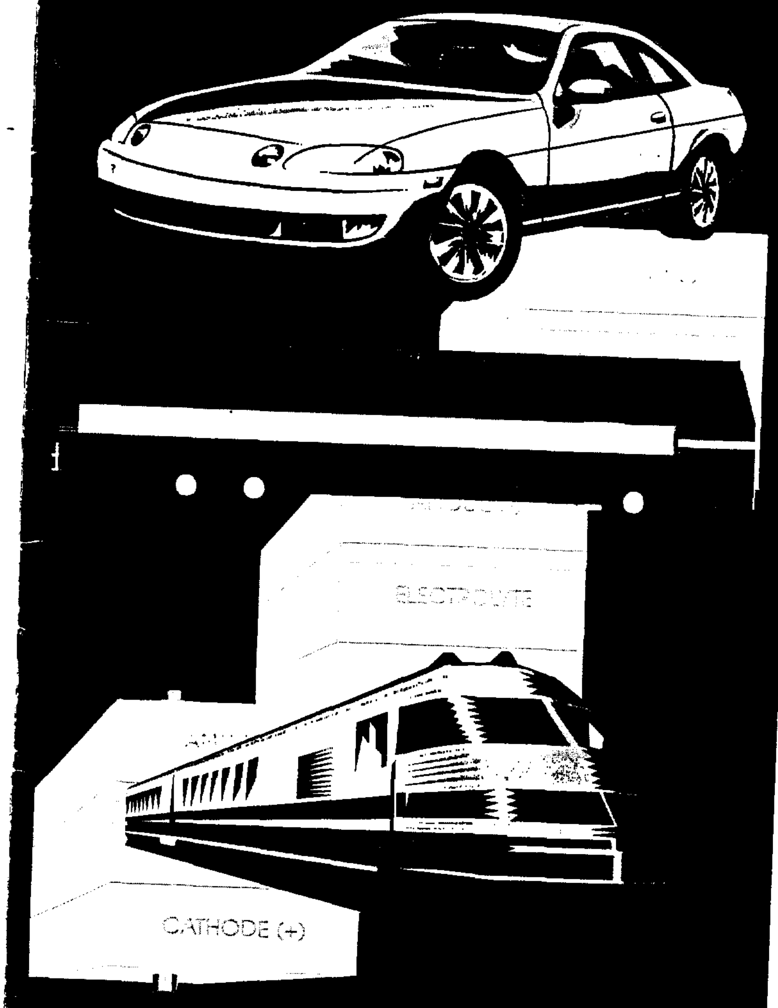
Fuel Cells in Transportation



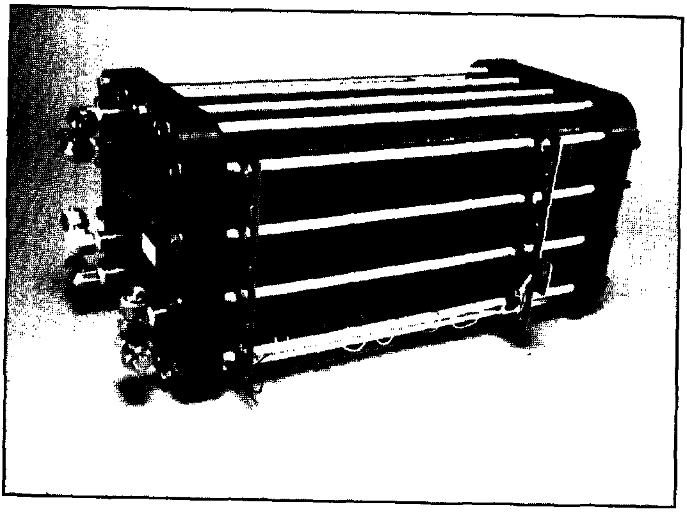
U.S. DEPARTMENT OF ENERGY

The U.S. Department of Energy (DOE) is conducting a research and development (R&D) program with the goal of developing a clean and efficient alternative to internal combustion engines (ICE) for the U.S. transportation sector as well as exports. DOE has been working for the past 30 years to develop fuel cells for generating electricity for commercial, industrial, and utility applications. In 1987, work began on DOE's R&D of fuel cells for transportation. Through its efforts, DOE has shown that fuel cells are a promising technology for solving the nation's air quality and foreign fuel dependency problems. As a result, the goal of the Fuel Cells in Transportation Program has become the research, development, and commercialization of fuel cell vehicles as economic competitors for ICE vehicles as rapidly as possible. DOE is spearheading efforts to form government/industry alliances to define and carry out the R&D needed to develop and manufacture fuel cell-powered vehicles (FCV). This will give the U.S. the opportunity to retain leadership in developing fuel cell technologies and to increase U.S. industrial competitiveness worldwide.

Prepared for the U.S. Department of Energy
by Abacus Technology Corporation

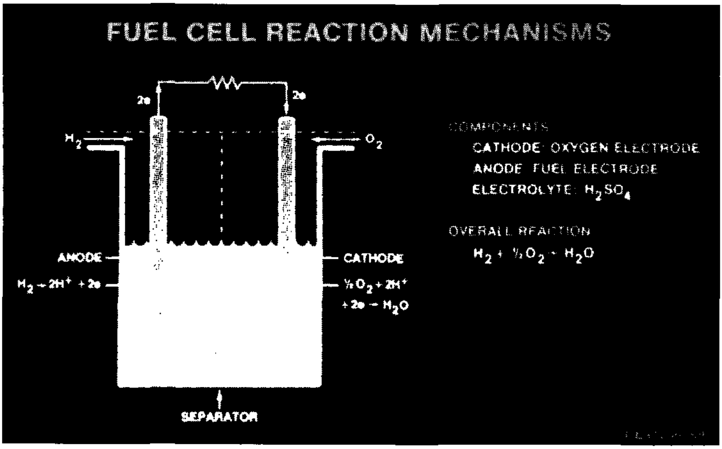
Q What are fuel cells?

A Fuel cells are devices that change chemical energy directly into electrical energy; no combustion is involved. They are an efficient, inherently clean option for generating electricity and can be fabricated in a wide range of sizes without sacrificing either efficiency or environmental performance.



Q How do they work?

