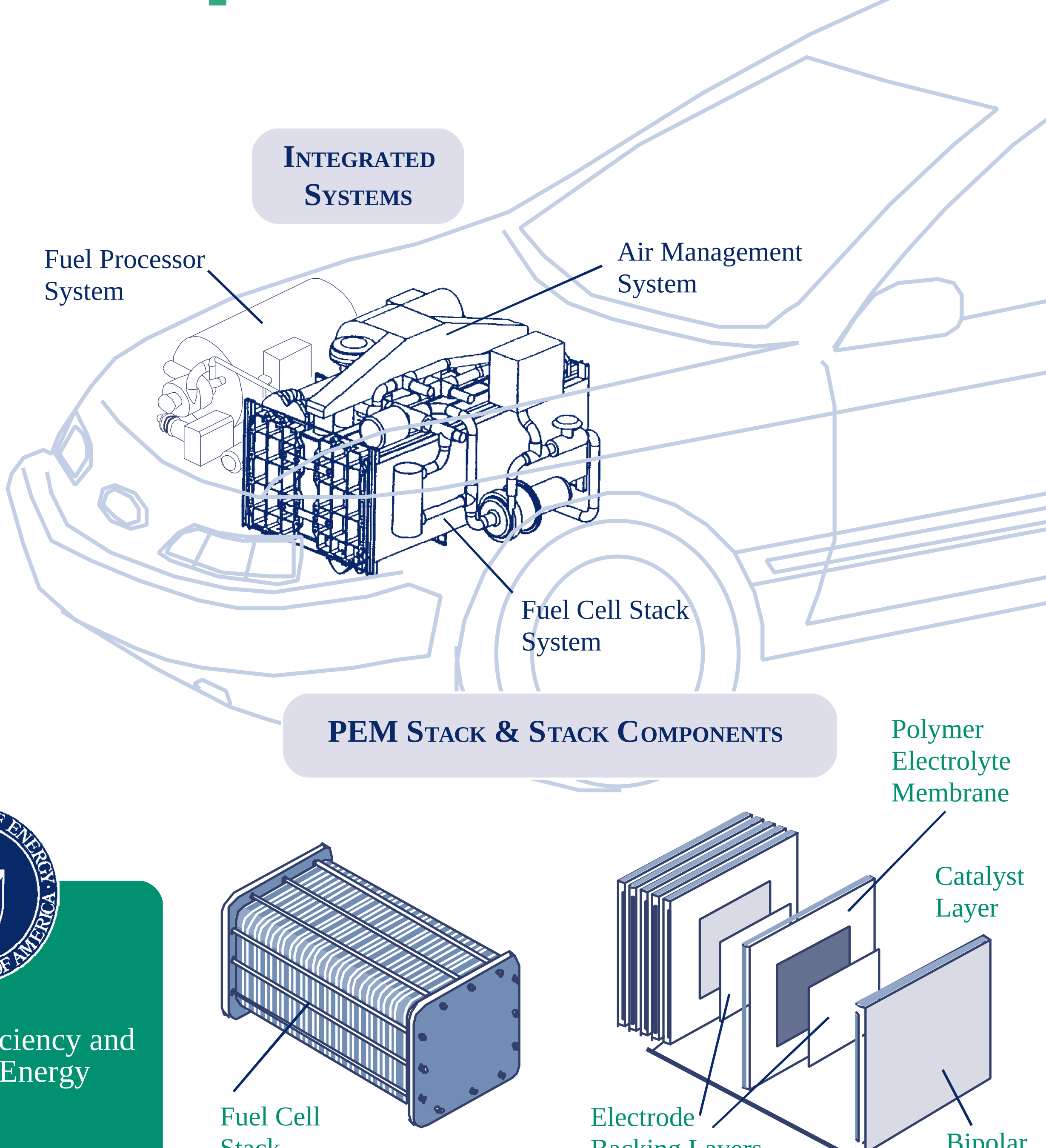
Fuel Cells
For Transportation



Energy Efficiency and Renewable Energy

Office of Transportation Technologies

Office of Advanced Automotive Technologies

Research & Development: Program Abstracts

June 1999

ENERGY EFFICIENCY AND RENEWABLE ENERGY
OFFICE OF TRANSPORTATION TECHNOLOGIES
OFFICE OF ADVANCED AUTOMOTIVE TECHNOLOGIES
ENERGY CONVERSION TEAM

Fuel Cell System Development
Patrick Davis
(202) 586-8061
Fax: (202) 586-9811
E-mail: patrick.davis@ee.doe.gov

Fuel Cell Core Technology R&D
JoAnn Milliken
(202) 586-2480
Fax: (202) 586-9811
E-mail: joann.milliken@ee.doe.gov

Fuel Cell System Development
Donna Ho
(202) 586-8000
Fax: (202) 586-9811
E-mail: donna.ho@ee.doe.gov

Mailing Address
U.S. Department of Energy
Office of Advanced Automotive Technologies, EE-32
1000 Independence Avenue, SW
Washington, DC 20585-0121

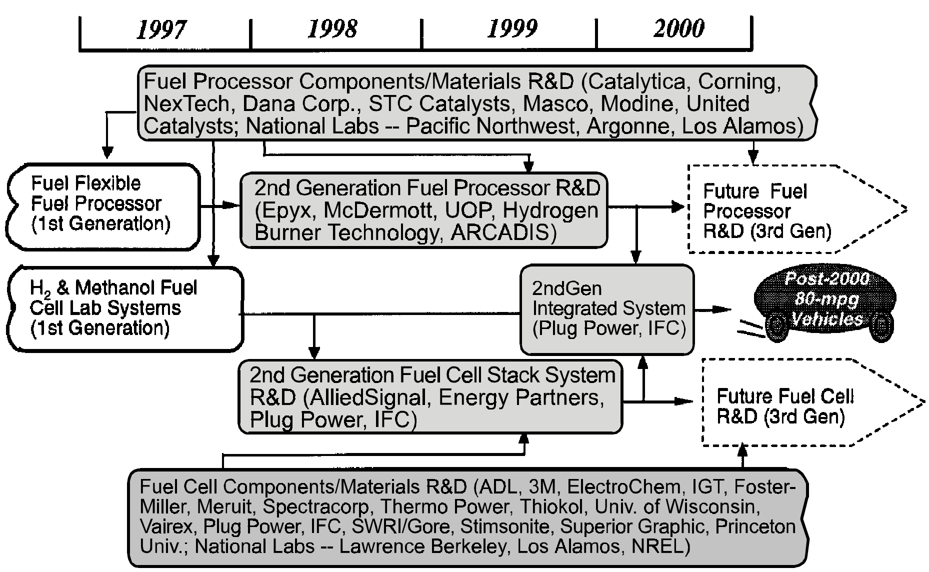
DOE Fuel Cells for Transportation Program: Implementation Strategy

Stimulating an Emerging Growth Industry:

Remarkable progress has been achieved in the development of proton-exchange-membrane (PEM) fuel cell technology since the U.S. Department of Energy (DOE) initiated a significant developmental program in the early 1990s. This progress has stimulated enormous interest worldwide in developing fuel cell products for transportation as well as for stationary and portable power applications. The potential markets are huge, but so are the R&D risks. Given the potential for PEM fuel cells to deliver large economic and environmental benefits to the Nation, DOE continues to take a leadership role in developing and validating this technology. DOE's strategy to implement its Fuel Cells for Transportation program has three components: an R&D strategy, a fuels strategy, and a management strategy.

R&D Strategy — Overcoming the Most Critical Technical Barriers:

The main objective of DOE's R&D program is to develop an automotive-sized (i.e., 50-kW) power system that operates on conventional and alternative fuels. The Fuel Cells for Transportation program will not develop fuel cell cars, but will facilitate the critical technology for a fuel cell system necessary to power an 80-mpg automobile. As a result of DOE projects initiated in the early 1990s, a 50-kW, fuel-flexible fuel processor has been developed in the laboratory by Arthur D. Little (now Epyx). This fuel processor was used in October 1997 in the world's first gasoline-to-electricity experiment with a PEM fuel cell. This laboratory set-up demonstrated the technical feasibility of DOE's fuel-flexible fuel strategy. Other accomplishments under the DOE program include Ford/IFC's 50-kW hydrogen fuel cell system, and General Motors' 30-kW, steam-reformed methanol fuel cell system. These are considered first-generation systems because they are first-of-a-kind lab systems. At least two more generations of hardware development will be required to address all major technical barriers (see figure). In October 1997, development of a second-generation, 50-kW, fuel-flexible fuel



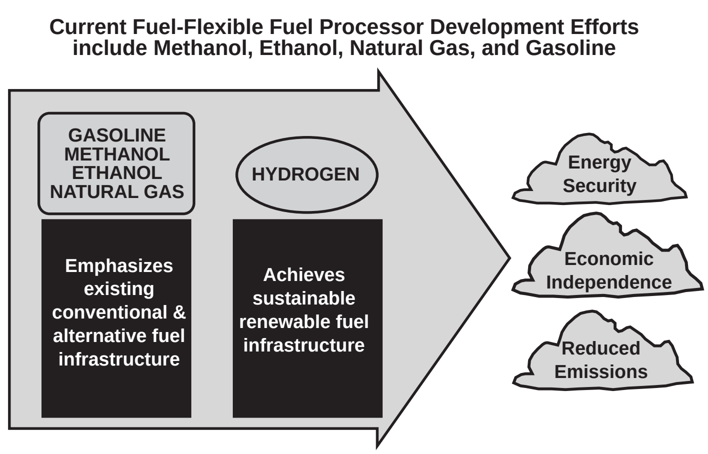
DOE Program Approach to Address Key Technology Barriers for Post-2000 Fuel Cell Concept Vehicles with 80-mpg Fuel Economy

processor was initiated with Epyx and Hydrogen Burner, and a 50-kW, reformate-capable, stack system was initiated with AlliedSignal, Energy Partners, Plug Power, and IFC. These projects will have to overcome the technical challenges associated with fuel cell performance on hydrocarbon reformate, challenges that are significantly greater than with pure hydrogen. Plug Power and IFC will combine the fuel cell and fuel processor subsystems to provide a complete automotive-sized, fuel cell power system meeting the technical targets established for the year 2000 by the Partnership for a New Generation of Vehicles (PNGV). If development of the integrated power system is successful, these systems will be made available to DaimlerChrysler, Ford, and General Motors for testing and possible subsequent integration into concept or test vehicles. In 1999, Epyx, McDermott Technology, and UOP are initiating the development of 50-kW, fuel-flexible fuel processors that meet the technical targets established by the PNGV.

