual methanol exiting the reformer, one for shifting CO to H_2), and preferential oxidation (prox) unit for oxidizing CO such that final CO concentration is less that 10 ppm at steady state. The reformer and converter use copper oxide and zinc oxide catalysts. CO content out of the converter is about 1.5% and out of the prox less than 10 ppm at steady state but as high as 100 ppm during transients. They have coupled this fuel processing system to a 5 kW Ballard PEM fuel cell stack. Start up time is 2 minutes; methanol conversion is better than 99%.

Mentioned some problems with running on 75% hydrogen/25% CO_2 compared to 75% hydrogen/25% N_2. It seems the CO_2 may adsorb with H_2 on the Pt catalyst in the fuel cell to make CO or other undesirable intermediates. Mixing 2% air in with the fuel supply gas takes care of this problem and at the same time controls CO poisoning. Another approach may be to add ruthenium to the Pt catalyst.

GM accomplishments to date include:

-system and vehicle model

-R&D on thin film electrodes - have electrodes that are < 0.40 mils thick

-have achieved 2-3 ppm CO levels out of the fuel processor

-have tested stack and processor 1000s of hours

Their plan is to have a proof of concept vehicle by 1997-99, with intermediate goals of working on a 10 kW system from 1990-94 and a 30 kW system from 1994-96.

In response to a question, indicated that some water (1-2 liters) *(for start-up)* may need to be carried onboard. Mentioned some experimental results using 0.1 mg/cm^2 Pt and 0.1 mg/cm^2 ruthenium at the anode, with just 0.1 mg/cm^2 Pt at the cathode.

Gorik Hossepian - Allied Signal Aerospace

Explained that Allied Signal Aerospace is part of the team that also includes Chrysler Liberty and Pentastar. They consider DOE their customer; cosponsors are the California EPA and SCAQMD. A goal of this team as part of a 30 month project is to deliver, in 20 months, a 30 kW PEM fuel cell stack (to Chrysler?). Allied Signal Aerospace is involved in bipolar plates, H_2 storage, gas management, electronics, electrodes, membranes, and stacks. He emphasizes that Allied Signal knows how to manufacture for the automobile industry and make money at it. Stressed Allied Signal's commitment to this project.

Al Meyer - International Fuel Cells

Discussed IFC's 30 year participation in the power plant business; they have experience making fuel cell systems that work on "pushbutton" operation. Said they make (phosphoric acid) fuel cells for less than $3000/kW and they make money at it, with 57 customers worldwide.

Mentioned two systems they have developed: a 500 watt demonstrator (PEM?) and a 20 kW alkaline system for ARPA for undersea applications. This latter system operates on deadended pure H_2/O_2, delivering 20 kW at 0.82 volts with water the only circulating fluid. On H_2/air it can deliver 40 kW at 0.7 volts; on H_2/O_2 it can deliver 50 kW at 0.7 volts. Its dimensions are 24" x 34" x 34" (? on last dimension).

Pointed out cost is very important; they feel targets PEM fuel cell systems will have to reach for autos are:
- 5-9 lbs/kW (0.24-0.44 kW/kg)
- 0.1-0.3 ft^3/kW (0.12-0.35 kW/liter)
- $30-50/kW

Mentioned two concepts IFC has for PEM fuel cells:

A. 220 kW	B. 50 kW
4 lbs/kW (0.55 kW/kg)	8 lbs/kW (0.27 kW/kg)
0.33 ft^3/kW (0.11 kW/liter)	0.4 ft^3/kW (0.09 kW/liter)

These numbers are based on single-cell data 2-3 years old; he feels they might do better than this; said the technology was "within striking distance" of where it needs to be for auto applications on performance, but not on cost.

On cost, IFC projects $250/kW for PEM fuel cells *(it was not clear whether this is stack or system cost)* at manufacturing volumes of 1000-2000 units per year and at membrane cost of $25/$ft^2$ ($270/$m^2$). Talked about innovations like making parts multifunctional (for example, tie rods and manifolding all together) to limit the number of parts involved.

On funding support, said to develop a PEM system needed $50-75 million over 5 years, about $12 million/year, emphasizing that this must be secure from year to year so projects are not disrupted.

How does IFC feel?