A Similar to batteries, fuel cells are made of two electrodes with a conductive electrolyte between them. Unlike a battery, however, a fuel cell does not run down or require recharging. It will produce energy as long as fuel is supplied to it. At the anode, hydrogen electrode, hydrogen ions and electrons are formed. The hydrogen ions then travel through an electrolyte to the cathode, oxygen electrode. Simultaneously, the electrons move through an external circuit to a load and then to the oxygen electrode. At the oxygen electrode, the oxygen, hydrogen ions, and electrons combine to form water.



Q What fuels do they run on?

A Fuel cells can run on hydrogen. Hydrogen can be generated from methanol, ethanol, natural gas, propane, and other hydrocarbon fuels. Several fueling options are possible: 1) stored hydrogen can be provided directly to the fuel cell as a pure gas; 2) methanol, ethanol, or natural gas can be processed (reformed) in an external reformer to provide a hydrogen-rich gas for consumption in the fuel cell; 3) high temperature fuel cells can reform hydro-carbon fuels internally; and 4) in direct methanol fuel cells, methanol is provided directly to the fuel cell and electrochemically oxidized there.

Q *Are these fuels readily available?*

A The use of alternative fuels such as natural gas, liquefied petroleum gas, ethanol, and methanol in alternative fuel vehicles is on the rise in the U.S. It is estimated that more than 380,000 vehicles in the U.S. operate on these fuels. As a result of the increasing population of these vehicles and the subsequent increased use of these fuels, the number of refueling stations for these fuels is rapidly increasing. While hydrogen as a transportation fuel is currently not readily available to consumers, this situation is expected to change as vehicles designed to operate on hydrogen, including fuel cell vehicles, are developed and integrated into government and private vehicle fleets.