National laboratories, universities, and industry suppliers are engaged in supporting the DOE R&D effort on fuel processor and fuel cell stack systems. The laboratories and universities apply the extensive scientific and technical expertise of their staff to such high-risk issues as the clean-up of carbon monoxide, development of catalysts, and other advanced components. The laboratories also work directly with suppliers in overcoming specific technological hurdles and by providing independent test facilities to verify hardware performance for suppliers and automakers. Industry suppliers are focusing on the development of compressors/expanders, low-cost component designs, and high-volume manufacturing processes. For example, 3M and SwRI/Gore are developing high-volume manufacturing processes for the membrane electrode assembly, and the Institute of Gas Technology and Energy Partners are developing high-volume processes for bipolar plates. The ongoing second-generation R&D effort will be followed by a third-generation effort that will take a similar approach and is expected to achieve PNGV's technical targets for the year 2004.

Fuels Strategy — Building the Capability for Fuel-Flexible Fuel Processing:

Fuel processing technology developed under the DOE program must convert gasoline, ethanol, methanol, and natural gas into hydrogen-rich streams for the fuel cell. This fuel-flexible, fuel neutral, fuel processing strategy accepts the reality of today's fuel infrastructure while creating pathways for alternative fuels. Although it is less efficient than a zero-emissions, direct-hydrogen fuel cell, a fuel-flexible powered PEM fuel cell is expected to have far lower emissions than are allowable with even the most strict California standards proposed. Very recently, several major

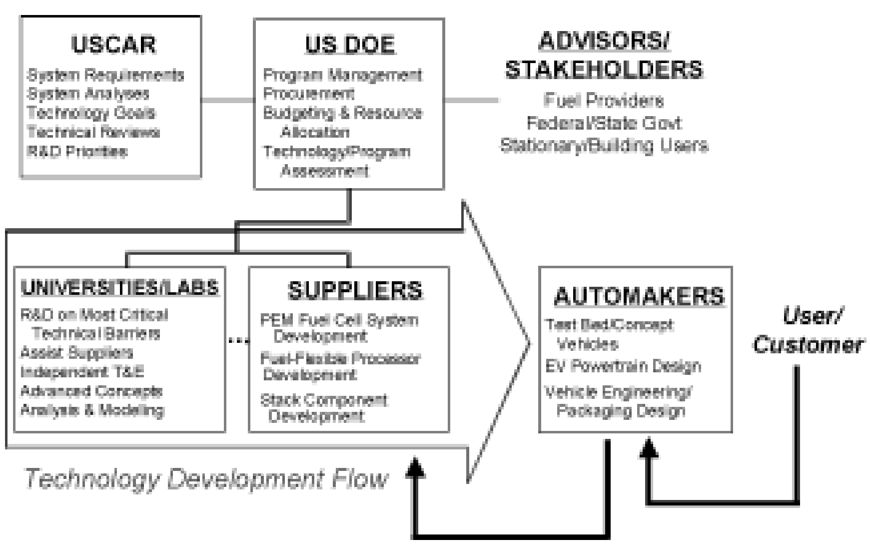


Fuels Strategy for Transportation Fuel Cell Program

oil companies agreed to begin working with the PNGV and DOE to take a closer look at petroleum-based fuels for fuel cells. This could lead to a more “fuel processing friendly” fuel than gasoline as we know it today. 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. As the infrastructure for these fuels develops, the fuel cell system technology for the vehicle will be ready. It is possible that the infrastructure for centrally fueled vehicles, such as buses, could be available within the next 10 years. Natural gas is included in the fuels strategy to maintain synergism with stationary power applications. Natural gas could also be utilized in heavy vehicle applications where greater packaging volume is available for fuel storage. Small-scale natural gas reformer technology can be used for off-board generation of hydrogen for a direct-hydrogen fuel cell vehicle. DOE believes that sustainable, renewable hydrogen is the best long-term fuel strategy.

Management Strategy — Clearly Defining Roles and Responsibilities for Program Participants:

DOE is taking a leadership role in the development of PEM technology by providing strong technical direction to the program, focusing and prioritizing technical resources, and managing financial resources. With the help of PNGV technical teams, DOE identifies the major technical barriers and submits competitive procurements to conduct the necessary R&D. With input from industry, DOE makes funding decisions based on evaluations of the progress achieved in ongoing laboratory R&D and in hardware-development programs undertaken by industry suppliers. The majority of R&D is carried out by suppliers through cost-shared cooperative agreements and contracts with DOE. Currently, over 40 suppliers with cutting-edge technology and innovative ideas are working closely with DOE, laboratories, other suppliers, and the automakers, and delivering hardware, where appropriate, for integration and testing. This level of participation by suppliers has increased steadily since the start of the DOE program. The DOE national laboratories and universities conduct the long-term, high-risk, high-payoff R&D. Their customers are the industry suppliers. The auto manufacturers, DaimlerChrysler, Ford, and General Motors, remain individually responsible for fuel cell vehicle development and integration. However, they are working collectively with DOE (through the U.S. Council for Automotive Research or USCAR) to help define system requirements, technology goals, and R&D priorities for fuel cell



The Fuel Cells for Transportation Program “Team”

power systems and their components. Participation by USCAR in technical reviews of the R&D projects ensures that DOE establishes realistic requirements for fuel cell automobiles and that the car makers are kept informed about the status of the technology. DOE is also working with major oil companies, as well as with other federal and state agencies, to resolve fuel processing and infrastructure issues. Cross-cutting technology requirements are being addressed jointly with related DOE programs focusing on stationary fuel cell applications in buildings and industry.

S. Chalk

Steven G. Chalk
Energy Conversion Team Leader
Office of Advanced Automotive Technologies
Office of Transportation Technologies

Power System Development

Fuel Cell Power System

Contractor: Plug Power — *Latham, NY*
Contact: Dr. William D. Ernst — *(518) 782-7700, Ext. 126*

Fuel cells have a great advantage over electricity in transportation applications because they eliminate charging time, allow a wide range of speeds, and operate as long as fuel is supplied. Like electric vehicles, they have near-zero emissions.

Plug Power, the largest fuel cell developer in the United States, has been working with DOE and several industrial partners since 1997 to develop lower-cost, lighter-weight, and more powerful PEM fuel cell power systems for automotive applications. The project goals are to improve system reliability and durability, enhance the processes that allow fuel cells to operate on available fuels, and work to make the price of the system comparable to that of today's internal combustion engines. We have teamed with automotive suppliers and a leading fuel processing company (UOP) to develop a 50-kW, hydrocarbon-fueled PEM fuel cell system that operates at greater than 40% efficiency. The system is designed to have a power density of 250 watts per liter and a durability of 2,000 hours. We are developing new designs and methods for instrumentation, freeze protection, sealing technology, rapid startup, and transient operation. UOP will rely on its experience in fuels and refining operations to develop a multi-fuel processor for the system. We will demonstrate the durability of both the PEM stack and the fuel processor.

So far, Plug Power and its partners have demonstrated power capacities approaching 40 kW operating on hydrogen fuel through a federal urban driving cycle in our laboratories. We are now working to improve the power densities of the system.

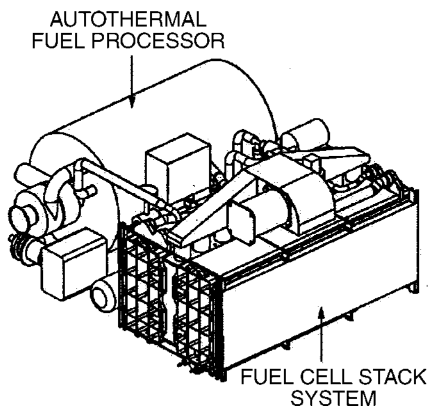
In October 1997, three months after receiving one of the largest single awards ever granted for automotive fuel cell research, Plug Power along with DOE's Los Alamos National Laboratory and Epyx (formerly Arthur D. Little), was the first team to demonstrate a gasoline-to-electricity fuel cell. In January 1999, we demonstrated an advanced automotive fuel cell system that is responsive to actual vehicle power requirements to a major American automaker. The system exceeded its design specifications for power output, provided maximum efficiency by adjusting its rate of fuel flow, and attained 75% of its power in 1/10 of a second of operation — demonstrating its "cold-start" capabilities. Plug Power is now working with DOE to further test that system.

