

Challenges for fuel cells in transport applications

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Abstract

The US Department of Energy (DOE) and the US automotive industry are working cooperatively under the auspices of the Partnership for a New Generation of Vehicles (PNGV) to develop a six-passenger automobile that can achieve up to 80 miles/gal. These partners are continuing to invest heavily in research and development of polymer electrolyte membrane (PEM) fuel cells as a clean and efficient alternative technology for transport applications. In the past few years, US automakers have made significant advances in fuel cell technology and have announced plans to put fuel cell vehicles on the market by 2004. DOE is working with industry suppliers to address some of the biggest remaining challenges, which include fuel processing and lowering the cost of fuel cell systems. The refueling infrastructure necessary to support fuel cell vehicles presents additional unresolved issues. This paper provides a status report on the PNGV program and provides an overview of the technical accomplishments and future plans of the DOE Fuel Cells for Transportation Program. © 2000 Elsevier Science S.A. All rights reserved.

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1. US transport sector

US planners and decision-makers face major challenges in meeting continually growing demands for transport goods and services while mitigating the adverse effects of increased vehicular traffic on energy use, environmental quality, and the economy. The entire transport sector of the US is more than 97% dependent on petroleum-based fuels and consumes approximately two-thirds of the nation's oil demand. Largely due to the popularity of vans, trucks, and sport utility vehicles, the average fleet efficiency for new cars and trucks has been declining since 1987. This situation, coupled with increases in population, in the number of vehicles used, and in per-capita miles driven, has propelled US petroleum consumption upward. The US now consumes more petroleum for highway transport purposes than is produced domestically, and, as shown in Fig. 1, the gap is expected to grow significantly over the next 20 years. In 1997, about 51% of the total US petroleum consumption by all sectors was met by imports, contribut-

ing US\$69 billion (38%) of the nation's merchandise trade deficit. The Energy Information Agency (EIA) forecasts that by 2020, imported petroleum will account for 73% of the total domestic petroleum consumption by all sectors at a cost to the nation of nearly US\$95 billion [1,2].

There is also continuing concern by many in the US health and environmental sectors about the poor air quality in metropolitan areas and the increasing levels of greenhouse gases in the atmosphere. In 1998, the United States Environmental Protection Agency (EPA) estimated that in the US over 113 million people lived in areas not meeting National Ambient Air Quality Standards [3]. The transport sector contributes heavily to non-attainment in many of these areas. Additionally, increasing levels of carbon dioxide (CO₂) and other greenhouse gas emissions are becoming a global issue. Atmospheric concentrations of CO₂ are now 32% higher than they were 150 years ago at the onset of the Industrial Revolution (circa 1850) [4]. In the US, the transport sector accounts for one-third of CO₂ emissions, and over the next 20 years is projected to become the leading carbon emitter. Clearly, to meet these energy and environmental challenges, breakthroughs in transport technologies are required — breakthroughs that will enable a

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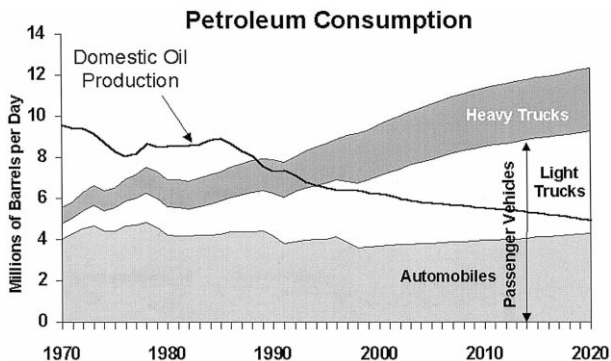


Fig. 1. U.S. highway transport now uses more oil than is produced domestically.

transition to a sustainable energy future based on the use of domestic fuel energy resources and highly efficient, clean transport propulsion systems. An industry–Government partnership is well underway to address these challenges and to provide the necessary breakthroughs.

2. Partnership for a New Generation of Vehicles (PNGV)

The PNGV was established in 1993 as a cooperative research and development (R&D) program between the Federal Government and the United States Council for Automotive Research (USCAR), which represents DaimlerChrysler, Ford, and General Motors. The focus of the PNGV is to substantially improve the fuel efficiency of today’s automobiles and to enhance the productivity and competitiveness of the US domestic automobile industry. As shown in Fig. 2, the PNGV brings together the extensive R&D resources of seven participating Federal agencies, national laboratories, and universities with the capa-

bilities of USCAR partners and their suppliers in vehicle design, development, manufacturing, and marketing. Together, these groups expect to achieve three interrelated goals [5].

The three goals of the PNGV are closely interrelated, yet maintain discrete characteristics. Goal 2 focuses on near-term improvements in conventional vehicle technologies and Goal 3 targets longer-term, breakthrough technologies, while Goal 1 is cross-cutting in nature by focusing on the manufacturing of the vehicles themselves. The objectives of Goals 1 and 2 will contribute significantly to achieving Goal 3, especially in the development of manufacturing capabilities for advanced automotive technologies. Goal 3 of the PNGV presents the difficult challenge of developing, by the year 2004, a production prototype of an 80 miles/gal or 34 km/l family sedan that will meet customers’ needs for quality, performance, and utility, as well as the Government’s safety and emissions requirements. Because the role of the Federal Government is primarily to support longer-term, high-risk R&D, the majority of Federal support is directed to technology R&D applicable to Goal 3. These technologies have significant promise in addressing the energy, emissions, and global climate change challenges facing the US. More than 80% of Federal funding for Goal 3 of the PNGV is provided by the US Department of Energy.

2.1. Goal 1: Significantly improve national competitiveness in manufacturing

Collaborators in the PNGV are working to improve the productivity of the US manufacturing base by significantly upgrading US manufacturing technology, including the adoption of agile and flexible manufacturing and the reduction of cost and lead times, while reducing the environmental impact and/or improving product quality.

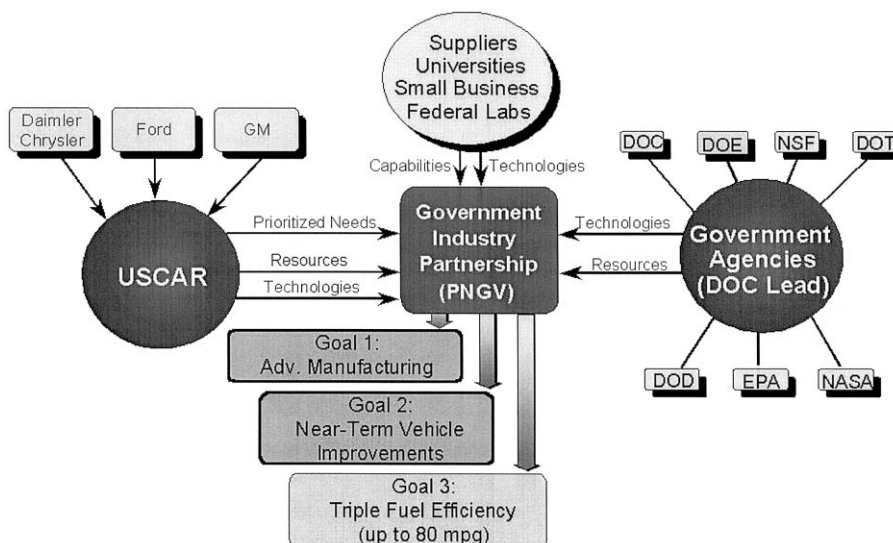


Fig. 2. The Partnership for a New Generation of Vehicles is a collaboration between the public and private sectors.