Q *Are these fuels safe?*

A The safety of natural gas, liquefied petroleum gas, ethanol, and methanol when used in transportation applications has been widely demonstrated. These fuels are as safe as and in some cases are safer than conventional petroleum fuels. The safety of hydrogen gas in FCVs has yet to be demonstrated because hydrogen has not been used to a great extent. However, initial indications are that with proper safety features designed into vehicles powered by hydrogen, these vehicles will meet if not exceed all Federal motor vehicle safety standards.

Q What is the history of fuel cells?

A The first fuel cell was developed by Sir William Robert Grove in 1839. His device used hydrogen as fuel and oxygen as the oxidant, platinum electrodes, and dilute sulfuric acid for the electrolyte. Although Grove conclusively demonstrated the principles of fuel cell operation, it was not until the 1950s that Francis Bacon succeeded in building a device that could generate practical amounts of power over prolonged periods. The largest unit he built produced 6 kW of power.

The success of Bacon was built upon by Pratt and Whitney Aircraft to develop a fuel cell for the Apollo Space Program. By 1965, fuel cells were routinely used in space flight and are still used by NASA today. The private sector and DOE have been working for the past 30 years to develop fuel cells for generating electricity for commercial, industrial, and utility applications. DOE's R&D of fuel cells for transportation began in 1987.

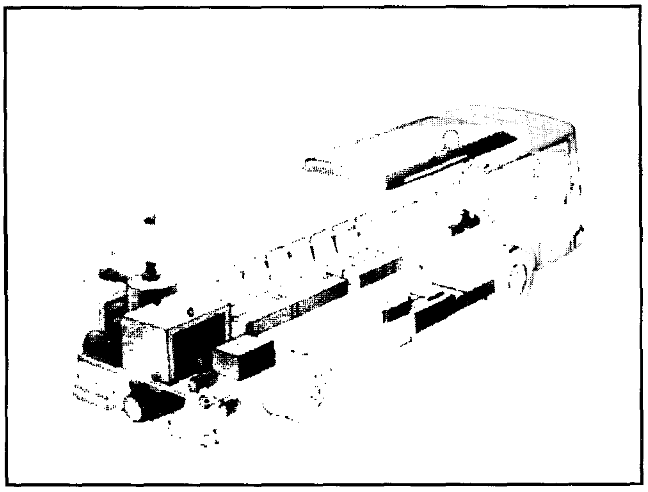
Q What are the various types of fuel cells?

A Fuel cells are often categorized by the electrolyte used. Five major classes of fuel cells generally considered to be in the mainstream of the technology are discussed here.

1) ***Alkaline Fuel Cells*** - Used by the U.S. space program and incorporated into most of the manned space missions, they offer high power outputs in relative small sizes and are very reliable. Unfortunately, their potassium hydroxide electrolyte reacts with even minute traces of car-

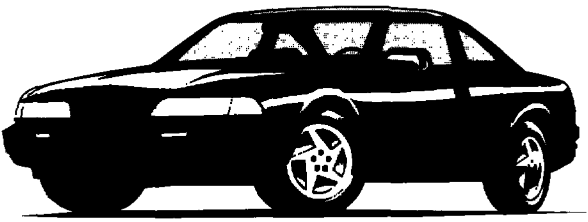
bon dioxide and eventually renders the cell useless, and extensive cleaning to remove residual carbon dioxide from the air and fuel is required. This is a very costly procedure with any known technology.

2) ***Phosphoric Acid Fuel Cells*** - The most technologically mature of the terrestrial fuel cell technologies. The electrolyte tolerates carbon dioxide, operating temperatures are above 400°F, and overall fuel-to-electricity efficiencies are about 40% (with cogeneration efficiencies approaching 85%). They are commercially available in sizes that range from a 24-volt, 250-watt portable unit for small appliances, to on-site power generators supplying up to 200 kilowatts of electricity, to a central station power plant in Tokyo that produces 11 megawatts of electricity. Phosphoric acid fuel cells are well suited for buildings and heavy-duty transportation applications. They are used in the DOE Urban Transit Bus Program.