Subcontractors:
Epyx Corporation, Cambridge, MA
Masco Corporation., Taylor, MI
UOP LLC, Des Plaines, IL

Deliverables: *10-kWe stack subsystem, fuel processor capable of transient operation, and 5,000-hour stack and fuel processor endurance test results (06/01)*
50-kW fuel-flexible system (03/00)

Power System for Transportation

Contractor: International Fuel Cells Corp. — South Windsor, CT
Contact: Murdo Smith — (860) 727-2269

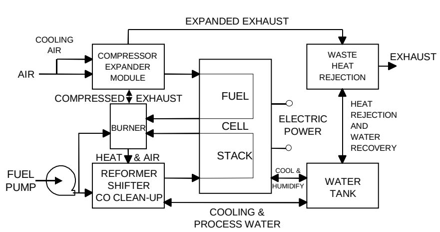


The fuel cell has been proven to be an attractive prime mover for automotive applications because it can be the cornerstone of a sustainable energy program in the United States. It can provide the highly efficient conversion of fuel to PNGV mileage goals, and can do so with either zero-emissions or the lowest emissions possible when using conventional motor fuel. A major challenge however in introducing the fuel cell into automotive service quickly is to find a way to make it compatible with gasoline or diesel fuel, the traditional automotive fuels, and to reduce its cost, weight and volume to competitive automotive targets. Recent development work in compact ambient pressure fuel cells and fuel-flexible fuel processors has produced great strides in moving these technologies toward satisfying automotive goals. This program will bring these technologies together into a demonstrator fuel cell power plant which is on the path toward meeting all automotive goals both near term, using current infrastructure fuels, and long term using renewable fuels.

<u>Deliverables</u>: *50-kW fuel flexible autothermal reformer (01/00)*
50-kW (net) PEM stand alone power system-Series 200 (05/00)

Fuel Cell System Design and Analysis

Contractor: Argonne National Laboratory — Argonne, IL
Contact: Romesh Kumar — (630) 252-4342



We have developed a comprehensive system modeling capability for the design and analysis of gasoline-fueled automotive fuel cell systems. The research uses GCtool, a comprehensive systems analysis software package that has also been made available to the various contractors in the DOE Fuel Cells for Transportation program. The work at Argonne is addressing design issues, such as operating pressures, as well as performance issues, such as the influence of the various design and operating parameters on system efficiency. These analyses are being used to identify the key improvements needed in component performance to achieve the PNGV targets of system weight, volume, packaging, and efficiency. For example, the Argonne analyses have shown that to achieve a fuel cell system efficiency of 45% at the design point, an operating cell voltage of 0.8 V will be needed. Similarly, the effects of available and projected efficiencies of compressors and expanders on system performance have been analyzed. Such analyses are being used to delineate the specific advantages and disadvantages, for example, of operating the automotive fuel cells at ambient pressures or at pressures of 30 psig (or even higher). Developers are pursuing both types of systems, and these analyses will help to provide a common means of evaluating the relative merits of each.

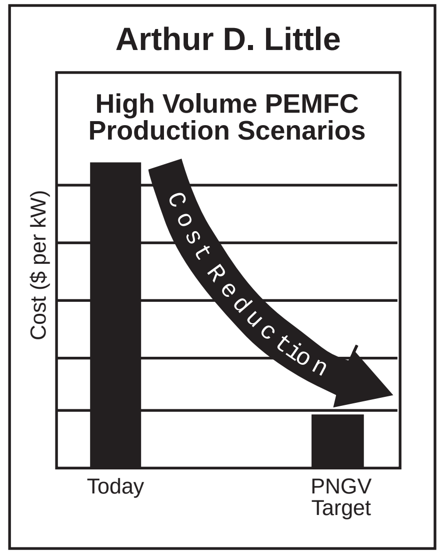
<u>Deliverables</u>: *Workshops and reports on system design, integration, and trade-offs needed to develop efficient automotive fuel cell systems*

Cost Analyses of Fuel Cell Power Systems

Contractor: Arthur D. Little, Inc. — *Cambridge, MA*
Contact: Eric J. Carlson — *(617) 498-5903*

Arthur D. Little, Inc. (ADL), is conducting a structured cost analysis of proton-exchange-membrane (PEM) fuel cell (FC) systems to assist DOE in assessing the economic viability of PEMFC systems in automotive markets and to identify cost reduction strategies. The analyses address the following questions:

- What would projected PEMFC systems cost if they were produced in automotive market volumes using available technology?
- What are the critical assumptions embedded in this cost projection?
- How do operating parameters impact subsystem and overall system design and cost? For example, will higher operating temperatures allowed by higher temperature PEM membranes under development lead to lower fuel processor costs?
- How do improvements in subsystem performance (e.g., stack power density) impact overall system cost?
- What are the critical materials, components, or subsystems to target for technology development and/or cost reduction?



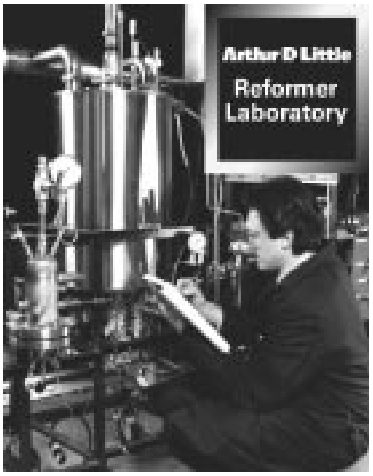
ADL is developing a year 1999 cost model and database on the basis of costing methodologies, systems analysis, and discussions with major fuel cell system developers. ADL will update the cost projection for the next four years as fuel cell and subsystem component technologies evolve.

<u>Deliverables</u>: *Baseline cost model and PEM system technology synopsis (09/00)*
Annual model updates for four years

Fuel Processing Subsystem

Advanced Fuel Processor Development for Transportation Fuel Cell Power System

Contractor: Epyx Corporation/Arthur D. Little *Cambridge, MA*
Contact: William L. Mitchell *(617) 498-6149*



Epyx Corporation, a wholly-owned subsidiary of Arthur D. Little, Inc. (ADL), is developing a 50-kWe fuel-flexible fuel processor capable of processing gasoline and alternative fuels, such as ethanol. Major technical issues to be addressed in this program include the following: advanced catalysts, CO cleanup, transient controls, and reformer start-up/shut-down time.

As a part of this program, Epyx is also developing and testing an advanced 50-kWe PROX device based on proprietary catalyst technology. A major focus of fuel processor development will be gas purity when gasoline and ethanol are used in operation. Epyx will support Plug Power on the development of a 50-kWe fuel cell power system.

In a recent DOE award, Epyx will develop a fully optimized fuel processing subsystem. Working with Energy Partners, Epyx will integrate existing hardware into a 10-kWe multifuel power system so that key system-level trade-offs in the design of a fuel processing subsystem can be identified allowing computer models developed both internally and by Argonne National Laboratory to be validated. In the second part of the program, Epyx will use existing integrated and modular fuel processors to perform endurance testing that will identify and address material and catalyst degradation mechanisms. The major element of the third part of the program will be an in-depth catalysis R&D program to identify high-activity, low-cost catalysts. The new catalysts and supports will be integrated into a fuel processor package specifically suited to the optimized catalyst suite. The output of this program will be a fully integrated fuel processing subsystem that meets or exceeds 2004 PNGV targets.

Subcontractor/Partners:
Corning, Inc., Corning, NY
Dana Corporation, Paris, TN
Energy Partners, West Palm Beach, FL
Modine Manufacturing Co., Racine, WI
STC Catalysts, Inc., Hampton, VA
United Catalysts, Inc., Louisville, KY
Universal Oil Products, Des Plaines, IL

Deliverables: 50-kW fuel processor system (02/00)
10-kWe fuel cell power system to Argonne National Laboratory for testing (02/00)
Demonstration of two 50-kWe fuel processing subsystems that meet or exceed the 2004 PNGV targets (01/02)

Fuel-Flexible Fuel Processor for Fuel Cell Electric Vehicle Applications

Contractor: McDermott Technology, Inc. Alliance, OH
Contact: Robert M. Privette (330) 829-7370

The team of McDermott Technology, Inc., and Catalytica Advanced Technologies will design, build and demonstrate a fully integrated 50-kW catalytic, autothermal fuel processing system. The fuel processor will produce a hydrogen-rich gas for direct use in proton exchange membrane fuel cell systems for electric vehicle applications. The processor system will consist of a liquid-phase desulfurizer, an autothermal reformer, high- and low-temperature water gas shift units, a selective oxidizing unit, and associated pumps, compressor/expander, heat exchangers, and controls.

