SAE TECHNICAL PAPER SERIES

2001-01-2508

Development of the Jeep Commander 2 Fuel Cell Hybrid Electric Vehicle

Doanh Tran and Michael Cummins
DaimlerChrysler – Chrysler Group - Liberty and Technical Affairs

Reprinted From: Hybrid Electric Vehicles 2001 (SP–1633)

The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

Future Transportation Technology Conference
Costa Mesa, California
August 20-22, 2001

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

ISSN 0148-7191

Printed in USA

2001-01-2508

Development of the Jeep Commander 2 Fuel Cell Hybrid Electric Vehicle

Doanh Tran and Michael Cummins
DaimlerChrysler – Chrysler Group - Liberty and Technical Affairs

ABSTRACT

On-board fuel reforming for fuel cells is an important strategic option in the development of mass production fuel cell vehicles. Based on a reforming concept similar to DaimlerChrysler's NECAR 3, the concept prototype Jeep Commander 2 implements a methanol reforming fuel cell engine with a 90 kW NiMH battery pack. Driving and dynamometer testing results show good driving performance, fuel economy and emissions. However, significant improvements are needed on fuel reforming systems to achieve competitive levels of power density, cost and reliability, compared to internal combustion engines.

INTRODUCTION

The introduction of fuel cells for automobiles sparks many discussions on the 'fuel of choice" [1-3]. The cleanest fuel cell engine (i.e. zero emissions) requires the cleanest fuel, hydrogen, to produce electricity. The source of hydrogen for the fuel cell presents major technical challenges for on-board hydrogen storage, fuel reforming systems and fuel infrastructure. To meet consumers' needs, fuel cell vehicles must provide a competitive driving performance and range compared to internal combustion engines. On-board fuel reforming for fuel cells is a necessary alternative until hydrogen storage can achieve competitive specific weight, energy density and storage efficiency compared to liquid fuels.

Liquid fuels, such as methanol, offer the advantages of cost, storage, ease of dispensing and transporting compared to hydrogen fuel. In addition, methanol is simpler to reform and produces lower emissions than a gasoline reformed fuel cell engine. As for new fueling infrastructures, methanol will be easier to implement than hydrogen.

DaimlerChrysler has been quite proactive in the pursuit of methanol as a fuel since the introduction of the NECAR 3 in 1997. Other automotive OEMs were also interested in on-board methanol fuel reforming for fuel cells development. Each introduced their versions of methanol fuel cell concept vehicles, such as GM's FCEV based on the Zafira platform, Toyota's FCEV based on the RAV4 platform and Nissan's FCEV based on the R'nessa/Altra EV platform [4-6]. The Chrysler Group has been interested in on-board gasoline fuel reforming since 1997 and introduced the Jeep Commander I in 1999. The variation in concentration of the current gasoline formulation creates many technical challenges for on-board fuel reformers, hindering this reforming technology from concept vehicle integration for the Commander I. In 1998, capitalizing on the development synergy of NECAR 3 technology from DaimlerChrysler, the Chrysler Group developed the Jeep Commander 2 to maximize the benefits of on-board fuel reforming and minimize the limitations of fuel reforming through hybridization. Thus, Jeep Commander 2 is an extension of knowledge gained from the extensive work in hybrid powertrain technology at the Chrysler Group that developed engineering vehicles such as the Dodge ESX, ESX2, ESX3, Neon hybrids, the production-intent Durango TTR hybrid and Contractor Special.

In October 2000, DaimlerChrysler introduced the Jeep Commander 2 methanol fuel cell hybrid electric vehicle at the Environmental Conservation Conference in Lansing, Michigan. Since then it has been all over the world at various demonstration events for media and engineering personnel to test-drive. The Jeep Commander 2 is the first hybrid methanol fuel reforming fuel cell automobile available for media demonstration events and to demonstrate the packaging flexibility of a fuel cell engine.

VEHICLE DESCRIPTION

The DaimlerChrysler Jeep Commander 2 (Figure 1) is a four-wheel-drive hybrid electric methanol fuel cell vehicle. This concept vehicle's overall dimensions are similar to the current Jeep Grand Cherokee, except for the width, which is about 18 cm wider. This provides enough room for five passengers and complete luggage space. The

Figure 1. DaimlerChrysler Jeep Commander 2 FCV

vehicle body is constructed of lightweight, injection-molded plastic to help offset the additional weight of the fuel cell engine. The primary by-products from this fuel cell engine are water vapor and carbon dioxide. The battery pack provides instantaneous power for performance and allows recapture of braking energy through the front and/or rear 83 kW AC induction traction motor. A summary of the Jeep Commander 2 characteristics is given in Table 1.