PHOSPHORIC ACID FUEL CELL BATTERY POWERED BUS

3) ***Proton Exchange Membrane (PEM) Fuel Cells*** - Also known as polymer electrolyte fuel cells, operate at relatively low temperatures, 175-200°F, have high power density, meet shifts in power demands quickly, and are suited for applications where quick start-up is required. They are primary candidates for buildings, for light-duty vehicles, and potentially for much smaller applications.

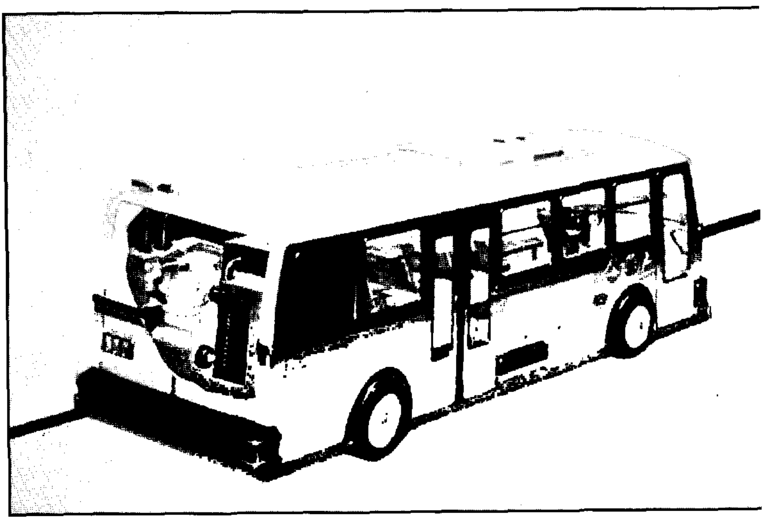


4) ***Molten Carbonate Fuel Cells*** - Use a lithium and potassium carbonate electrolyte, operate at about 1200°F, and have efficiencies of 60% for generating electricity and 80% or more when cogenerating usable heat. Capital costs are expected to be lower than phosphoric acid fuel cells. The first full-scale stacks have been tested and demonstration units will begin operation in 1994 and 1995 in a California municipal utility and hospital.

5) ***Solid Oxide Fuel Cells*** - Still in the R&D stages, they use a hard ceramic material instead of a liquid electrolyte, allowing temperatures to approach 1800°F. Efficiencies are projected to be 60% for these fuel cells, which can be configured in tubular, planar, or honeycomb structures. Their potential for internal fuel processing, high power density, and low cost makes them candidates for transportation applications.

Q *What types of vehicles can run on fuel cells?*

A Fuel cells are being developed to power light duty vehicles (cars, vans), heavy-duty vehicles (buses, trucks), and off-road vehicles (railroad locomotives).



Q *Are these vehicles currently available?*

A None of these vehicles are available at the present time, although prototype vehicles are being developed and will begin operation and testing before the turn of the century. The first DOE demonstration fuel cell bus will begin operation in 1993, the second in 1994, and the third in 1995. Proof-of-concept automobiles and a prototype locomotive are scheduled to begin operation by 1999. The DOE program plan's aim is for commercial availability following these vehicle demonstration projects.

Q *Are fuel cell vehicles safe?*

A Fuel cell vehicles are being designed to meet or exceed all Federal motor vehicle safety standards. Special features have been developed to provide protection from the heat generated by the fuel cells that operate at high temperatures as well as the acidic electrolyte used in most fuel cells.

Q *How do fuel cell-powered vehicles perform?*

A Since fuel cells continue to produce power as long as fuel is supplied such as methanol or ethanol, fuel cell vehicles can offer essentially the same or higher performance, range, and rapid refueling as conventional gasoline-fueled vehicles.