Subcontractors:
Catalytica Advanced Technologies, Mountain View, CA
NexTech, Columbus, OH

Deliverable: 50-kW fully integrated fuel processor (04/02)

Fuel-Flexible Fuel Processor (F^3P) Subsystem Development

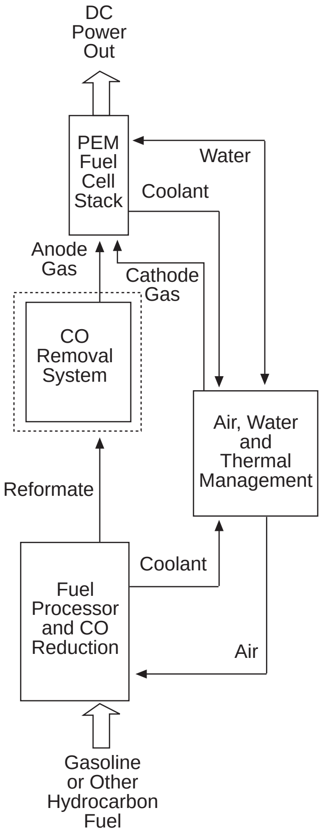
Contractor: Hydrogen Burner Technology, Inc. Long Beach, CA
Contact: Richard R. Woods (562) 597-2442

HBT is completing testing and performance mapping on its prototype 50-kW F^3P subsystem, designed to provide a hydrogen-rich stream with less than 10 ppm of carbon monoxide. This unit precedes the actual program deliverable — the fabrication, testing, and delivery of a second-generation, "pre-commercial" F^3P subsystem to a DOE subcontractor.

HBT's F^3P subsystem technology employs a durable, noncatalyzed partial-oxidation reforming process that is suitable for converting infrastructure hydrocarbon fuels like gasoline and diesel to hydrogen-rich product gases for fuel cell applications. The compact, lightweight design incorporates advanced low-density, high- and low-temperature-shift catalysts to meet the goals of the PNGV program. This subsystem approach integrates reforming, shift conversion, and steam generation components to improve efficiency.

HBT is also developing a humidified low-temperature-shift reactor system to minimize the thermodynamic approach conditions, thereby maximizing conversion of carbon monoxide and water to carbon dioxide and hydrogen.

Deliverables: 50-kW peak, integrated fuel-flexible fuel processor (F^3P) subsystem (12/99)
50-kW humidified, low-temperature-shift (HLTS) reactor (12/99)



Novel Concept Device for Removal of Carbon Monoxide in Automotive PEM Fuel Cell Power Plant

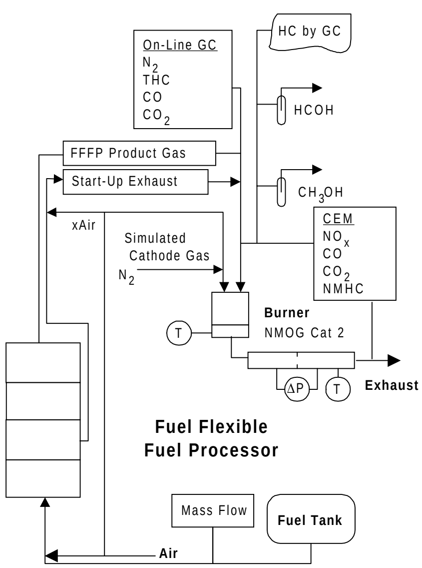
Contractor: AlliedSignal-AES *Torrance, CA*
Contract: Tim Rehg *(310) 512-2281*

The removal of carbon monoxide (CO) from the fuel processor reformate stream is a critical process in any PEM fuel cell system because CO poisons the noble metal anode electrocatalyst in the fuel cell. The goal of this program is to develop, implement, and demonstrate a novel CO-removal system for PEM fuel cell systems fueled by reformate. The system employs a regenerable adsorption bed that has a high affinity for CO; the bed will be incorporated between the fuel processor and the PEM fuel cell, as shown in the figure.

During the first year of this program, we will explore two innovative CO-removal methods that have already been demonstrated on a small scale in the AlliedSignal laboratories. At the end of the first year, each method will be critically evaluated, and the most promising technique will be implemented in a breadboard prototype sized to operate with a 10-kW fuel cell stack. The prototype will be delivered to Argonne National Laboratory for further testing and evaluation.

Subcontractor:
AlliedSignal-ASRT, Des Plaines, IL

Deliverable: *Subscale regenerable CO adsorption bed for use with 10-kW PEM fuel cell stack (09/01)*



Fuel Processor Emissions Measurement

Contractor: ARCADIS Geraghty & Miller, Inc. *Mountain View, CA*
Contact: Stefan Unnasch *(650) 254-2413*

ARCADIS Geraghty & Miller is measuring the cold startup and normal operating emissions — NO_x, CO and CO_2, methane, nonmethane hydrocarbons (NMHCs), carbonyl group compounds (aldehydes), and speciated hydrocarbons (both light-end and mid-range hydrocarbon group components) — from a partial-oxidation reformer (POX) before and after treatment by an anode gas burner. Different anode-gas-burner catalyst formulations and four fuels (gasoline, methanol, ethanol, and natural gas) are being tested. The project will determine whether a fuel cell vehicle with a multifuel reformer can meet the Federal Tier 2 emission standards for automobiles and light-duty trucks.

Subcontractor:
Hydrogen Burner Technology, Inc., Long Beach, CA

Deliverable: *Emissions data from multifuel fuel reformer (11/99)*

Advanced Fuel-Flexible Fuel Processor

Argonne National Laboratory | *Argonne, IL*
Contact: Mike Krumpelt | *(630) 252-8520*

For use with automotive fuel cell power systems, onboard fuels other than hydrogen must first be converted to hydrogen using a reformer. Argonne is developing a more advanced system which is a catalytic partial-oxidation reformer to convert gasoline, as well as alternative fuels (methanol, ethanol, natural gas, and other hydrocarbons) to a hydrogen-rich fuel gas. This compact, lightweight reformer is designed for rapid startup and excellent dynamic response. The reformer uses a unique family of bifunctional catalysts that has demonstrated the ability to convert a variety of transportation fuels to hydrogen at temperatures of 750°C or less. When compared to non-catalytic processes which may require 1000°C or more, the much lower temperatures required by the Argonne reformer yield a product gas that contains less undesirable components (e.g., CO). In addition, the reactor can be constructed from simpler materials, and is suited for faster startups. A prototype version of the Argonne reformer, containing 1.7 liters of the proprietary catalyst, has demonstrated the generation of 40 L/min of hydrogen, sufficient for a 3-kWe fuel cell stack. A revised version of the reformer integrates the reforming together with the shift conversion of byproduct carbon monoxide, all inside a 15 L envelope. This reformer will provide the equivalent of 8 kWe, and is being developed to offer rapid startup and excellent dynamic response.

Deliverable: *Demonstrate operation of catalytic partial-oxidation reformer integrated with a 10-kW fuel cell (07/99)*

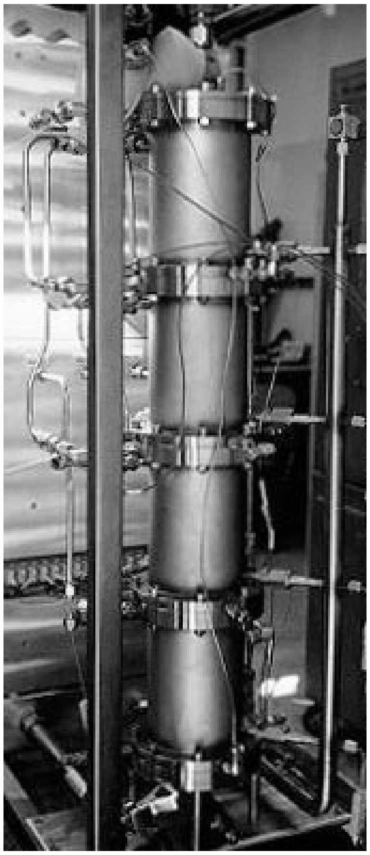
Microchannel Fuel Processor Development

Pacific Northwest National Laboratory | *Richland, WA*
Point of Contract: Robert S. Wegeng | *(509) 375-3710*

Developing an onboard fuel-processing system to produce hydrogen gas from liquid hydrocarbons for use in fuel cells presents a number of technical challenges, including process miniaturization and thermal energy integration. During 1997 and 1998, we developed and demonstrated extremely compact fuel vaporizers that capture and recycle energy from unused hydrogen in the waste gas of the fuel cell by catalytically reacting it with air and then routing the stream through microchannel heat exchangers, within which the liquid hydrocarbon fuel is evaporated. At 18 $in.^3$, the full-scale gasoline vaporizer (pictured) is approximately one-tenth the size of a conventional vaporizer and supplies the complete fuel stream for a 50-kWe system.

In 1999, we are demonstrating a microchannel steam-reforming reactor and microchannel recuperative heat exchangers. If the complete fuel-processing system can be miniaturized in this manner, we anticipate that the system would be smaller than one cubic foot in volume.

Deliverable: *Demonstration of a bench-scale, steam-reforming reactor and recuperative heat exchanger system that validates design for compact fuel processing system (09/99)*



Fuel Processing R&D

Los Alamos National Laboratory *Los Alamos, NM*
Contact: Nick Vanderborgh *(505) 667-6651*

The LANL fuel processing work continues to focus on contaminant control through modification of fuel processing conditions to either remove contaminants or convert them into less troublesome compounds. One LANL thrust is to optimize the components necessary for utilization of commercial fuels. We are continuing with the development of a preferential oxidation (PROX) reactor to reduce the outlet CO levels from fuel processors to PEM fuel cell quality. Recent accomplishments include the design, fabrication, and testing of a 50-kW PROX with three active catalyst stages (shown left) that demonstrated the control of simulated gasoline reformate CO concentrations in the range of 8,000 to 12,000 ppm during both steady-state and transient performance testing. A second PROX unit was also developed and delivered to Energy Partners where it is undergoing testing in a 10-kW fuel cell power system. Work includes testing with modern fuel cell stack hardware to document the effects of various cleanup options on fuel cell performance.