The packaging configuration of the Jeep Commander 2 is shown in Figure 2. The current level of methanol fuel reforming technology requires innovative packaging techniques to prevent cabin intrusion. The separation of the fuel reforming system from the fuel cell stacks is necessary for component allocation and vehicle weight balance. The high temperature part of the fuel processing system, or "hot box", is in the front of the vehicle, along with the de-ionized water reservoir. The fuel cell stacks, air compressor and the low temperature CO gas clean up selective oxidizers (SelOx), are located in the rear of the vehicle. The battery pack is in the center of the vehicle. In addition, collaborative system integration between DaimlerChrysler and Xcellsis eliminated a few heavy and bulky components from the fuel cell engine. The electric powertrain is based on the FWD Chrysler's Electric Powered Interurban Commuter (EPIC) minivan but doubled to drive the individual front and rear axles of the Commander 2 along with upgraded inverters and traction motors.

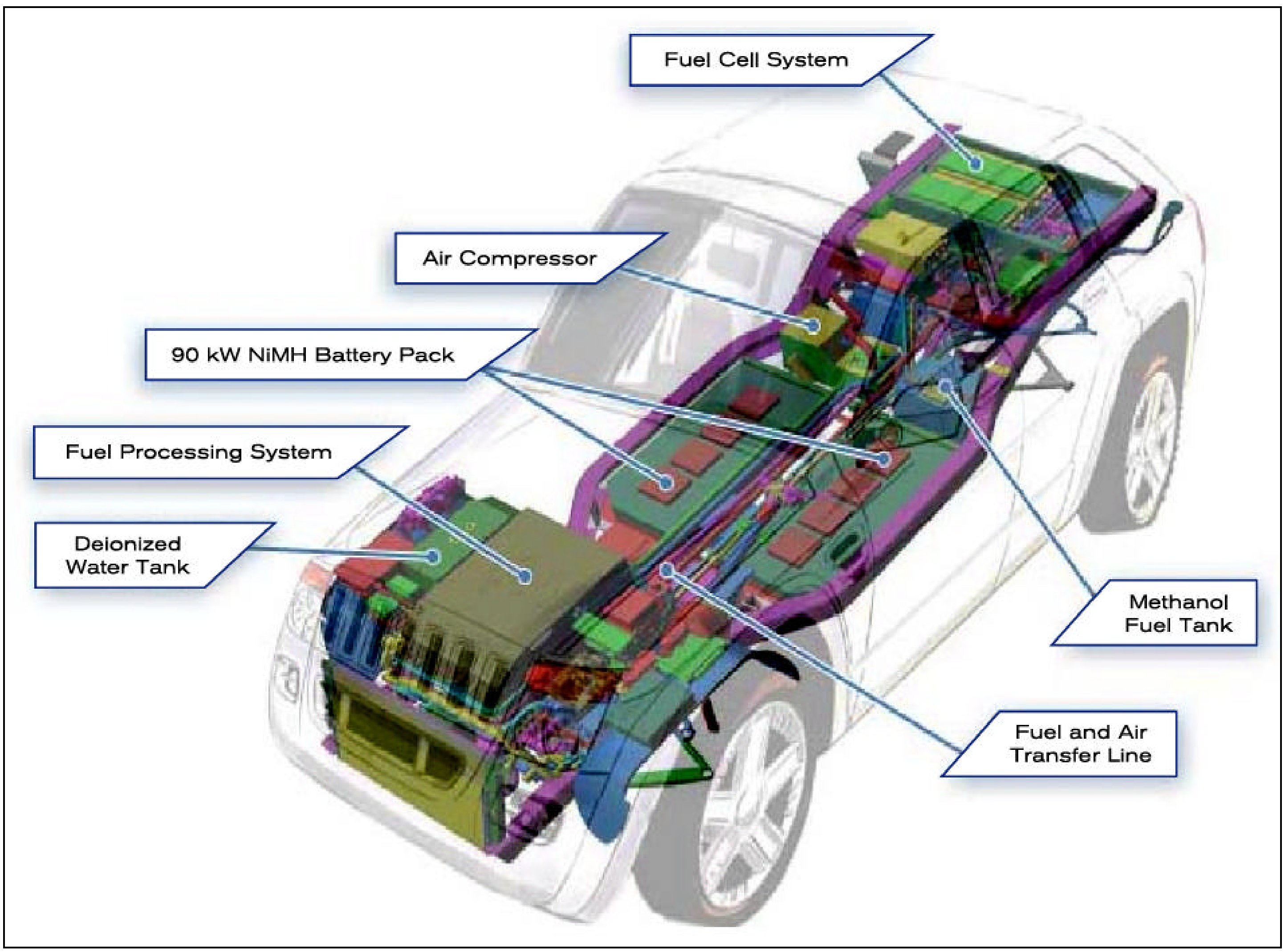

Figure 2. Commander 2 Packaging Configuration

Table 1. Jeep Commander 2 Vehicle Characteristics

Jeep Commander 2 Vehicle Specifications	
Dimensions	
Overall length	4.72 m
Overall width	2.03 m
Overall height	1.76 m
Wheelbase	2.9 m
Curb weight	2590 kg
Tire (F&R)	275/55R20
Powertrain	
Engine	Methanol fuel cell
Type	PEM
Power (gross/net)	50 kW / 38 kW
Number of stacks	2 (Ballard MK 705)
Operating voltage	270 to 220 V
Electric Drive	Dual motors (front & rear)
Type of motor	AC Induction
Power	83 kW peak; 35 kW nom
Peak torque	239 Nm
Transaxle	Single speed - 11.4:1 GR
Battery pack	324 V NiMH (nominal)
Power	90 kW
Capacity	28 Ahr
Fuel	Neat methanol

MAJOR SYSTEM COMPONENTS

Fuel Cell Engine

The fuel cell engine consists of a methanol fuel reforming system and PEMFC stacks. Xcellsis developed the fuel reforming system and balance of plant around the two 25 kW fuel cell stacks supplied by Ballard Power Systems. The fuel cell stacks require humidified hydrogen (fuel) on the anode side and humidified oxygen (oxidant) for the cathode side. Pressurized ambient air is supplied to the cathode side as the oxidant by the air compressor. On-board fuel processing provides pressurized humidified hydrogen for the anode. The two most common types of fuel processing for carbon-based fuels are steam and partial oxidation.