-the benefits are enormous
-it can be done quickly - about 5 years for FC power plant system, 10 years for whole car
-government support is critical

Romesh Kumar - Argonne National Lab

Placed direct methanol fuel cells (DMFCs) in context of various alternatives for fuel cell vehicles: reform onboard - transient response, size, weight problems
direct H_2 fuel cell - storage problems
direct methanol - not as far along but offer "tantalizing" performance

Latest data on direct methanol fuel cells shows they have about half the power and half the efficiency of reformed methanol PEMFCs (about 0.3 amps/cm^2 at 0.4 volts). But many groups are looking at them:

80°C operation: Giner Inc.
IFC
Jet Propulsion Lab
Lawrence Berkeley Lab
Los Alamos National Lab

200°C operation: Case Western Reserve University

450°C operation: Argonne National Lab

Others looking at DMFCs: University of Illinois, IIT, Imperial College, Texas A&M, Clemson, Colorado State, New Castle, Essex, Grenoble Poly, Brookhaven, Naval Research Lab, GM/Ballard.

The two main problems of DMFCs are catalyst poisoning and methanol crossover and they are being worked on. Approaches are to modify the catalyst or the operation. Using Pt with ruthenium instead of just platinum may help catalyst poisoning by CO. Designing electrodes to minimize methanol concentration at the membrane - an IFC approach - will help reduce methanol crossover. Working at higher temperature helps, since then there is less CO adsorption. This is the Case Western approach; he mentioned the membrane they are using is not the usual perfluorinated sulfonic acid as in the PEM. The work at higher temperature (450°C) uses a solid oxide electrolyte rather than a membrane; in this case methanol crossover and CO adsorption aren't a problem because the oxide ion rather that the proton is being transported. The higher temperature also helps lower the activation barrier and simplifies water management, but right now the low temperature technology is the leader.

Further challenges: -startup time
-cyclability
-ruggedness

In response to a question about startup times he said high temperature SOFCs could heat up from 25°C to 800°C in less than 2 minutes without cracking the ceramic monolith. In this discussion it was mentioned that reformer transient response time for a 200 kW system can be 10% of full load/second and might possibly improve to 20% of full load/second.

Peter Teagan - A. D. Little

Discussed fuel processing options. Feels multiple-fuel capability will be the key to developing large markets. Compressed natural gas, for example, is finding itself in a chicken and egg situation; multifuel capability would prevent this. AD Little has considered biomass to ethanol, natural gas to methanol and hydrogen, petroleum, and electrolysis.

For onboard reforming they considered steam reforming, autothermal reforming, and partial oxidation (pox). They think partial oxidation might be the best for this application. Although it has some efficiency penalty relative to steam reforming, it does offer multifuel and quick start capability. They are doing modeling and lab work with a hybrid partial oxidation reformer. It is a hybrid because it does incorporate a catalyst for converting residual hydrocarbons in a low temperature (1600°F or 870°C) zone following the high temperature (1800°F or 980°C) burner zone.

The lab hybrid pox they are testing is cylindrical in shape, about 18" long and 9" in diameter for a 50 kW system. It is designed for multi-fuel flexibility. An outer metal shell surrounds inner ceramic insulation. In addition to this hybrid pox unit, the fuel processing system would also incorporate a shift reactor. Gas composition coming out of the hybrid pox going to the shifter is (input fuel was not specified):

H_2:	24%
CO:	20
H_2O:	2
CO_2:	10
N_2:	44

Modeling this hybrid pox performance is tough because it is a nonequilibrium system. Startup time is measured in seconds; the system should easily load follow over 50% of capacity, there is some question about its load following ability below that. The hybrid pox system uses standard burner technology (including a spark plug to light things off) and common materials of construction. The catalyst involved is a monolith design similar to automotive catalyst designs. What about emissions? The temperature is too low for NO_x, others not discussed.

Dr. Vernon Roan - University of Florida

Observed that fuel cells for autos have been on a 13 year coffee break, as he had helped organize and chair a 1981 meeting on the same subject in Washington that concluded that fuel cells for autos was a good idea.

Reviewed R&D needs for fuel cells:

1. Compatibility with Automotive Requirements
   cost, size, operating characteristics

2. Determine Appropriate Fuel
   available in quantity
   cost to consumer
   distribution/infrastructure feasibility
   safety/environmental issues
   onboard/utilization issues

3. Integrated Design/Optimization
   hybrid energy storage-appropriate battery, capacitor, or other device
   appropriate fuel storage/conditioning
   control strategy optimized for efficiency and ease of operation

4. Customer Acceptance Issues
   initial and operating costs
   performance/driveability
   reliability and maintenance issue
   education and buyer incentive
   appropriate auxiliary and comfort systems (air conditioning, power steering)

Auto engines cost $25-50/kW
Cost of 1st generation (phosphoric acid) fuel cells is $1000-3000/kW

Dr. Roan was the only speaker to stress the importance of power electronics. He noted that the size of the power conditioner and fuel processor are **each** on the order of the size of the fuel cell stack itself; reminded group that the power conditioner is large and expensive.