A second focus of the LANL effort explores the influence of fuel constituents and fuel contaminants on fuel processing (hydrogen generation) options. Right now considerable global effort seeks improved fuels for cleaner internal combustion engines. These newer fuels and fuel blends create new options for transportation fuel cell systems. Los Alamos is installing two different 50-kW fuel processors that will be used to evaluate reformate cleanup technology for both conventional fuels and for newer fuels such as dimethoxy methane. These experiments will also evaluate the consequences of specific fuel composition on cleanup technology, with considerable study of the fuel impurity effects. Supporting research seeks information about dynamics in fuel processing catalysis reactivity resulting from utilization of various fuels, with the intent of understanding mechanisms of performance loss. The intent is to assist development of improved, more robust reactors for on-board hydrogen generation.

Deliverable: *Successfully demonstrate the integrated operation of a 50-kW POX with a 50-kW PROX to generate PEM-quality reformate (09/99)*

Fuel Cell Stack Subsystem

High-Efficiency, High-Power Density, CO-Tolerant PEM Fuel Cell Stack System

Contractor: AlliedSignal-AES *Torrance, CA*
Contact: Tim Rehg *(310) 512-2281*

The PEM fuel cell power plant holds considerable potential as a cleaner, more efficient alternative to the automobile internal combustion engine. To warrant consumer acceptance, however, power plant performance must be comparable to that of today's automobiles at a comparable price and utility. We are developing a 50-kW (net) PEM fuel cell power system that will operate on reformed hydrogen derived from conventional and alternative fuels such as methanol, ethanol, natural gas, and gasoline. The PEM fuel cell system will demonstrate the capability to achieve a fuel efficiency of 40% at 12.5 kW (cruising conditions), a compact size (0.35 kW/L) and weight (0.35 kW/kg), and a high-volume production cost of $100/kW.

In the past year, AlliedSignal has developed and tested a 15-kW, reformate-tolerant PEM fuel cell stack with a power density of 1.16 kW/L and specific power of 0.62 kW/kg. In the next year, the program will focus on (1) advancing the AlliedSignal PEM stack technology, and (2) system integration and testing.

Subcontractors:
AlliedSignal-ASRT, Des Plaines, IL, and Morristown, NJ
AlliedSignal Automotive, Southfield, MI

Deliverable: *50-kW (net) PEM fuel cell stack system (07/00)*

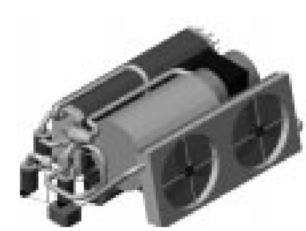
Design and Evaluation of Advanced, Low-Cost, PEM Fuel Cell Stack Powered by Reformed Gasoline

Contractor: Energy Partners, Inc. *West Palm Beach, FL*
Contact: Jay Neutzler *(561) 688-0500*

The goal of this program is to develop cost-effective fuel cell stacks/systems that run on reformed gasoline and alternative fuels for use in automotive applications. A primary focus is to reduce the material and processing costs of the bipolar plates. Energy Partners will develop and demonstrate bipolar plates for advanced molding processes and characterize membrane electrode assemblies (MEAs) for operation on reformed gas. We will also design and evaluate a fuel cell stack for reformate tolerance and performance and demonstrate it both as a 10-cell stack and as a 50-kW (net) stack. The 50-kW stack will be incorporated into an automotive-style system and demonstrated.

NG3000 50-kW Reformate Stack

Energy Partners has demonstrated high-performance hydrogen fuel cell systems with the NG2000 series. The NG3000 series for automotive applications is showing equally impressive performance on reformate. Phase I concluded with delivery of a NG3000 10-cell proof-of-concept fuel cell stack, as well as an optimized system design (3/31/99). At the conclusion of Phase II, a 50-kW (net) automotive reformate power system (excluding reformer) will be delivered.



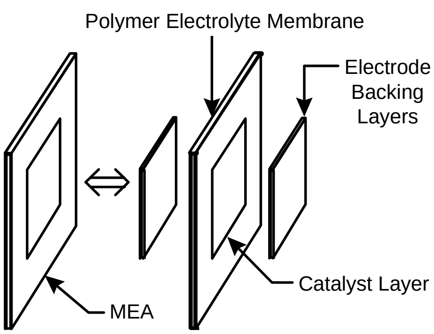
NG3000 50-kW Reformate System

Deliverable: *50-kW (net) PEM fuel cell stack system (09/99)*

PEM Fuel Cell Component Cost Reduction

High Performance, Low-Cost Membrane Electrode Assemblies for PEM Fuel Cell Components and Integrated Pilot Manufacturing Processes

Contractor: 3M Co. *St. Paul, MN*
Contact: Dr. Mark K. Debe *(651) 736-9563*
Dr. Judith B. Hartmann *(651) 736-1772*



Development of commercially viable fuel cell systems requires improvements in component performances in all subsystems along with reductions in material and manufacturing costs. 3M is developing components and manufacturing processes for novel membrane electrode assemblies based on a fundamentally new nanostructured thin film catalyst and support system that can facilitate high volume manufacturing. The current effort is directed toward demonstrating the feasibility of a continuous process for manufacture of high performance ultra-low loading catalyst electrodes in commercial membranes, obtaining new anode catalyst systems for optimized CO tolerance, and developing a continuously produced, low-cost carbon electrode backing media. Feasibility of the continuous manufacturing process for catalyst coated membranes has been demonstrated using the 3M nanostructured catalyst system and commercial membranes, and new nanostructured catalyst systems have been demonstrated with improved CO tolerance, including one with tolerance to 300 ppm. MEA performance testing is underway at the stack development subcontractor. Future effort will build on these results and be directed toward development of a set of high-performance, matched PEM fuel cell components and integrated manufacturing processes to facilitate high-volume, high-yield stack production. The goals include developing anode catalysts with ambient pressure high reformate tolerance, cathode catalysts with higher activity, and matching electrode backing and flow field media, and demonstrating integrated pilot manufacturing processes capable of being controlled by a robust quality system. The pilot manufacturing effort will provide the basis for an economic analysis relating to cost and volume targets.

<u>Subcontractor</u>:
Energy Partners, Inc., West Palm Beach, FL

<u>Deliverables</u>: *Advanced large-area MEAs for performance evaluation on reformate/air by stack development subcontractor (09/99)*
10-kW stack containing matched components (09/01)

Design and Installation of a Pilot Plant for High-Volume Electrode Production

Contractor: Southwest Research Institute — *San Antonio, TX*
Contact: Dr. James Arps — *(210) 522-6588*

Commercial acceptance of fuel cell technology for use in the automotive area requires a fuel cell system that meets the PNGV cost target of \$50/kW. One of the most critical components impacting overall system performance and economics is the Membrane Electrode Assembly (MEA). Therefore, it is anticipated that the MEA must be available for \$10/kW or less in order to meet the overall PNGV cost targets. The proposed project is aimed at the design and installation of a pilot manufacturing process for a crucial, cost prohibitive, element in the high-volume production of fuel cell MEAs that will address the needs for fuel cells in transportation applications. This pilot line will be scaled to catalyze up to 300,000 square meters of electrode material on a three-shift basis–enough to allow the fabrication of MEAs for 50,000 fuel cell-powered automobiles. The proposed plant concept will incorporate continuous, independent catalyzation of electrode materials with a final assembly step. All remaining elements are commercially available, including electrode substrate materials and membranes, which will be purchased in large, low-cost, production quantities through W.L. Gore and Associates. The products delivered by the end of the project will indirectly demonstrate sufficient production levels necessary to achieve MEA production costs below \$10/kW. The centerpiece of this effort will be a vacuum coating unit with the capability to produce millions of square feet of high performance, ultralow-load electrodes per year. SwRI initially demonstrated feasibility of this nanoscale, precious metal technology as part of a DOE-sponsored program on advanced fuel cells for transportation applications.

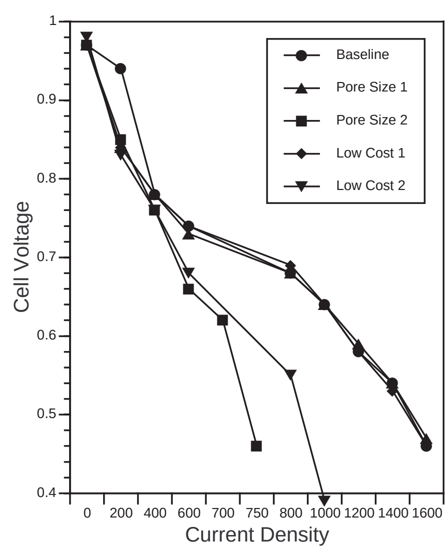
Subcontractors:
W.L. Gore and Associates, Elkton, MD
General Motors Corp., Detroit, MI

Deliverable: *A 50-kW fuel cell stack utilizing MEAs made by large-scale, continuous electrode catalyzation methods (09/01)*

Optimized Porous Carbon Gas Diffusion Electrodes

Contractor: Spectracorp Ltd. — *Lawrence, MA*
Contact: Gerald J. Fleming — *(978) 682-1232*

For fuel cells to be commercially successful, their cost must be reduced significantly while still maintaining their performance. We have developed a matrix to examine numerous variations in gas diffusion electrode composition (such as pore size and distribution, density, conductivity, and thickness) and manufacturing method in order to optimize the cost-versus-performance equation. Extensive fuel cell testing has demonstrated significant cost reduction potential while maintaining state-of-the-art performance levels. Preliminary results are being reproduced and will be confirmed through long-term testing of the most promising materials.