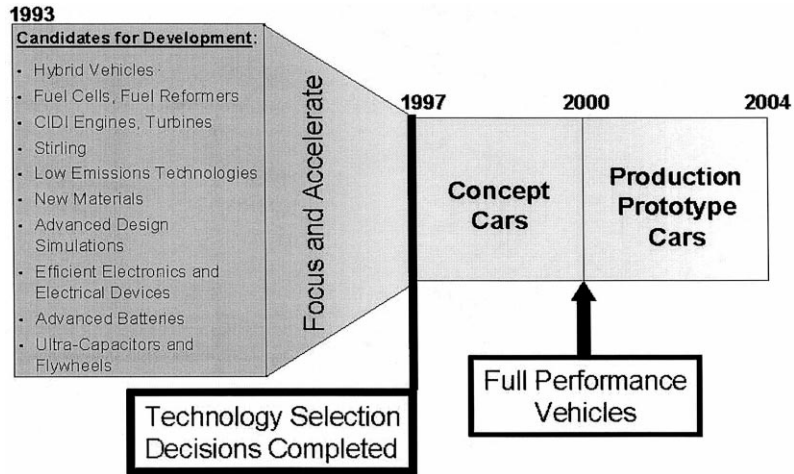


Fig. 3. The timetable for the PNGV Program runs through the year 2004.

2.2. Goal 2: Implement commercially viable innovations from ongoing research in conventional vehicles

The PNGV will pursue technology advances that can lead to near-term improvements in fuel efficiency and reductions in the emissions of standard vehicle designs, while pursuing advances to maintain safety performance. Research will focus on technologies that reduce the demand for energy from the engine and drivetrain. From the inception of the research program, the industry has pledged to apply those commercially viable technologies resulting from this research that would be expected to significantly increase vehicle fuel efficiency and lower emissions.

2.3. Goal 3: Develop vehicles that can achieve up to three times the fuel efficiency of comparable 1994 family sedans

Within 10 years, the PNGV will increase vehicle fuel efficiency up to three times that of the average 1994 Concorde/Taurus/Lumina automobiles (26.6 miles/gal

or 11.3 km/l), with equivalent cost of ownership adjusted for economics.

2.3.1. PNGV technology selection

The PNGV goals are tied to an aggressive timetable for developing a new generation of vehicles (see Fig. 3). During the first 4 years of the PNGV, USCAR and the Federal Government examined many technologies that could possibly contribute to the success of the PNGV. The 2004 deadline for production prototype vehicles, combined with resource constraints, mandated selection of the most promising technologies by the end of 1997. As a result, the PNGV adopted a selection process recognizing that some technologies are suitable near-term candidates for the PNGV, others are very promising but likely on a longer-term development schedule, and some are unlikely to be viable for passenger cars in the foreseeable future. Fig. 4 presents the most promising technologies identified by the PNGV for the 80-miles/gal vehicle. During the technology-selection process, decision-makers focused on the most

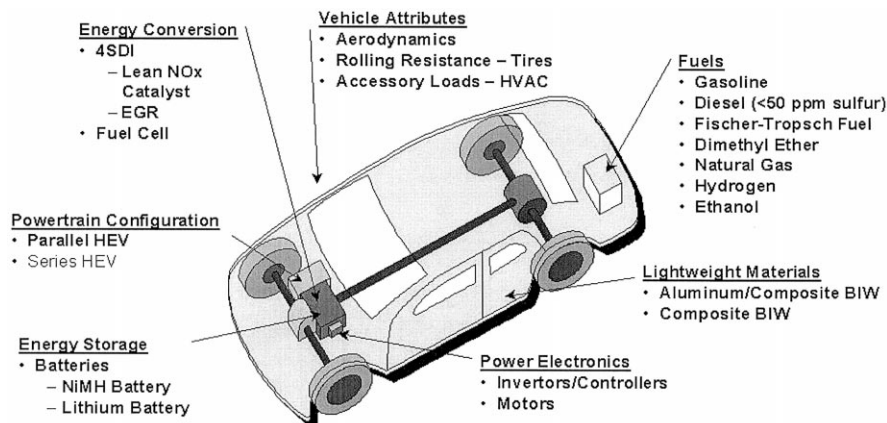


Fig. 4. Promising technologies have been identified for the PNGV 80-mpg vehicle.

promising energy conversion systems. A variety of factors were considered including performance, fuel efficiency, emissions, cost, size, weight, and state of development. Each USCAR partner has given near-term priority to the development of the compression–ignition direction–injection (CIDI) engine. However, the CIDI engine does face significant challenges in meeting the EPA’s proposed emissions standards for oxides of nitrogen (NO_x) and particulate matter in the year 2004, and in reducing the weight and cost of the powerplant. Fuel cells have also been identified as excellent energy conversion systems for the PNGV and as having the best prospect for high efficiency and low emissions.

Each USCAR partner has built test vehicles incorporating some of these advanced technologies and are now focusing on the design and construction of concept vehicles. Some of the most promising technologies will be incorporated in early concept vehicles for the year 2000, while others will be developed for use in post-2000 concept vehicles. As concept-vehicle technologies are further developed through additional government and industry R&D, the USCAR partners will incorporate them into production prototype vehicles. Production prototype vehicles are initially scheduled for 2004 and will demonstrate the PNGV’s performance targets, as well as manufacturing feasibility leading to the achievement of acceptable costs.

A standing peer review committee of the National Research Council (NRC) was formed at the onset of the program to continually evaluate candidate technologies and the progress of the PNGV. The committee has published a report for each of the past 5 years examining PNGV-relevant technologies, research progress, the relevance of ongoing research toward meeting the PNGV goals and schedule, and the overall thrust of the PNGV within the context of changing market environments. The committee commends the PNGV for making impressive progress in critical areas for fuel cells, as well as for responding positively to the committee’s recommendations. Nevertheless, a long list of identified deficiencies (and many not yet identified) remain to be resolved. The possible benefits of automotive fuel cell systems, however, are sufficiently high to justify the PNGV’s continued efforts in this area [6].