Q *How are fuel cell-powered vehicles different from battery-powered vehicles?*

A Fuel cell-powered vehicles do not have the range limitations or long recharging times that are characteristic of battery-powered vehicles. Unlike a battery, a fuel cell does not run down or require recharging. It will produce energy as long as fuel is supplied to it.

Q *How do fuel cells differ from internal combustion engines (ICE), turbines, and other heat engines?*

A Fuel cells are unlike ICEs, turbines, and other heat engines in three fundamental respects: 1) fuel cells produce power without chemical combustion, and thus they are inherently cleaner than heat engines could ever be; 2) fuel cells are not subject to the same fundamental laws of thermodynamics that limit the maximum efficiency of turbines and ICEs, fuel cell efficiency is twice as high as current heat engine efficiencies; 3) fuel cells have no moving parts, and therefore, are much quieter, have greater reliability, and require less maintenance than the high-speed rotating or reciprocating parts of turbines and ICEs.

Q *What is the operating life of fuel cells in vehicles?*

A Fuel cells most likely to be used in light-duty vehicles will be proton exchange membrane (PEM) fuel cells. They have an estimated life of at least

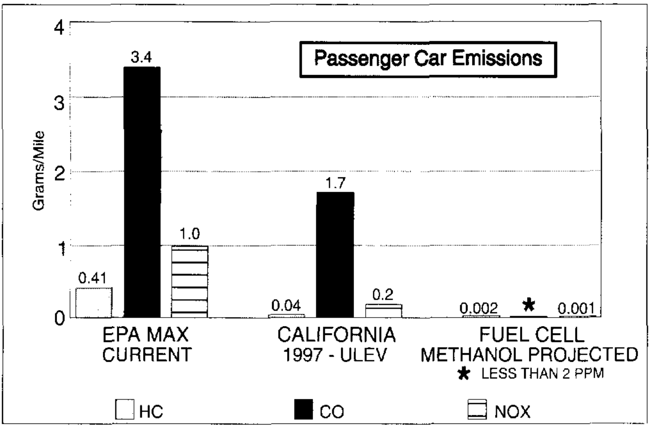
5,000 to 10,000 operating hours which should correlate to 100,000 to 200,000 miles. Phosphoric acid fuel cells have an estimated life of 5 to 10 years when used in heavy-duty vehicle and off-road vehicle applications.

Q *What are the benefits of fuel cells?*

A Fuel cells have numerous benefits including: emission reduction, high efficiency, quiet operation, very few moving parts (only those pumps and blowers needed to provide fuel and coolant), greater reliability, require less maintenance, modularity, and packaging flexibility. The development of fuel cells and their widespread use in the transportation sector would reduce the U.S. dependence on petroleum fuels, minimize air pollution from the transportation sector, and enhance the U.S. leadership in fuel cell development and manufacturing. In addition, the modularity and packaging flexibility result in cost savings in manufacturing and permit incremental power levels to match applications.

Q *What are the environmental benefits?*

A If hydrogen is carried on-board and used as fuel, fuel cell vehicles have zero emissions. Fuel cell vehicles operated on methanol or other alternative fuels can achieve emission levels for carbon monoxide, nitrogen oxides, and non methane organic gas far less than those levels established for the California Ultra Low Emission Vehicle standards, and approaching almost zero emissions. Benefits obtainable with only a 10% penetration of the light-duty vehicle market by fuel cell vehicles include avoided emissions of regulated air



pollutants of more than 1 million tons per year, and carbon dioxide reduction of 60 million tons per year, which is 5% of the projected total carbon dioxide emissions by the year 2007.