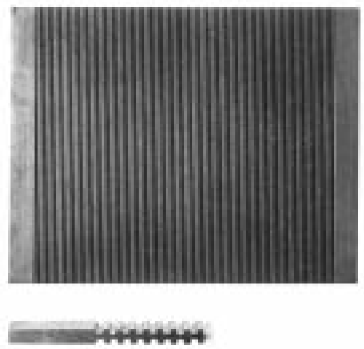
Subcontractor:
Energy Partners, Inc., West Palm Beach, FL

Deliverable: *Optimized porous carbon paper that has been tested in 160-cm^2 membrane electrode assemblies (07/99)*

Development of a $10/kW Bipolar Separator Plate

Contractor: Institute of Gas Technology — *Des Plaines, IL*

Contact: Leonard G. Marianowski — *(847) 768-0559*



IGT, working with its subcontractors in Phase I — Stimsonite Corporation and Superior Graphite Corporation — have developed molded composite bipolar separator plates that

- Exceed all DOE requirements for conductivity and chemical and physical stability,
- Have demonstrated performance and endurance that matches those of traditional machined graphite,
- Have been successfully scaled up from 60 cm^2 to 300 cm^2 of active area, and
- Have demonstrated expected performance and thermal management in short (300 cm^2) stacks via the use of water-cooling.

On the basis of this progress, we are proceeding with Phase II — building a pilot molding production line and evaluating the endurance of the molded composite plates in stacks at IGT and at other fuel cell stack developers. Our achievements have prompted Stimsonite Corporation and ENDESCO Services, Inc., to form a joint venture (PEM Plates, LLC) to mold bipolar plates to be used by developers worldwide in PEM fuel cells.

Subcontractors:
Allied Signal-AES, Torrance, CA
Stimsonite Corporation, Niles, IL
Superior Graphite Co., Chicago, IL

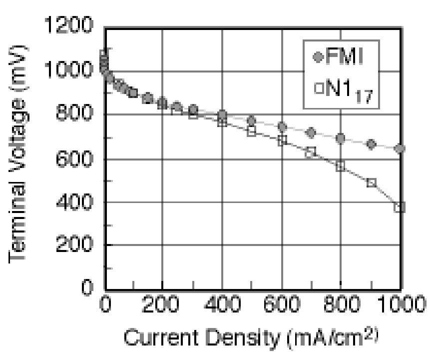
Deliverable: *Performance tested molded graphite composite bipolar plates in 5-, 10-, and 20-cell stacks (05/00)*

Low-Cost, High-Temperature, Solid Polymer Electrolyte Membrane for Fuel Cells

Contractor: Foster-Miller, Inc. — *Waltham, MA*

Contact: Dr. Robert F. Kovar — *(781) 684-4114*

Comparative FMI Film Fuel Cell Performance (IR-Included)



Operating Conditions:
30 psig H_2/O_2 Pressure
80° Cell Temperature

The market for fuel cell membranes is projected to be greater than 20M m^2/year by 2010. It is estimated that Foster-Miller's new, high-temperature, solid polymer electrolyte membrane, now being developed, will cost $45/$m^2$ in quantities of 20M m^2/year using current system parameters. Foster-Miller has synthesized:

- wholly aromatic Ion Conducting Polymers (ICPs) with ionic conductivity of 0.07 to 0.1 S/cm. The ICPs' Tg was measured to be 290 to 310°C.
- thin (< 0.4 mil), high-strength poly-p-phenylene (benzobisoxazole) substrates via film casting and extrusion
- composite membrane samples having an area-specific resistance of 0.11 Ohm•cm^2 (48% less than Nafion) and gas permeation rates approximately 70% less than Nafion.

The composite membranes showed outstanding dimensional stability and excellent mechanical properties. Membrane electrode assemblies (MEAs), fabricated with the composite membranes, demonstrated single-cell performance (at 80°C), comparable to the performance of Nafion-based MEAs.

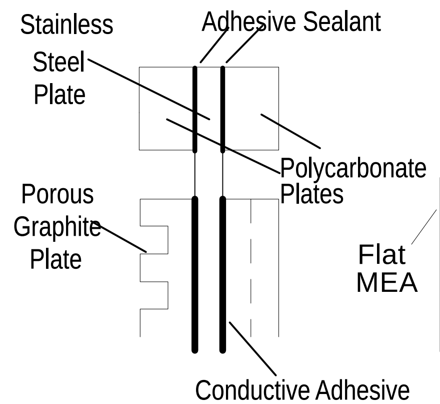
Subcontractor:
Giner, Inc., Waltham, MA

Deliverable: *MEAs will be tested at standard (80°C) and elevated temperatures (>100°C) in operating H_2/O_2 fuel cells (09/99)*

Layered Bipolar Plates for PEM Fuel Cell Stacks

Contractor: ElectroChem, Inc. *Woburn, MA*
Contact: Dr. Radha Jalan *(781) 938-5300*

Cost is the principal factor inhibiting the widespread use of fuel cells as electrical power sources. The most expensive component in the manufacture of lower cost PEM fuel cells is the solid graphite bipolar separator plates. ElectroChem has developed a novel, low-cost design for a bipolar separator plate which incorporates several commonly available materials into a layered structure. Its electrical resistance has been demonstrated at less than 1778 μΩ•cm. Several laboratory prototype fuel cell stacks (with 50 cm^2 active area) have been assembled and tested with pure hydrogen and oxygen under severe conditions. The longest operating stack has been tested for 3500Ah without any significant corrosion or decreases in the membrane electrode assembly's (MEA's) performance.



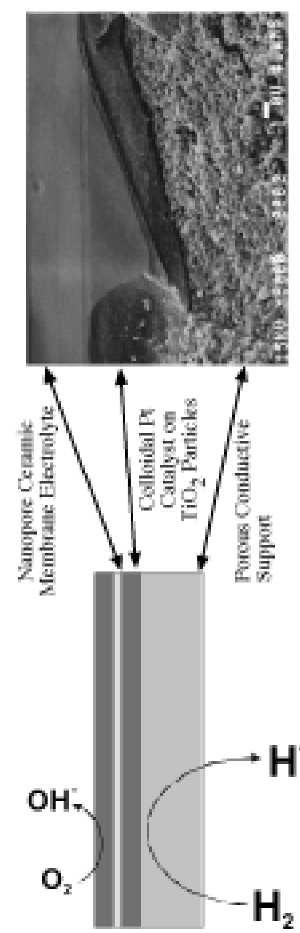
ElectroChem also investigated an alternative design for a larger fuel cell stack (with 232 cm^2 active area) that enhances the MEA's performance and reliability under peak power and long-term operating conditions by incorporating cooling into each separator plate. An initial analysis of this layered design shows that its cost can be reduced to $10.60/kW.

<u>Deliverable</u>: *A 6" by 6" prototype PEM stack with layered bipolar plates (09/99)*

Nanopore Inorganic Membranes as Electrolytes in Fuel Cells

Contractor: University of Wisconsin *Madison, WI*
Contact: Marc Anderson *(608) 262-2674*

Proton exchange membrane (PEM) fuel cell transportation technologies based on organic polymer membranes (perfluorosulfonated polymer – sold under the trade name Nafion) operate at relatively low temperatures (60-80°C). Very poor proton conductivity at higher operating temperatures is caused by the organic polymer membranes' inability to retain water. Higher fuel cell operating temperatures would increase the activity of the anode and cathode platinum-based electrocatalysts, thereby reducing the amount of platinum required and lowering system costs. The tendency of anode catalysts to be fouled by carbon monoxide in reformate fuels may also be eliminated by higher operating temperatures.

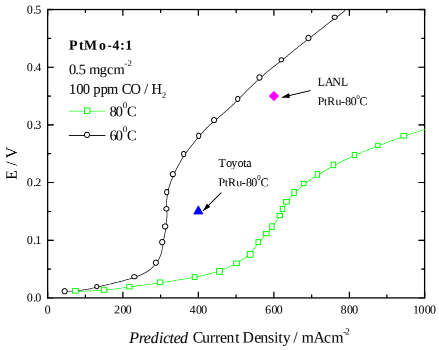


The overall objective is to develop fuel cells that incorporate novel ceramic electrolyte membranes based on nanoparticulate oxides, specifically Al_2O_3 and TiO_2. These high-surface-area porous oxide membranes should be capable of operating at temperatures above 100°C while displaying minimal water management problems. Consequently, the intrinsic proton conductivities of these materials are expected to be of at least the same order of magnitude as, or better than, their organic counterparts.