2.3.2. Fuel cells for PNGV

Fuel cells are likely to be the long-term replacement for internal combustion engines in automobiles and other transport systems and the PNGV is pursuing this technology for its capability to provide the high efficiency, low emissions, and fuel flexibility sought in the PNGV vehicle. Fuels cells have demonstrated significant progress in virtually all areas including fuel processing, stack subsystem components, and overall systems integration. However, key technical challenges still remain for polymer electrolyte membrane (PEM) fuel cells to be viable for transport applications, and it is likely that the developmental

time frame for fuel cells will extend beyond the present 2004 schedule of the PNGV. Fuel cell technologies must be validated within the context of an integrated system to confirm achievement of performance goals. Advances in fuel formulation, processing, and delivery are required to support fuel cell systems. Significant cost reductions must be achieved before fuel cells will be competitive with internal combustion engines, and the size and weight of fuel cells must be reduced to accommodate vehicle packaging requirements.

3. DOE’s Fuel Cells for Transportation Program

Under the auspices of the PNGV, the DOE is leading an ambitious, cost-shared, government–industry R&D program to develop automotive fuel cell power system technologies. These technologies are expected to be highly efficient with low or zero emissions, cost-competitive, and to operate on conventional and alternative fuels. The program targets for integrated fuel cell power systems are shown in Fig. 5.

The DOE is supporting a broad range of R&D projects for PEM fuel cell technology focusing on systems analyses, fuels, fuel processing, and stack subsystems. To address the challenges facing fuel cells for transport requires a range of developmental projects with suppliers to the automotive industry, national laboratories, and universities. Contracts and cooperative agreements with industry and universities are implemented through competitive tendering while national laboratories are directly funded based on their capabilities and performance. The DOE fuel cell R&D projects require a minimum cost-share of 25% from industry partners. In 1999, DOE committed US\$33.7 million to the program.

3.1. Systems analyses

In 1999, increased emphasis is being placed on developing tools that simulate fuel cell systems. Los Alamos

Characteristic	PNGV Targets*
Energy efficiency @ 25% peak power	48%
Power density	300 W/l
Specific power	300 W/kg
Cost	\$50/kW
Start-up to full power	0.5 min
Transient response (from 10 to 90% power)	10 sec
Emissions	<Tier 2
Durability	5000 hours

Fig. 5. Ambitious program targets have been set for the PNGV’s integrated fuel cell power systems.

	Power Level, Net*	
	50 kW	12.5 kW
Cell Voltage, V	0.772	0.896
Current Density, mA/cm ²	680	139
Fuel Utilization, %	85	85
Operating Pressure, atm	3	1.6
Efficiency, Compressor, %	75	65
Efficiency, Expander, %	90	80
Efficiency, Fuel Processor, %	80	80
Efficiency, Stack Subsystem, %	48	60
Efficiency, Total System, %	38	48

Fig. 6. ANL's system analysis identifies component and operating challenges to meet PNGV program targets.

National Laboratory (LANL) will help improve performance in fuel cell stacks by providing a better understanding of two-phase (gas, liquid water) fluid transport under simulated fuel cell conditions, stack operation on dilute hydrogen and reformat containing no contaminants, and temperature distributions in the stack during air addition. LANL is also developing models of anode performance using simulated gasoline reformat. Models of PEM fuel cell systems and components by Argonne National Laboratory (ANL) will help identify key design parameters and operating efficiencies to simulate start-up and dynamic performance and provide information to support fuel cell developers. These models are also being used to better understand the trade-offs between ambient and pressurized fuel cell systems. ANL is working with Epyx and Energy Partners to validate the models on a 10-kW gasoline fueled system and to compare the performance of various fuels.

Fig. 6 presents an analysis by ANL of the challenges that exist in meeting efficiency targets for fuel cell systems. To meet the program's target efficiencies of 48% at 25% power (12.5 kW) and 38% at full power (50 kW) will require fuel cell stack voltages of approximately 0.9 and 0.77 V, respectively. This is a significant challenge, as fuel cell stacks typically operate at cell voltages of about

0.6–0.7 V. Additionally, the fuel processor must achieve an overall efficiency of 80%, which is a major challenge when using petroleum-based fuels.

3.2. Fuels for PEM fuel cells

Fuel processing technology developed under the Fuel Cells for Transportation program must be fuel-flexible — able to convert petroleum-based fuels, ethanol, methanol, and natural gas into hydrogen-rich streams for fuel cells (see Fig. 7). This fuel processing strategy accepts the reality of today's fuel infrastructure while creating pathways for alternative fuels. Gasoline is a primary focus because of its easy availability and low cost today and for, perhaps, the next 50 years. Although it is less environmentally compatible than a zero-emissions, direct-hydrogen fuel cell vehicle, a gasoline-powered PEM fuel cell vehicle is expected to have far lower emissions than are allowable under the strictest California standards proposed. Ethanol and methanol are part of the DOE fuels strategy because they are renewable and can be made from domestic energy sources, providing the most oil displacement. Natural gas is included in the fuels strategy to maintain synergism with DOE stationary and portable power applications and for possible heavy vehicle applications [7].

An important new aspect of the program is determining the effects of fuel constituents, additives, and impurities on the performance and durability of fuel processors and fuel cell stacks. ANL and LANL are examining petroleum-based and alternative fuels (methanol, ethanol, dimethyl ether, and Fischer–Tropsch liquids) to identify appropriate fuel compositions for use with fuel cells. ANL is conducting autothermal reforming of major constituents in a microreactor to examine by-product formation, catalyst deactivation, and the dependence of hydrogen yield and conversion efficiency on reactor temperature and residence time. In a parallel effort, ANL is defining the maximum concentration of hydrogen sulfide (H₂S) in gasoline reformat that is compatible with fuel processors and fuel cell stack catalysts. ANL will develop an H₂S adsorption bed

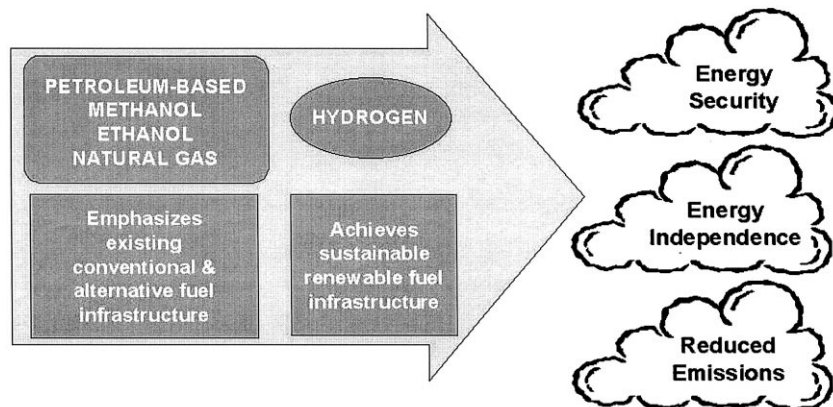


Fig. 7. DOE Fuel Strategy for Fuel Cells.