Steam reforming offers the highest hydrogen concentration in the reformate gas using an endothermic reforming process. Steam reformation of methanol optimizes the low heat energy requirement for methanol and highest hydrogen product concentration yield. Partial oxidation provides fast exothermic reforming reactions but the lowest yield in reformate hydrogen product gas concentration [7]. Figure 3 shows the basic fuel processing technique of the methanol fuel steam reforming system in the Jeep Commander 2. Detailed subsystem chemical reactions on a similar Xcellsis methanol reforming system can be referenced in literature [8,9]. Due to the maturity status of on-board fuel processing technology, the vehicle requires two modes of operation: stationary cold start and normal operations. In cold start, the fuel cell system uses the battery pack, pure hydrogen from off-board, and methanol to bring the

$$CO + \frac{1}{2}O_2 = CO_2$$

fuel processing system to the optimal operating temperatures. To cold start the fuel cell engine, the air compressor and a few other fuel cell auxiliary components use the battery pack power, via the bi-directional DC/DC converter, to start the flow of oxidant into the cathode side of the fuel cell stacks. Pure hydrogen flows into the anode side from the off-board compressed hydrogen bottles. The fuel cell stacks generate power within a few seconds and all auxiliary loads switch to using power from the fuel cell stacks. This 6 kW gross idle electrical load helps warm up the whole fuel cell engine. After the fuel processing system is partially heated to 240°C, processing of the methanol begins. Until all the fuel processing components reach their designed reaction temperatures, the reformed fuel is catalytically burned in the combustor and afterburner, heating the oil circulation loop to bring the fuel processing system to its optimal reforming temperature of 270°C.

In the normal operating mode, the electronic grade/neat methanol is pumped from the 40 liter stainless steel fuel tank to the fuel processing system, or “Hot box”, in front of the vehicle. The “Hot box”, as shown in Figure 4, consists of the vaporizer, reformer, selective oxidizers (SelOx) (1) and (2), combustor, and afterburner. First,