<u>Deliverables</u>: *Proton conducting ceramic xerogels (07/00)*
Composite electrodes (10/00)
Proton exchange ceramic membrane fuel cell prototype for testing at a national laboratory (02/01)

Electrode Kinetics and Electrocatalysis

Lawrence Berkeley National Laboratory — *Berkeley, CA*
Contact: Philip N. Ross, Jr. — *(510) 486-6226*

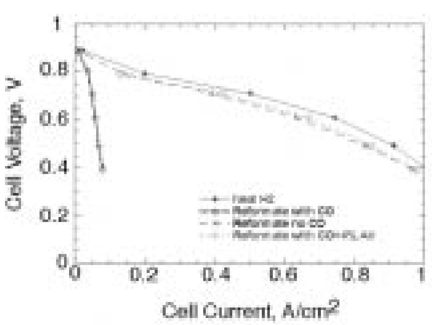


Research is conducted on the kinetics and mechanisms of the electrode reactions in low temperature, polymer electrolyte membrane (PEM) fuel cells. Based on these results new electrocatalysts are being developed using a material-by-design approach. Multimetallic catalysts are synthesized under carefully controlled conditions producing tailor-made surfaces. Surface composition and structure is determined using a combination of surface analytical techniques, Low Energy Electron Diffraction (LEED), Low Energy Ion Scattering (LEIS) and Auger Electron Spectroscopy (AES). It was found that a new Pt-Mo alloy electrocatalyst produced the highest level of CO-tolerance (defined as electro-oxidation of H_2 in the presence of small amounts of CO) in a PEM fuel cell anode of any material yet investigated. Even more promising multimetallic systems are under development.

<u>Deliverable</u>: *Anode catalyst with tolerance to CO levels > 100 ppm (06/00)*

Advanced PEM Fuel Cell R&D

Los Alamos National Laboratory — *Los Alamos, NM*
Contact: Shimshon Gottesfeld — *(505) 667-6832*



Los Alamos National Laboratory is advancing PEM fuel cell technology to support the introduction of fuel cell vehicles into global markets. One major focus of the work at LANL is to improve the tolerance of the anode catalyst to the CO in reformate fuel streams and minimize losses caused by hydrogen dilution. We are realizing improved CO tolerance by implementing improved catalysts, designing and implementing improved anode structures to enhance effectiveness of anode air injection for CO removal, and operating at higher cell temperatures. Recent achievements include the completion of a 1400 hours lifetest in a 50 cm^2 cell showing full tolerance to 100 ppm CO in hydrogen by means of air bleed, and the demonstration in a similar cell of 95% neat hydrogen performance with a 40% hydrogen fuel feed stream containing 100 ppm CO, using just 0.5 mg Pt/cm^2 at the anode. Work is in progress to further improve the anode structure and reduce the catalyst loading.

A second major thrust of our program is the development of direct methanol fuel cells (DMFCs). This effort has the objective of developing the materials, components, and operating conditions that would improve the potential of DMFCs for transportation applications. A recent program milestone was the demonstration of 0.15 W/cm^2 peak power in a DMFC operating continuously at a constant voltage of 0.4 V for 2000 h with fuel utilization close to 90%. The overall DMFC 36% energy conversion efficiency achieved compares favorably with a system based on onboard reforming of methanol.

<u>Deliverables</u>: *500 hours life test of 50 cm^2 cell demonstrating complete tolerance to 100 ppm, with catalyst loading of 0.5 mg Pt/cm^2 at 80°C (06/99)*
Build and test short DMFC stack operating at 100-110°C (04/99)

Air Management Subsystems

Turbocompressor with Variable Geometry for PEM Fuel Cells

Contractor: AlliedSignal Inc. - AES *Torrance, CA*
Contract: Mark K. Gee *(310) 512-3606*

Proton-exchange-membrane (PEM) fuel cell systems for transportation require a compact, low-weight, and efficient air compressor that provides a clean flow of air to the fuel cell stack. AlliedSignal is developing a turbocompressor to address these requirements. In 1998, full performance and initial durability testing of the baseline turbocompressor was completed. The baseline turbocompressor was then modified to investigate extending the efficient operating range of the flow, particularly at low flows. Such a low-flow turbocompressor will better enable the PEM fuel cell to meet system efficiency goals at low power levels. In 1999, durability testing of the baseline turbocompressor design and performance testing of the low-flow turbocompressor will be completed. By using the results from tests of both the baseline and low-flow turbocompressor, an optimized turbocompressor and motor controller will be developed in 2000.

<u>Deliverable</u>: *Turbocompressor/motor controller optimized for an automotive fuel cell system (03/01)*

Scroll Compressor/Expander Module for PEM Fuel Cell Pressurization

Contractor: Arthur D. Little, Inc. *Cambridge, MA*
Contact: Detlef Westphalen *(617) 498-5821*

Automotive proton-exchange-membrane (PEM) fuel cell systems will require a compact, reliable, and efficient compressor/expander module (CEM) for pressurization. Air must be supplied at the elevated pressure levels of anticipated fuel cell systems, and energy from the pressurized exhaust gases in an expander must be recovered to achieve acceptable system efficiency. First-generation scroll CEM development demonstrated the technology’s superior efficiency and operating range for this application. Development of a second-generation scroll CEM started in late 1997. A series of design improvements (e.g., improved seal design, elimination of belt drive, increased displacement, higher speed, use of magnesium alloy, and better machining tolerances) is expected to result in increased performance range and increased efficiency and durability. Testing of this prototype began in April 1999. After general performance testing, the CEM will be integrated into an Energy Partners fuel cell system to demonstrate the operation of a fully integrated fuel cell system.

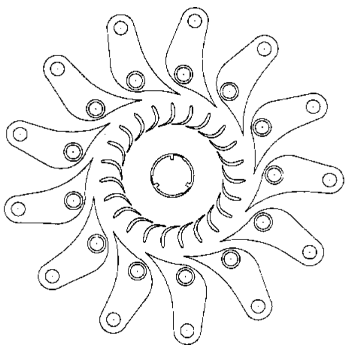
First-Generation Scroll CEM

<u>Subcontractor</u>:
Scroll Corporation, Carlisle, MA

<u>Deliverable</u>: *Second-generation CEM delivered to Energy Partners for performance testing in an integrated fuel cell system (05/99)*

Advanced Gas Bearings for Turbocompressors

Contractor: Meruit Inc. *Santa Monica, CA*
Contact: G. Fonda-Bonardi *(310) 453-3259*



Turbocompressors used to feed air to fuel cells and driven by the fuel cell exhaust require that internal (bearing) losses be minimal and that the feed air not be contaminated by oil. Because gas bearings solve both problems at once, they are the preferred choice if they can be made (1) low-cost, (2) long-lived, and (3) sufficiently rugged to withstand the shocks inherent in vehicular use. Meruit has built and tested a set of radial and thrust gas bearings designed for use in a turbocompressor to supply air to the U.S. Department of Energy's (DOE's) 50-kW net vehicular proton-exchange-membrane (PEM) fuel cell. The gas bearings, which perform as theoretically predicted, appear to be well-suited to their intended use. Meruit is now designing an experimental turbocompressor, with gas bearings matched to the expected characteristics of the 50-kW fuel cell, for verification of the aerodynamic performance of the turbine and compressor wheels. Two prototypes will be delivered to DOE, one for independent testing and the other for integration into the selected fuel cell air system.

<u>Subcontractor:</u>
Test Devices, Inc., Hudson, MA

<u>Deliverables</u>: *Two gas bearing turbocompressors for testing and evaluation (11/99)*

Integrated Compressor, Expander, and Motor (I-CEM)

Contractor: Vairex Corporation *Boulder, CO*
Contact: Jeremiah Cronin *(303) 444-4556*

The VAIREX I-CEM program builds upon the successful demonstration in laboratory hardware of variable, independent control of pressure ratio and mass flow with an integrated compressor and expander. In this phase, an I-CEM appropriate for both laboratory and vehicle proton-exchange-membrane (PEM) fuel cell system demonstration projects will be delivered. The complete I-CEM is expected to meet or exceed U.S. Department of Energy (DOE) performance guidelines. The mass of the compressor portion of the I-CEM has already been reduced from about 27 kg to about 10 kg, while its mass delivery capability has increased by about 50%. Meaningful reductions in I-CEM size and parts count, as well as improvements in projected efficiency, also have been achieved. Full-up testing at the compressor/motor level will be completed early this year; information on characteristics at this level will be made available to PEM fuel cell system integrators. Thereafter, the compressor portion of the I-CEM device will be available for integration at the system level. Expander development will continue until later in the year. Both devices will then be integrated into a complete I-CEM, and full-system testing will be performed. Performance characteristics will be determined and made available for PEM fuel cell system evaluations.

<u>Deliverable</u>: *Performance-tested variable Integrated-Compressor/ Expander Motor (I-CEM) (12/99)*

Hydrogen Storage Systems[1]

High-Pressure Conformable Hydrogen Storage for Fuel Cell Vehicles

Contractor: Thiokol Corporation — *Brigham City, UT*
Contact: Dr. Richard K. Kunz — *(435) 863-8799*

Non-cylindrical (conformable) high-pressure hydrogen storage tanks offer the capability for resolving range and on-board fuel packaging issues for fuel cell vehicles through more efficient use of available vehicle storage space. By application of advanced design, analysis, and fabrication techniques, Thiokol has developed full-scale carbon composite plastic-lined conformable tanks. Extensive development and testing have resulted in burst pressures as high as 13,750 psi. Current activities are focused on liner material selection, considering hydrogen permeation, processability, and mechanical properties. A special test apparatus for high-pressure, hydrogen permeation testing has been developed, enabling rapid material screening. Three liner materials have been selected for on-going testing in full-scale tanks. Future development efforts will be directed toward tank durability and life-cycle testing.