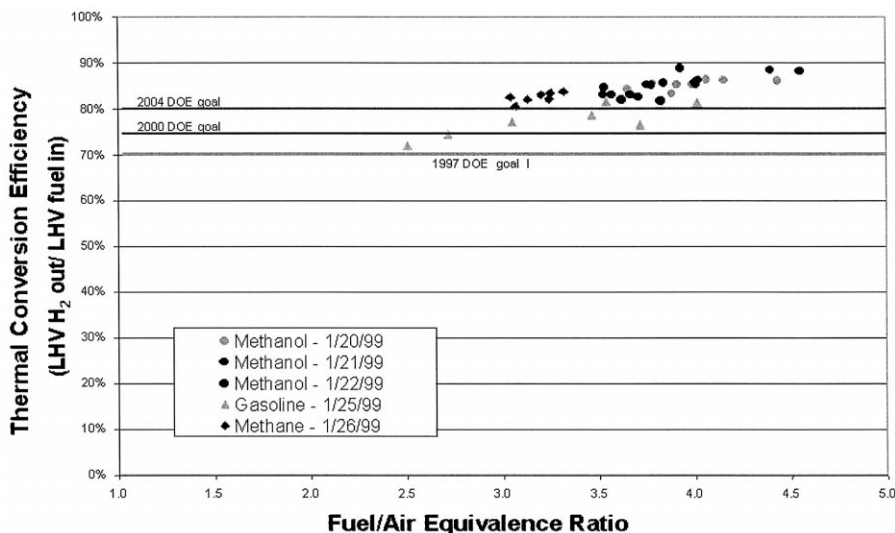


Fig. 8. Epyx’s POX fuel reformer (excluding PROX) shows a high thermal conversion efficiency with methanol, gasoline, and methane (from EPYX Model B testing, January 20–26, 1999).

for evaluation in an integrated fuel processor system. LANL is exploring fuel processing reactions with reacting (catalyzed) surfaces and with homogenous (non-catalyzed) mixtures. LANL also successfully completed its studies on mitigating the effect of certain impurities and constituents on fuel cell stacks including ammonia, methane, hydrogen sulfide, chloride, aromatics, and olefins.

Recognizing the need to further address fuel-related issues, the DOE is spearheading the industry–government Advanced Fuels Technology (AFTEC) Initiative to characterize fuels and emissions control technologies for fuel cells and CIDI engines. Initiated in 1998, this effort is pulling together all the requisite partners from industries, trade associations, and the Federal government who represent emissions control, energy/oil, and automobile interests. The partnership will focus on how petroleum-based

fuels affect the performance and emissions of PEM fuel cells and CIDI engines, recognizing that significant reformulation of fuels will have widespread impacts on the refueling infrastructure. An advanced petroleum-based fuel may consist of a highly refined petroleum base blended with non-petroleum derived blending agents. This effort could lead to a more fuel processing friendly fuel than gasoline as it exists today. The DOE program has also initiated an Advanced Petroleum-Based Fuels Program Plan, which will be available for industry review in late 1999.

3.3. Fuel processing

In recent years, the DOE Fuel Cells for Transportation Program has increased its emphasis on fuel processing,

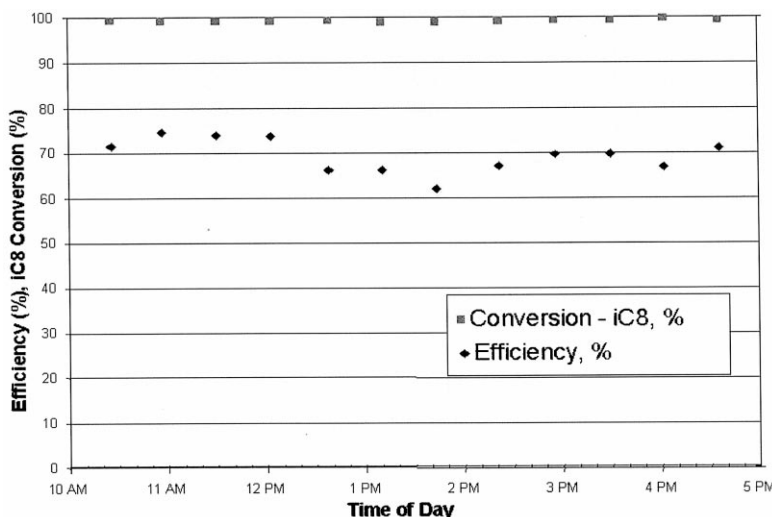


Fig. 9. ANL’s autothermal reforming of iso-octane shows high conversion levels and efficiency.

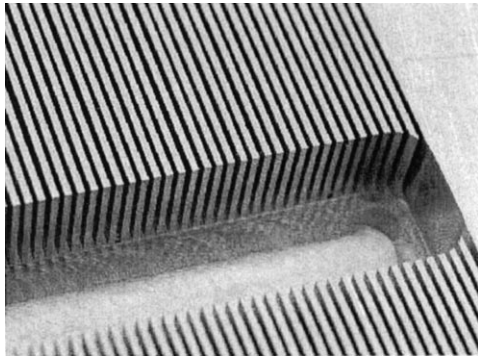


Fig. 10. PNNL is using engineered microstructures in its fuel processing technology.

recognizing that fuel flexibility and compatibility with the existing fuel infrastructure are key requirements of its program. Historically, the development of fuel processing technologies has lagged behind fuel cell stack development. This is especially true for PEM fuel cells because of the challenges to purify the reformat gas. In terms of transient response and start-up capabilities, fuel processing technologies have not yet achieved performance levels acceptable for automobiles. Research is addressing critical technical barriers including carbon monoxide (CO) clean-up and fuel processor durability, emissions, efficiency, and system integration. As mentioned earlier, a major challenge is to achieve an overall efficiency of 80% for the fuel processor, especially when using petroleum-based fuels.

Epyx has developed a 50-kW_e, partial-oxidation (POX), fuel-flexible processor that has demonstrated more than 300 h of operation. Fig. 8 contains data on the performance of the Epyx multi-fuel processor operating on methanol, gasoline, and methane. This processor demon-

strates efficiencies of greater than 70% for all three fuels as well as for ethanol. These efficiencies have been maintained over a wide range of operating conditions and presently exceed PNGV efficiency targets for years 2000 and 2004 when operating with methanol and methane.