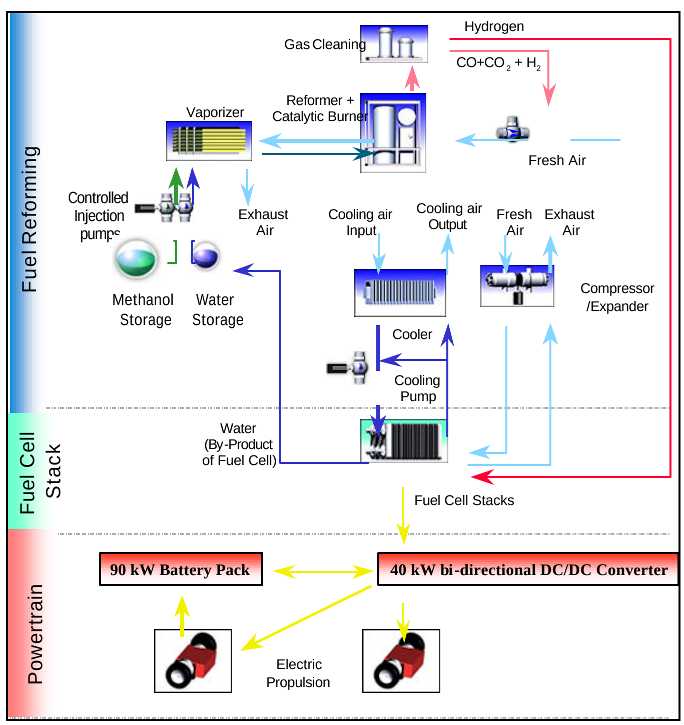

Figure 3. Jeep Commander 2 System Schematic

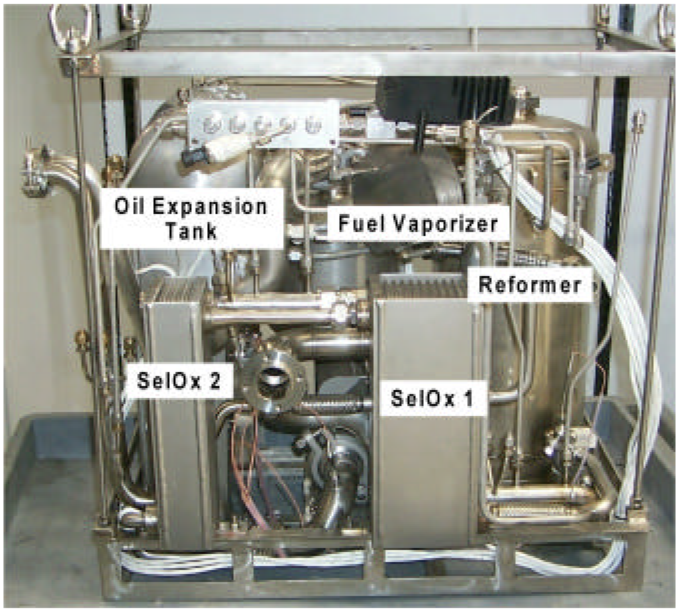

Figure 4. Jeep Commander 2 'Hot Box"

methanol and water are converted into steam in the vaporizer. Next, in the reformer, the methanol is converted into a reformate gas consisting of H_2, CO and CO_2. The fuel cell stacks can operate with CO_2 but not with CO in the H_2 mixture. This is because CO is adsorbed onto the catalysts and blocks reaction sites for the hydrogen molecule on the electrodes of the MEAs of the fuel cell. The overall reversible effect minimizes reaction sites for the H_2 which reduces the fuel cell power output. To remove the CO, the selective oxidizer (Selox) converts the CO to CO_2 with the minimum amount of H_2 consumption. The heat generated in the exothermic reaction in Selox 1 and Selox 2 is used to drive the steam reforming reaction. Oil is the heat transfer medium used on the high temperature components in the process. This thermal integration helps improve the overall efficiency of the fuel processing system.

Reactant flow and current distribution conditions create a demand that inhibits 100 percent fuel utilization on the anode side. The exhaust hydrogen anode gas goes to the combustor to generate heat for the fuel processing system. This thermal recycling contributes to the overall efficiency of the fuel cell engine. In addition, air and methanol are fed to the combustor when more heat is required to keep the reforming system at designed operating temperatures.

Bi-Directional DC to DC Converter

In the Jeep Commander 2, the fuel cell operating voltage is lower than, or equal to, the battery voltage. With two distinct operating modes of the fuel cell engine, a design specific 60 kW DC to DC converter had to be developed. In the primary, normal, or 'boost' mode, the DC/DC converter is current controlled because the fuel cell is a current source. The DC/DC converter raises the output voltage to charge the battery pack and drive the two traction motors efficiently. The secondary mode is to provide battery power to the fuel cell to run the auxilliary components in the start mode. In this span of 10 seconds, the DC/DC converter operates in a voltage controlled mode, or 'buck' mode, where the converter provides a fixed programmed voltage output to the main auxilliary components to start the fuel cell engine. The fixed output voltage is dependent on the current battery voltage.

High Voltage Battery Pack

A 90 kW NiMH battery pack works in conjunction with the fuel cell engine to provide instantaneous power so the vehicle will have good driving performance and also to capture regenerative braking energy. This high voltage battery pack consists of 56 modules to provide a nominal operating voltage of 324 V and weighs nearly 230 kg. In the hybrid mode, the state of charge is maintained between 40 to 80 percent.