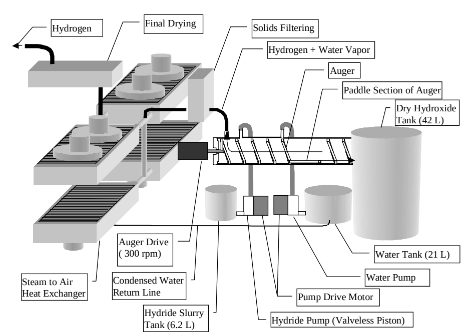
Subcontractors:
Aero Tec Laboratories, Ramsey, NJ
Southern Research Institute, Birmingham, AL

Deliverable: *Strength, durability, and lifecycle testing of full-scale conformable high-pressure hydrogen storage tanks, (05/00)*

Advanced Chemical Hydride Hydrogen Generation/Storage System for PEM Fuel Cell Vehicles

Contractor: Thermo Power Corporation — *Waltham, MA*
Contact: Dr. Ronald W. Breault — *(781) 622-1046*

To supply high-purity hydrogen for fuel cell-powered vehicles, Thermo Power Corporation is developing a system that employs a chemical hydride/organic slurry as the hydrogen carrier and storage medium. At the point of use within the vehicle, the high-purity hydrogen is produced through a reaction of the hydride slurry with water. The system (shown in the figure) has a projected energy density of greater than 3,355 Wh/kg (1,300 Wh/l), which exceeds DOE goals. Thermo Power Corporation has also developed a conceptual process for recovery and regeneration of the spent hydride. The process can deliver hydrogen at a cost ranging from \$3 to \$6 per million Btu. Not only is the technology capable of meeting DOE's hydrogen storage goals, but the entire process is economically feasible and environmentally friendly. The research program focuses on the development of a prototype hydrogen supply system that can deliver the equivalent of 50 kW of electrical power. The program spans 30 months. During the first 15 months, the concept was optimized using a laboratory reactor. In the upcoming 15 months, the design, fabrication, and testing of a prototype system encompassing all the major components will be completed.



Deliverable: *50-kW prototype of a hydride hydrogen-fueled PEM fuel cell system (03/00)*

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[1] These projects are co-funded by the U.S. DOE Hydrogen Program. For further information contact Sigmund Gronich, Program Manager, U.S. Department of Energy, 1000 Independence Ave., SW, Washington, DC 20585. Phone: (202) 586-1623; Fax: (202) 586-5127.

Fuel Cell Information Sources

Additional sources of information on fuel cells, other advanced power and vehicle technologies, and alternate fuels include the following:

- **U. S. Department of Energy, Energy Efficiency and Renewable Energy NETWORK**
  http://www.eren.doe.gov/transportation

- **U.S. Department of Energy, Office of Transportation Technologies Home Page**
  http://www.ott.doe.gov

- **The National Alternative Fuels Hotline (of the Alternative Fuels Data Center)**
  (800) 423-1DOE
  Fax: (202) 554-5049
  P.O. Box 70879
  Washington, DC 20024
  E-mail: hotline@afdc.nrel.gov
  http://www.afdc.nrel.gov

- **Office of Transportation Technologies Strategic Plan**

- **Research and Development Plan for the Office of Advanced Automotive Technologies**

- **Program Implementation Strategy for the Fuel Cells for Transportation Program, Office of Advanced Automotive Technologies**

- **FY 1998 Fuel Cells for Transportation Program: Contractor's Annual Progress Report**

- **FY 1998 Fuel Cells for Transportation Program: National Laboratory Annual Progress Report**

Major DOE Fuel Cell Research and Development Contractors for Transportation Applications

NexTech
Columbus, OH

UOP
Des Plaines, IL

3M
St. Paul, MN

Institute of Gas Technology
Des Plaines, IL

Stimsonite
Niles, IL

McDermott Technology, Inc.
Alliance, OH

University of Wisconsin
Madison, WI

Argonne National Laboratory
Argonne, IL

United Catalysts
Louisville, KY

Modine Manufacturing
Racine, WI

Superior Graphite
Chicago, IL

Masco
Taylor, MI

Epyx/Arthur D. Little
Cambridge, MA

Plug Power
Latham, NY

Spectracorp, Ltd.
Lawrence, MA

Foster-Miller Inc.
Waltham, MA

Thermo Power Corp.
Waltham, MA

ElectroChem
Woburn, MA

Corning, Inc.
Corning, NY

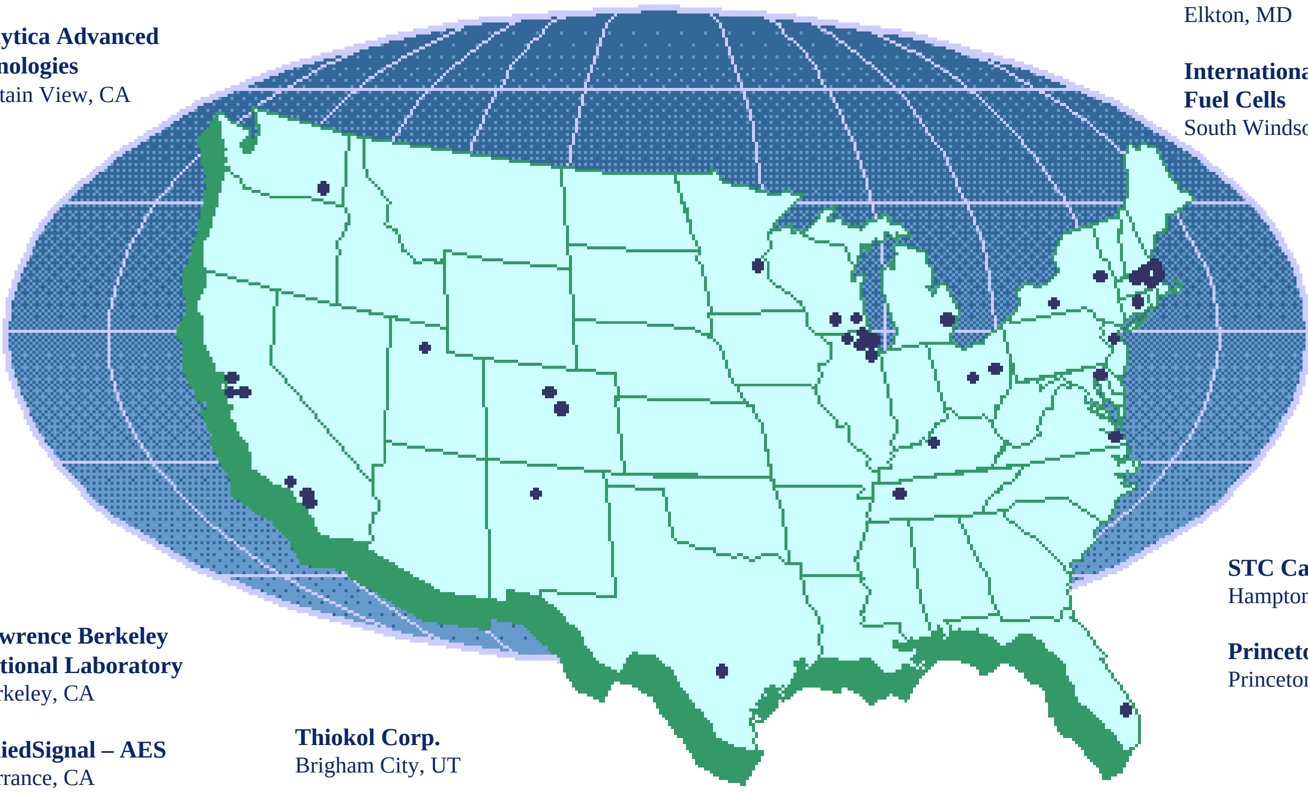
W. L. Gore
Elkton, MD

International Fuel Cells
South Windsor, CT

Pacific Northwest National Laboratory
Richland, WA

ARCADIS Geraghty and Miller, Inc.
Mountain View, CA

Catalytica Advanced Technologies
Mountain View, CA



STC Catalysts
Hampton, VA

Princeton Univ.
Princeton, NJ

Lawrence Berkeley National Laboratory
Berkeley, CA

AlliedSignal – AES
Torrance, CA

Hydrogen Burner
Long Beach, CA

Meruit, Inc.
Santa Monica, CA

Thiokol Corp.
Brigham City, UT

Vairex Corp.
Boulder, CO

National Renewable Energy Laboratory
Golden, CO

Los Alamos National Laboratory
Los Alamos, NM

Southwest Research Institute
San Antonio, TX

Dana Corp.
Paris, TN

Energy Partners, Inc.
West Palm Beach, FL

U.S. Department of Energy
Office of
Advanced Automotive Technologies, EE-32
1000 Independence Avenue, SW
Washington, DC 20585-0121