ANL is developing autothermal fuel processing technologies that offer the advantages of greater hydrogen selectivity and high activity at lower temperatures. ANL has demonstrated a fuel-flexible autothermal reformer operating on gasoline that has achieved hydrogen outlet concentrations of 38% in the reformat gas at a rate sufficient to power a 3-kW_e fuel cell stack. This system operates at relatively low temperatures (750°C) and ambient pressure, and is compact in size. The system has achieved rapid start-up with 30% hydrogen in the reformat gas in less than 4 min. Fig. 9 presents recent data collected during tests of iso-octane (a surrogate for gasoline) on the autothermal fuel processor being developed at ANL. Conversion of the iso-octane was essentially complete at all times and when the fuel processor was operated at 7 kW thermal of hydrogen production, efficiency varied between 70% and 75%. When the fuel processing rate was almost doubled to 13-kW thermal, the reformer efficiency decreased to approximately 65%. With improved thermal integration, ANL expects to achieve the targeted fuel processing efficiencies of 75% to 80%.

Conventional steam reforming invokes a highly endothermic reaction, which requires large hardware volumes and long residence times to transfer enough heat to achieve hydrogen fuel conversion. Traditionally, steam reforming has been considered too slow to meet the transient response requirements for transport applications. However, recent advances in microfabrication processes are yielding engineered microstructures with improved heat and mass

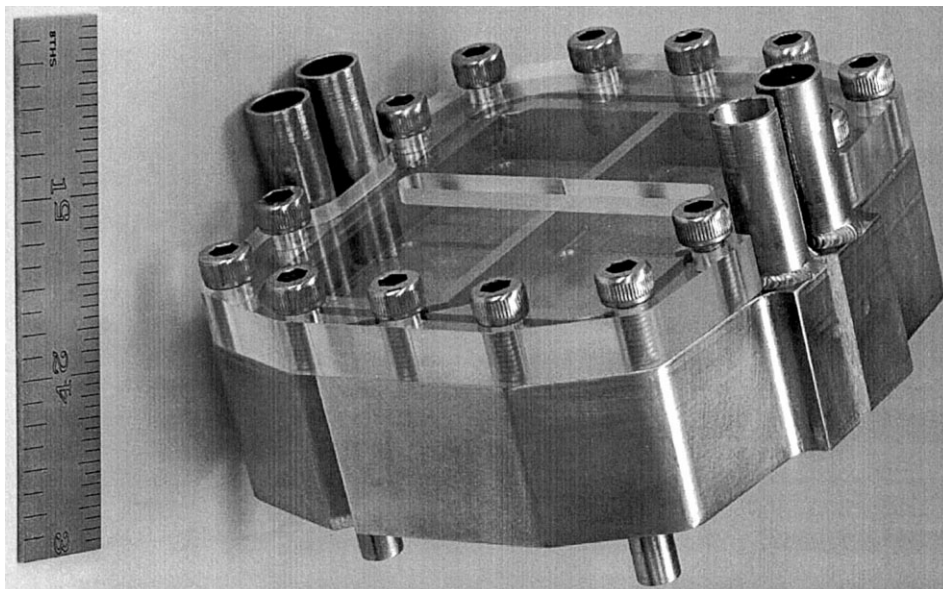


Fig. 11. PNNL's full-scale microchannel gasoline vaporizer has a 50-KWe capacity.

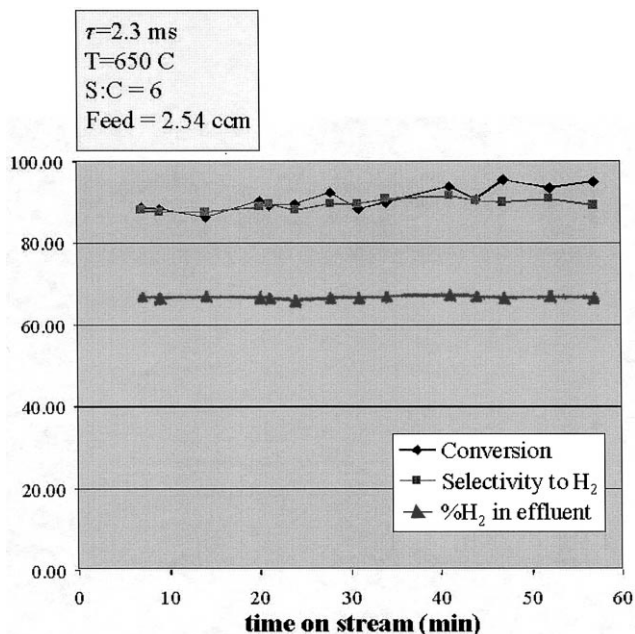


Fig. 12. Data obtained from PNNL's microchannel steam reforming system using iso-octane.

transfer characteristics, making steam reforming a viable fuel processing option for fuel cell technology.

Pacific Northwest National Laboratory (PNNL) is using engineered microstructures to develop ultra-compact reactors, separators, and heat exchangers to facilitate the reforming of liquid hydrocarbon fuels (see Fig. 10). PNNL has developed a 50-kW_e capacity microchannel gasoline vaporizer for POX and/or autothermal reformers, which has met performance goals at a volume of only 0.3 l (see Fig. 11). This technology has been transferred for testing to the industry fuel processor developers Epyx and Hydro-

gen Burner Technology. PNNL is also developing and testing the first proof-of-principle, single-cell, microchannel steam reformer. Steam reforming operates at lower temperatures ($\approx 650^{\circ}\text{C}$) than POX or autothermal reforming and at greater than atmospheric pressure without a compressor, while producing higher concentrations of hydrogen in the product stream. Fig. 12 demonstrates PNNL's success in using an integral microchannel reactor/heat exchanger leading to fast kinetics for steam reforming. The conversion and selectivity of iso-octane are both about 90% with a reactor residence time of just 2.3 ms. The dry gas content of hydrogen is between 65% and 70% compared to a dry gas content of 35% to 40% traditionally obtained with POX and autothermal reactors.

As part of fuel processing, reformat is subjected to a water-gas shift reaction where a portion of the CO is converted to carbon dioxide (CO₂) and additional hydrogen (H₂). The output from the shift reactor typically has approximately 0.5% CO (or 5000 ppm) that, along with other fuel stream contaminants, needs to be reduced to levels that do not degrade the fuel cell stack. Researchers are addressing the challenge of CO poisoning and working to better match the CO levels that can be tolerated by the fuel cell stack, approximately 100 ppm with air bleeds, with that resulting from gas clean-up systems (< 50 ppm).