Electric Propulsion

The 83 kW peak AC induction traction motor drives each axle of the vehicle to maintain the four-wheel-drive tradition of Jeep vehicles. With the exception of these traction motors and controllers, the rest of the electrical system comes from the Chrysler EPIC vehicle. Packaging constraints, performance requirements, time and cost affected the engineering selection. The motor controllers peak operating voltage was increased from 380 V to 410 V to allow for braking energy capture back to the high voltage NiMH battery pack. The two traction motors allow the driver to switch driving modes of Front Wheel Drive to Rear Wheel Drive to Four-Wheel-Drive instantly depending on the road and weather conditions.

ELECTRICAL ARCHITECTURE

The final high voltage architecture design of the Jeep Commander 2 is shown in Figure 5. The initial design uses two uni-directional DC/DC converters to support the two operating modes of the fuel cell engine. The first would convert 12V to 300V at 2.5 kW to run the fuel cell auxilliaries during start-up, similar to the converter used in the Ford P2000 [5]. The second converter boosts the fuel cell stack voltage up to a maximum of 405 V so that it could charge the battery pack and/or drive the traction motors. This initial configuration requires packaging volume that the Jeep Commander 2 did not have. A different electrical architecture design was implemented to use a single bi-directional DC/DC converter. This design conserved precious packaging volume and simplified the electrical and control systems. The final electrical architecture places the high voltage battery on the inverter bus, which provides direct power to the traction motors. This configuration allows the fuel cell engine time to spool up to full power during hard acceleration. This electrical architecture allows for parallel engineering development of the vehicle and the

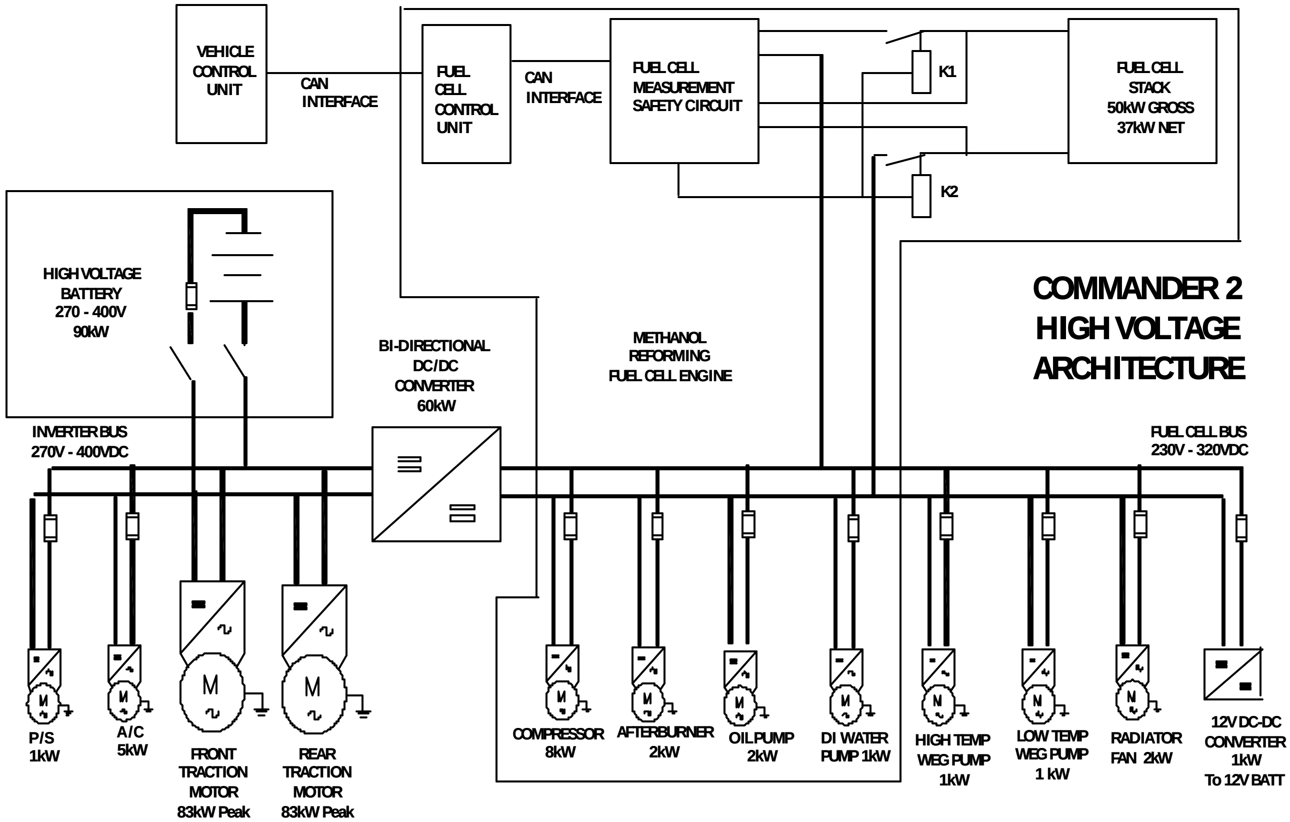

Figure 5. Jeep Commander 2 High Voltage Electrical Architecture

fuel cell engine; thus reducing the overall vehicle build timeline.