Typical automobile engine is 2-5 lbs/kW (0.9-2.3 kg/kW or 0.44-1.1 kW/kg)
0.1-0.3 ft^3/kW (2.8-8.5 liters/kW or 0.12-0.35 kW/liter)

1st generation (phosphoric acid?) fuel cell is 20-50 lbs/kW (9-23 kg/kW or 0.04-0.11 kW/kg)
1-3 ft^3/kW (28-85 liters/kW or 0.012-0.035 kW/liter)

Shoibal Banerjee - DuPont

Observed that DuPont is already a multibillion dollar supplier to the auto industry with products like wind shields, fuel delivery parts, and plastics. For the fuel cell DuPont makes the Nafion membrane, which is a commercial product. DuPont has multibillion dollar fluor products capability; they are integrated back to the fluorspar mines and have the capacity to meet market demand.

Their R&D philosophy: the membrane can affect the rest of the system; it impacts water management and heat management both, so a systems approach is needed. Membrane is also important in DMFC development. They also believe in internal and external partnering.

In discussing economies of scale in membrane manufacture he presented an interesting graph showing unit costs and production volumes of different polymers they produce; it showed dramatic cost reductions with volume manufacture (though the products were different). Products similar to Nafion showed a 10-fold decrease in cost per 100-fold increase in production *(70% progress ratio)*. He did say there was no reason why Nafion cost should be a hurdle to commercialization, since its cost should come down just as other membranes have.

He sees developing countries as early markets for fuel cells. They have pollution problems, lower powered vehicles are OK, and there is no existing fuel supply infrastructure to be overcome.

He talked about the technology switch in the chlor-alkali industry from a process based on mercury to Nafion membrane based electrolysis, noting that this change too was driven by environmental concerns, took place rapidly in the past decade, with the result that the membrane based process is now the most economically viable for chlor-alkali plants. In summary, he said fuel cells could be a technological revolution, that it could be global, and that DuPont is committed to this project.

Dr. Kathy Taylor - Director of GM's Physical Chemistry Lab

It will be a great challenge for the auto industry to put fuel cell vehicles on the road by 2004. Issues include:

1. Timing - with proof of concept by 2000 and production prototype by 2004, a commercial demonstration is missing

2. Money - needs lots of money for R&D. It takes $6 billion to bring a car to market when car companies know what to build

3. Technology - PEMFC and especially reformer based systems are still R&D activities

4. Performance

5. Durability - need 100,000 mile life; can fuel cells do better and offer a win to the consumer?

6. Emissions - fuel cell vehicles can be ZEVs, but there is the hydrogen infrastructure problem. Will zero emissions be the cost of market entry to the vehicle market in the next century? She says she thinks so

7. People - need flow of trained scientists and engineers

8. Customer Acceptance - need a distinct advantage, and there can be not even a perceived inconvenience. Fuel cell vehicles will have to operate at temperatures down to -30°F and up to 4000 meters altitude

9. Safety - both reality and perception

10. Infrastructure and fuel distribution

11. Bureaucracy - it takes a long time to get programs going

12. Competition - fuel cell cars will have competition from internal combustion engine hybrids and battery powered EVs

13. (brought up by a questioner) Serviceability and reliability

Speaker from Ford

We - car companies as well as university researchers - need to suspend our cynicism on this project. For example, when Detroit says people want certain qualities in a car they do so because these are real issues, not because they are trying to kill an alternative approach. Remember that these new technologies don't just go directly from lab into production - they need a pilot stage; we need someone to fund these. Final advice: don't let go of the systems approach including vehicle, service, and infrastructure.

President of Society of Automotive Engineers (SAE)

Throughout the symposium several speakers and participants brought up the lack of standards for reporting fuel cell and fuel cell system performance (ie, higher or lower heating value efficiencies, continuous or peak operation, definition of continuous and peak, the need to report reactant gas pressure with performance data, etc). At the end of the meeting the president of the SAE took the floor briefly to observe this theme and offer the organizational help of the SAE in developing such standards. He encouraged interested attendees to get in touch with Tom Price, SAE's Washington representative, to start a subcommittee for drafting such standards.

APPENDIX

Key Personnel From the Big Three

GM	FORD	CHRYSLER
Arvin Mueller Vice President	John P. McTague VP, Technical Affairs	Francois J. Castaing VP Engineering
Ron E. York Director, New Generation Vehicle Program Also USCAR	Robert F. Mull Director, New Generation Vehicle Program Also USCAR	Tim Adams Director, New Generation Vehicle Program Also USCAR