LANL has developed and tested the first 50-kW_e catalyzed preferential oxidation (PROX) CO clean-up system. The approach is to mix a small quantity of air into the fuel stream and react the mixture on low-temperature oxidation catalysts. Because of the preferential adsorption of CO compared with H₂, CO is preferentially oxidized to CO₂. The intent is to reach the required level of CO with a minimum of concurrent hydrogen consumption. LANL has conducted tests using simulated methane partial oxidation reformat with an inlet CO concentration of 1% at flow

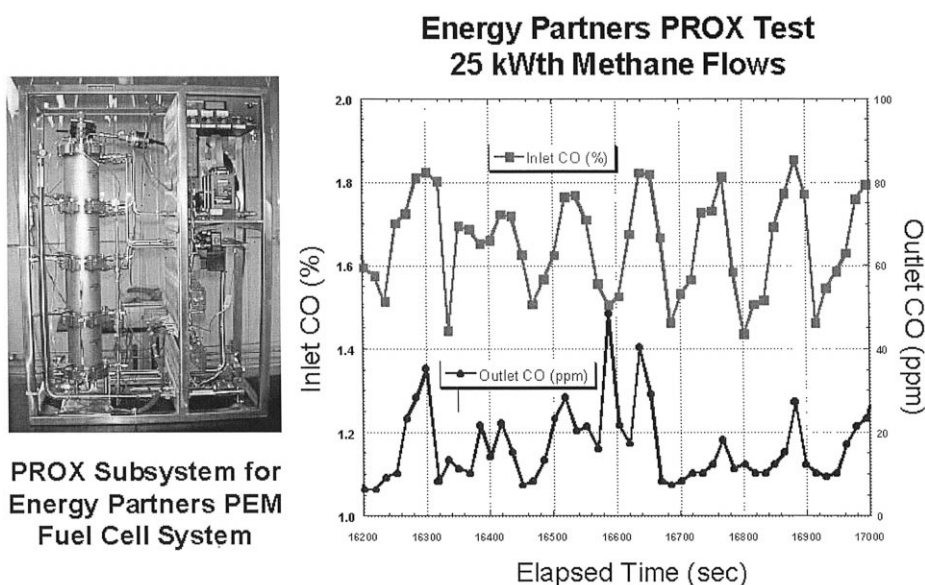


Fig. 13. Despite spikes in inlet CO concentrations, LANL's PROX CO clean-up system maintains outlet concentrations below 50 ppm.

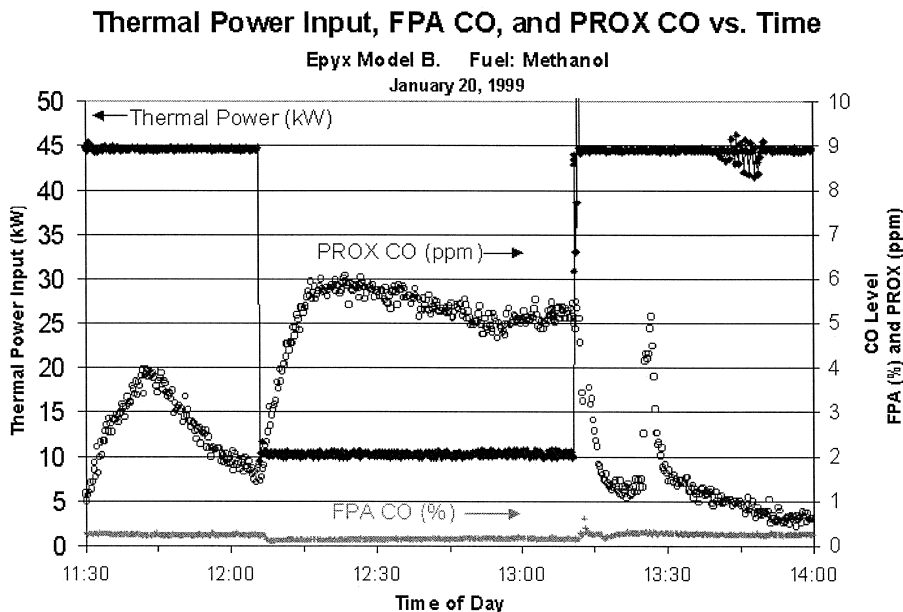


Fig. 14. Epyx's PROX CO clean-up system performs well under both steady state and transient conditions.

rates of 34-kW thermal and 15-kW thermal based on the lower heating value of methane. The three-stage PROX system consistently produces outlet CO concentrations that are below 50 ppm. The PROX subsystem has been installed in Energy Partners' natural gas PEM fuel cell system. Fig. 13 illustrates the system's ability to adjust to spikes in inlet CO concentrations while maintaining outlet CO concentrations of below 50 ppm.

Epyx is also developing a PROX CO clean-up system that has demonstrated excellent steady state and transient performance as shown in Fig. 14. Under steady state conditions, the CO concentration from the fuel processor is below 0.5% indicating a good shift catalyst; PROX outlet CO concentrations are below 4 ppm. In two-step transients from 45- to 10-kW thermal and from 10- to 45-kW thermal, reference outlet CO does not change appreciably

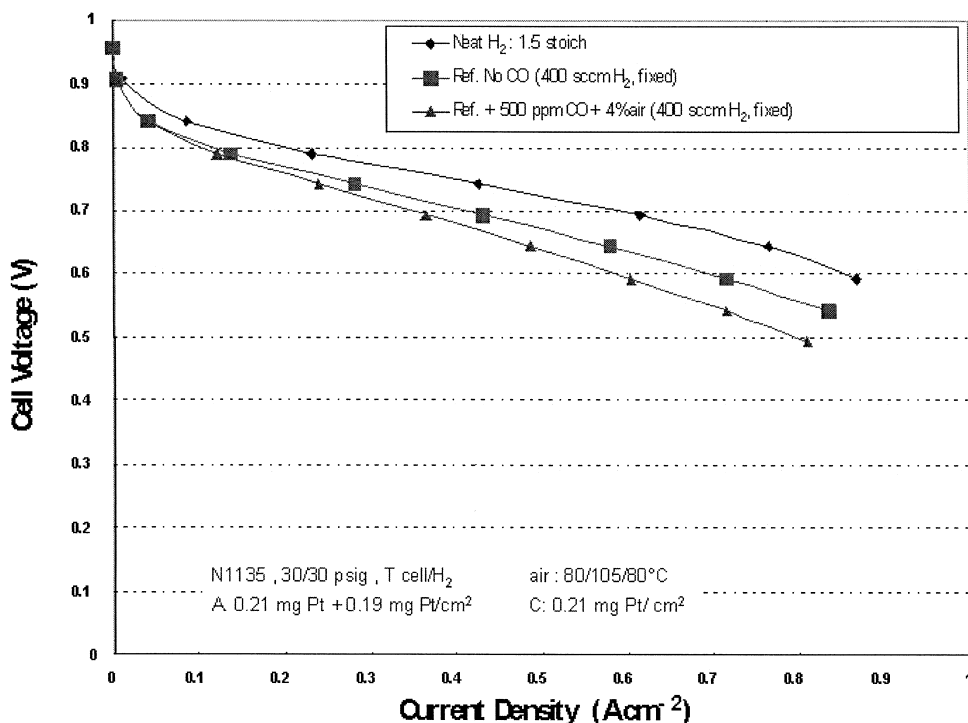


Fig. 15. LANL's new catalyst in a reconfigured anode allows significant tolerance to 500 ppm CO in reformat.