VEHICLE PERFORMANCE

The engineering performance targets for the Jeep Commander 2 were to achieve acceleration and performance comparable to vehicles in the same class with better fuel economy and drastically reduced emissions summarized in Table 2. Compared to the Chrysler EPIC minivan, the Jeep Commander 2 is much faster, with a longer driving range and refueling time, similar to gasoline vehicles. The fuel economy is expressed as a gasoline equivalent for direct comparison with today's SUVs. The high energy conversion efficiency of the fuel cell engine and electric propulsion allows the Jeep Commander 2 to achieve 10 kmpl during a combined metro/highway driving cycle. This is almost twice as efficient as today's SUVs while achieving zero federally regulated emissions. The long cold start time of the fuel reforming system requires improvement in on-board fuel reforming.

In the hybrid configuration, the Jeep Commander 2 is very responsive due to the battery and the electric motors. A typical drive around the test track can be summarized in Figure 6. The 90 kW high voltage battery provides the instantaneous power to the traction motors; thus, providing the instant acceleration on demand and additional time for the fuel reforming system to catch up with the higher load if needed. Although the onboard fuel reforming system is slower in response to a load change than a pure hydrogen fuel cell, it is quite sufficient in a hybrid configuration. In addition, hybridization allows the fuel cell engine to maintain a more steady state condition for operating at the highest efficiency and minimizes CO production as shown in Figure 7. Figure 7 is a close-up section in Figure 6 to show the operating strategies of the fuel cell engine in a hybrid vehicle configuration. An optimized control system can balance the power from the battery and the fuel cell engine to provide performance to meet the customer's need, along with high fuel economy and lower emissions to protect our environment.

REMAINING ENGINEERING CHALLENGES

Heat and water management are the two major technical challenges facing the fuel cell engine. The low operating

Table 2. Commander 2 Performance Characteristics

Performance	
Acceleration	13 seconds (0-100 kph)
Fuel economy	10 L/ 100 km G.E. est.
Emissions	CO_2, <100 ppm CO
Range	~ 190 km
Start up time (cold)	~ 45 minutes

.

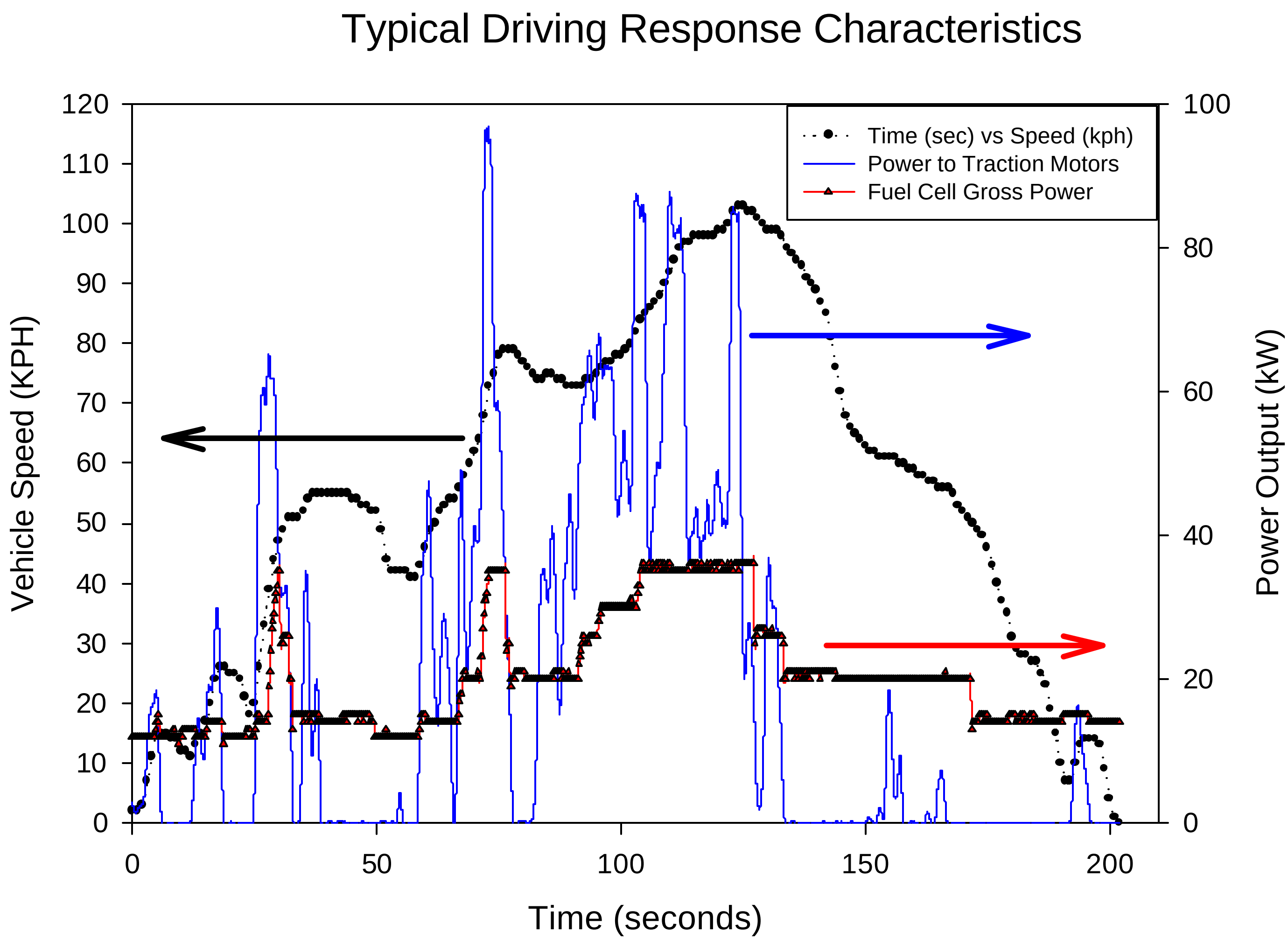

Figure 6. Jeep Commander 2 Driving Response

temperature of the fuel cell stacks and the limited frontal area of the vehicle create major problems for heat rejection, especially at higher ambient temperatures. Further thermal integration of the fuel processor is also needed to improve the overall efficiency of the fuel cell engine. Water management includes keeping a positive water balance for the fuel cell engine and freeze prevention of the de-ionized water used for humidification. The current PEM membrane requires humidification of the anode and cathode gases to provide proton transport to produces electrical power. De-ionized water is necessary to prevent a cell-to-cell electrical short circuit inside the fuel cell stacks. This creates a major challenge when fuel cell vehicles must operate, or soak, in sub-freezing temperature. The operating pressure of the fuel cell stacks varies with power output. At high power output, the system operates at a water surplus while at low power output, the system operates at a water deficit. Since the fuel cell stacks operate around 80°C, maintaining a equilibrium water balance is very dependent on the operating profile and ambient temperatures.

To be competitive with the ICE, the fuel reforming system weight needs to be reduced by at least an order of magnitude, along with cost. DaimlerChrysler NECAR 5 shows a major reduction in volume, but not in weight. A lighter fuel processing system will have lower thermal mass resulting in a faster cold starts. The cost must also be reduced drastically before fuel cell vehicles can enter the mass market. Reduced precious metal utilization along with innovative manufacturing techniques are critical goals that must be achieved.

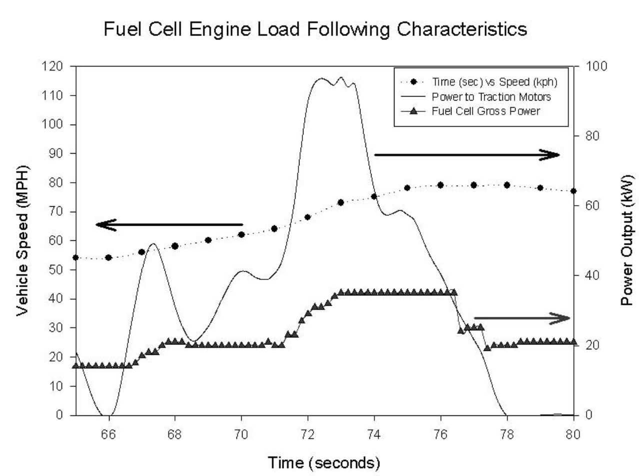

Figure 7. Fuel Cell Engine Driving Response

CALIFORNIA FUEL CELL PARTNERSHIP

DaimlerChrysler leads the automotive industry in designing, engineering, and testing fuel cell vehicles. Since 1994, with the New Electric Car (NECAR) I, DaimlerChrysler has unveiled five generations of NECAR along with a few fuel cell powered buses (NEBUS). DaimlerChrysler is committed to the development of safe, clean and fuel-efficient vehicles.