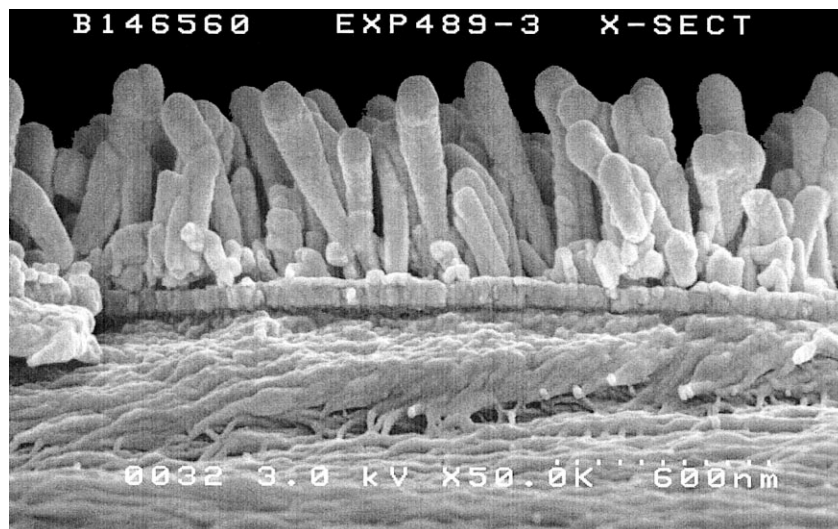


Fig. 16. A scanning electron micrograph shows 3M's nano-structured catalyst-coated film.

and PROX outlet CO remains below 10 ppm. Program targets for steady state and transient PROX outlet CO concentrations are 10 and 100 ppm, respectively.

LANL has developed a reconfigured anode (patent pending) that demonstrates excellent tolerance to CO in reformat. As shown in Fig. 15, a new catalyst in the reconfigured anode has recently demonstrated significant tolerance to 500 ppm CO in reformat, with a 4% air bleed. Here, the anode has a platinum loading of 0.4 mg/cm^2 and the cathode loading is 0.21 mg/cm^2 . The target is to develop an anode tolerant to 10 ppm CO at steady state conditions and 100 ppm under transient conditions with a platinum loading of less than 0.1 mg/cm^2 .

3.4. Stack subsystem components

Despite tremendous progress in PEM fuel cell stack technology in recent years, efforts are continuing to improve stack subsystem components. The prime challenge is to reduce the cost of components and subsequently of integrated fuel cell power systems from today's US\$500/kW to the program target of US\$50/kW.

Membrane electrode assemblies (MEAs) are the core of the fuel cell stack and require very high quality and production yields to achieve automotive cost and performance targets. 3M is developing novel MEAs based on nanostructured thin film catalysts and support systems. Fig. 16 shows a scanning electron micrograph of the company's high-surface-area, catalyst-coated nanostructure supports before transfer to a PEM surface to form a three-layer MEA. Most importantly, 3M is developing MEAs in parallel with high volume process development to meet the PNGV cost target of US\$10/kW. 3M is also developing proprietary catalysts based on the nanostructured films for optimized CO tolerance. Fig. 17 illustrates the performance comparison of a platinum ruthenium

(PtRu)-based system operating on pure hydrogen and 50 ppm CO with a 0.5% air bleed.

One of the most expensive components in the fuel cell stack system is the solid graphite, bipolar separator plates. The Institute of Gas Technology (IGT) is developing low-cost, compression-moulded, carbon composite bipolar separator plates and a conceptual design for their mass production. IGT has successfully selected, blended, and optimized inexpensive raw materials to meet or exceed all electrical, chemical, and physical property targets. As shown in Fig. 18, the performance of the moulded composite bipolar separator plates (300 cm^2) is comparable to state-of-the-art machined graphite plates. At a production level of 500,000 units per year, the program goal of US\$10/kW is expected to be met. The raw material cost is estimated at US\$1.46/lb accounting for US\$4/kW. IGT has transferred this bipolar plate technology to Stimsonite, which has fabricated moulds for pilot production and joined with ENDESCO in a joint venture called PEM Plates, LLC.

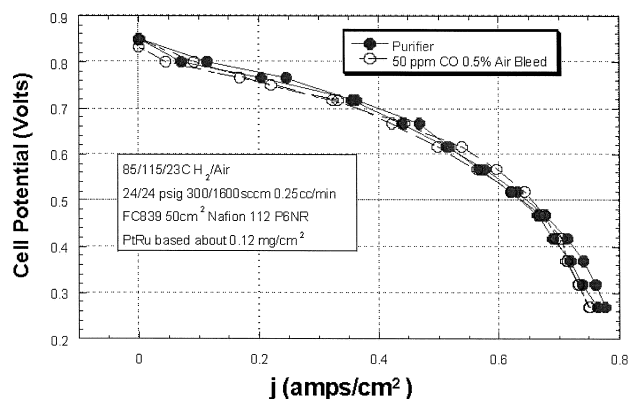


Fig. 17. Performance comparison of 3M CO tolerant anode catalyst based on microstructured films using pilot production processes.

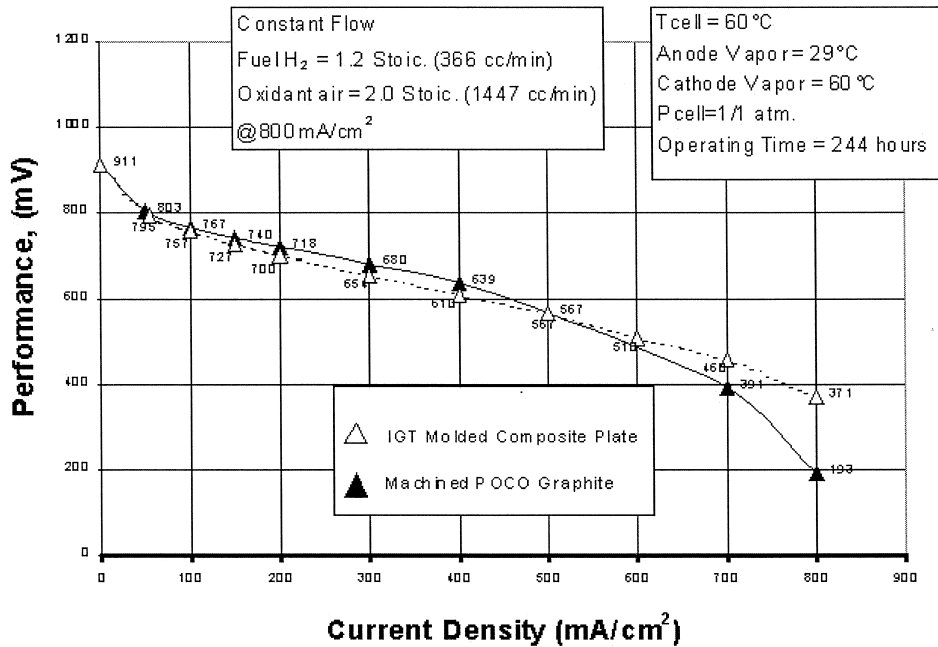


Fig. 18. The performance of an IGT molded graphite bipolar separator plate is similar to that of a machined graphite plate.