To address some of the challenges of fuel cell technology, DaimlerChrysler initiated the California Fuel Cell Partnership as the world's first partnership to demonstrate the feasability of fuel cell cars as an alternative drive solution. This voluntary alliance's main goals are to: 1) test the vehicles under day-to-day driving conditions; 2) determine the best fuel choice; 3) explore infrastructure requirements; and 4) expand public outreach [1-3]. The day-to-day vehicle operation will provide an engineering database to guide fuel cell technology development in a direction that will best serve the mass consumer.

SUMMARY AND CONCLUSION

The Jeep Commander 2 was able to overcome many challenges with on-board fuel reforming for PEM fuel cell by hybridization, use of lightweight body construction and more available packaging space. Although the fuel cell stacks have improved in weight and volume, the fuel processing system must make the same improvements. These reductions are necessary for fuel reforming fuel cell engines to achieve acceptable start-up time and competitive performance against ICE vehicles.

The Jeep Commander 2 hybridized electric powertrain overcomes the limitations of the current fuel reforming system. Preliminary road and dynamometer testing of the Jeep Commander 2 show good driving performance, fuel economy and emissions results. The high voltage battery provides instant power-on-demand to satisfy the driver's performance needs and a liquid fuel reforming fuel cell engine to provide the fuel economy, emissions and driving range acceptable to most customers. However, more technological innovations are needed for the reforming fuel cell engines to achieve competitive levels of power density, cost and reliability, as compared to internal combustion engines.

ACKNOWLEDGMENTS

The authors would like to thank Thomas Moore of Liberty and Technical Affairs for his relentless support to the development of fuel cell technology. The authors would also like to commend the remaining DaimlerChrysler fuel cell team members for their contributions to the success of the Jeep Commander 2: Christopher Borroni-Bird*, Gary Bronner, Jason Buelow, Jack Kulik*, Christian Mohrdieck, Dan Sauger, Mohsen Shabana* and Euthemios Stamos along with the Xcellsis team members Gerry Merten, Tavin Tyler, William Odell, Cathy Meyers, and Dave Higdon.

The authors would also like to acknowledge the assistance of Kevin Maloney from Methanex Corporation and James Flemming from Air Products and Chemical for their assistance to DaimlerChrysler's Jeep Commander 2 Media Ride and Drive events.

REFERENCES

1. C. Thomas, B. James, F. Lomax, I. Kuhn, "Societal impacts of fuel options for fuel cell vehicles," International fall fuels and lubricant meeting and exposition, SAE paper 982496, October 1998.
2. J. Mark, "Environmental and infrastructure trade-offs of fuel choices for fuel cell vehicle," Future Transportation Technology Conference, SAE paper 972693, August 1997.
3. S. Arbuckle, "Hydrogen refueling infrastructure for fuel cell vehicle," Batteries Digest Newsletter, January 2001, p. 58.3-58.9.
4. S. Ashley, "Fuel cells starts to look real," Automotive Engineering International, March 2001, p. 64-80.
5. J. Adams, W-c. Yang, K. Oglesby, and K. Osborne, "The development of Ford's P2000 fuel cell vehicle," SAE paper 2000-01-1061, March 2000.
6. Jack Yamaguchi, "Nissan's fuel-cell vehicle with methanol-reforming system", Automotive Engineering International, October 1999, p. 74-75.
7. R. Kumar, H. K. Geyer, R. Ahluwalia, and M. Krumpelt, " Polymer electrolyte fuel cell systems for different fuels and fuel processing options," Proceedings of the annual automotive technology development contractor's coordination meeting, p. 301-308, 1998.
8. R. Cooper, D. Brouwer, G. Feasey, "Development of a liquid PEMFC powerplant for a hybrid transit bus," SAE paper 97FTT-54.
9. R. Kumar, S. Ahmed, M. Krumpelt, K. Myles," Reformers for the production of hydrogen from methanol and alternative fuels for fuel cell powered vehicles," Argonne National Laboratory, DOE contract W-31-109-Eng. 38, August 1992.

CONTACT

For media information regarding DaimlerChrysler's technology, go to:

Http://www.media.daimlerchrysler.com

DEFINITIONS, ACRONYMS, ABBREVIATIONS

AC - Alternating Current

FCEV - Fuel Cell Electric Vehicle

FCV - Fuel Cell Vehicle

FWD - Front Wheel Drive

G.E. - Gasoline Equivalent

GR - Gear Ratio

ICE - Internal Combustion Engine

NiMH - Nickel Metal Hydride

PEM - Proton Exchange Membrane

PEMFC - Proton Exchange Membrane Fuel Cell

RWD – Rear Wheel Drive

Selox - Selective Oxidizer

SUV - Sport Utility Vehicle

TTR - Through-the-Road