3.5. Fuel cell system deliverables

In calendar year (CY) 2000, Energy Partners and Allied Signal Aerospace Equipment Systems will each build and test 50-kW reformate capable stack systems with supporting gas, thermal, and water management systems. Plug Power and International Fuel Cells (IFC) will each deliver integrated fuel cell systems combining their stacks with fuel-flexible processors and balance-of-plant components (see Fig. 19). Plug Power will deliver a pressurized 50-kW integrated system with an Epyx fuel processor while International Fuel Cells 50-kW integrated technology will operate at near-ambient pressure with IFC’s autothermal fuel processor. System testing will measure the progress achieved by the four contractors against PNGV targets for

year 2000 and will identify further challenges that will be used to direct future research efforts.

4. Future challenges and strengthening of program

Despite numerous successes in recent years, PEM fuel cell technologies for automotive applications face significant technical challenges. In the near-term, the US Department of Energy’s Fuel Cells for Transportation Program will increasingly emphasize emissions measurements and assessments of fuel cell systems, the development of improved water–gas shift catalysts for fuel processors, improved efficiency of air management systems, and development of detailed cost analyses for fuel cell systems. In

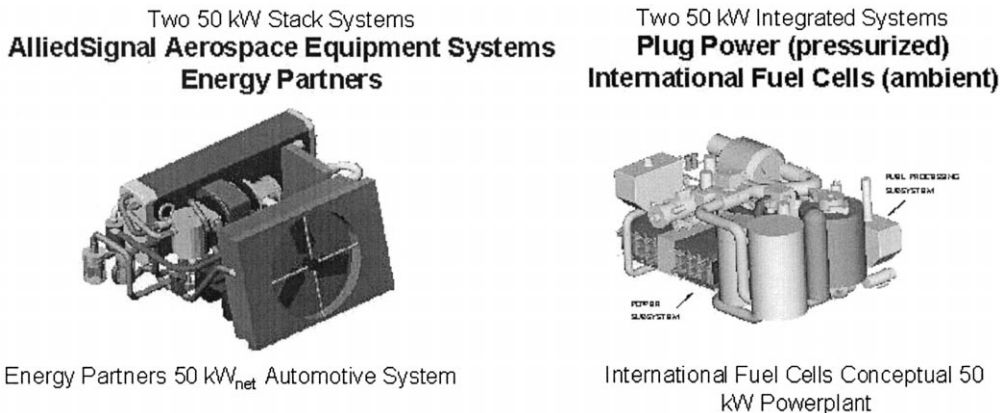


Fig. 19. The progress achieved by CY 2000 deliverables will be measured against PNGV year 2000 targets.

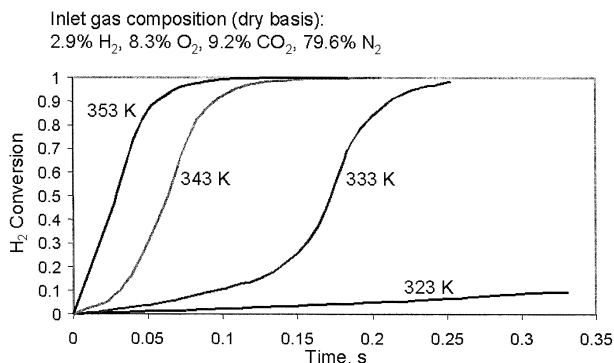


Fig. 20. ANL's preliminary results indicate the burner inlet temperature must be 333°K (60°C) to oxidize H₂.

fiscal year 2000, systems modeling by ANL and experimental measurements by Arcadis will be conducted to predict emissions over automotive drive cycles. A peer review will be convened to address stubborn efficiency and packaging challenges facing air management systems. Arthur D. Little will be conducting annual in-depth analyses of manufacturing costs for fuel cell power systems.

ANL has initiated modeling to simulate the kinetics of oxidation of hydrogen and other constituents of the anode exhaust gas and the formation of pollutant species at the catalytic spent gas burner. Fig. 20 shows the effect of the temperature of the burner inlet gases on the conversion of H₂ as a function of time. With an inlet temperature of 323 K (50°C), the oxidation of H₂ proceeds slowly, but with increasing inlet temperatures, the oxidation of H₂ proceeds much more rapidly. This modeling activity will be validated using experimental data and used to minimize emissions of regulated and unregulated trace pollutants. Future modeling will be conducted to examine the oxidation of other species including methane and other hydrocarbons.

Conventional low-temperature, copper–zinc oxide catalysts for the water–gas shift reaction must initially be activated in situ by reducing the copper oxide to elemental copper. This reaction is exothermic and must proceed under carefully controlled conditions to avoid sintering of the catalyst. Once activated, the catalyst must be protected from exposure to ambient air to prevent re-oxidation and must operate at less than 250°C to avoid degradation of the catalyst's activity. Conventional high temperature iron–

chromium catalysts also require activation through pre-reduction in situ and lose activity upon exposure to air. Rugged, thermally stable, shift catalysts with equal or better kinetics are needed that do not require in situ activation nor lose activity upon exposure to air, as well as catalyst supports with high surface areas.

In the longer term, the program is targeting higher-risk development of high-temperature, inexpensive membranes, and oxygen catalysts. Typically, fuel cell stack operating temperatures are limited to 80°C. Key advantages would be obtained from the development of an inexpensive, high-temperature membrane operating at 100–150°C that sustains current densities comparable to today's membranes and does not require significant humidification. This membrane would enhance CO tolerance and reduce heat rejection permitting a dramatic reduction in the size of the condenser and radiator. As mentioned earlier, higher operating voltages are required to meet efficiency targets for fuel cell systems. The development of improved oxygen reduction electrocatalysts with enhanced kinetics would be beneficial because the most significant contributor to cell voltage loss is polarization at the cathode. Additionally, advanced oxygen catalysts could reduce or eliminate the need for air compressors in fuel cell systems.

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