Q *What are the energy benefits?*

A Fuel cells can promote energy diversity and a transition to renewable energy sources. Alternative fuels (hydrogen, methanol, ethanol, natural gas, liquefied petroleum gas) can be used in a fuel cell vehicle. These fuels can be derived from a spectrum of energy sources. Hydrogen, ethanol, and methanol can be produced from renewable energy sources. Fuel cell vehicles afford an opportunity for a gradual transition to alternative fuels as the supply and distribution infrastructure is built up. With only a 10% market penetration by fuel cell vehicles, an imported petroleum displacement of 800,000 barrels per day could be achieved, which is 8% of the projected total petroleum use by the year 2007.

Q What are the economic benefits?

A successful U.S. transportation fuel cell program will greatly enhance the international competitiveness of U.S. industry in the worldwide transportation sector. The transportation sector accounts for $975 billion in gross domestic product and over 13 million jobs in the U.S. The transportation industry's health is essential to the economic well-being of the country. Establishing U.S. leadership in the development of fuel cells for transportation will lead to increased export opportunities and the creation of jobs. **A**

Q What are the costs compared to conventional transportation?

Fuel cell buses have a projected life-cycle cost lower than that for a comparable diesel bus. Although the initial cost for the fuel cell bus is higher than the diesel bus, maintenance and fuel costs are lower than those for the diesel bus. **A**

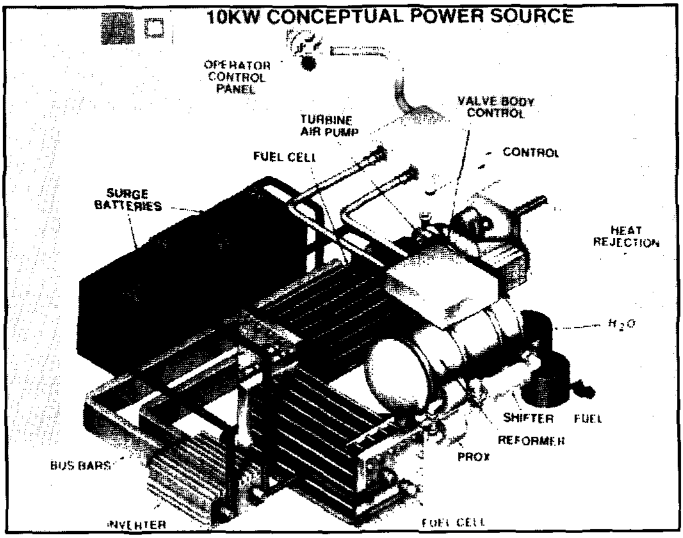
Q Why is there new interest in this technology?

The U.S. is attempting to balance its energy goals with its commitment to a cleaner, healthier environment, and fuel cells are one of the most promising energy technologies to achieve this balance. Several federal and state laws have also been enacted which require the development and use of vehicles with extremely low emissions and even vehicles with zero emissions. **A**

Q What are the major development needs for fuel cells in transportation applications?

A The constraints for fuel cells in transportation applications are considerably different and more demanding than for stationary applications. The size/weight of current fuel cell designs precludes their use in many applications, particularly light-duty vehicles; thus the power density of fuel cells (power output per unit volume or weight) needs to be improved. To achieve this result, fuel cell systems designed for use in vehicles need improvements in the fuel processor, fuel cell stack, and power plant and propulsion systems.

The fuel processor must be compact, rugged, low cost, have quick start and transient response, and emit low carbon monoxide during transients. The fuel cell stack needs low cost, reliable membranes/electrodes, catalysts (minimal use of noble metals), and bipolar plates, and must have improved power densities on reformate/air at low pressures, heat and mass (gas and water) transfer, and tolerance to CO/CO_2. The power plant system challenges include minimizing volume and weight, integrating thermal and functional compo-



nents, optimizing control modes, sensors, system start-up, transients, and low temperature survivability. The propulsion system needs include optimization of components for applications, optimization of drivetrain/control modes/electronics, and integration of vehicle/propulsion system interfaces.

Q *What is DOE's role in development of this technology?*

A DOE's program implementation strategy is to form alliances of government, industry, national labs, and universities to advance the development of fuel cell vehicles. DOE's program consists of four mutually supporting elements: light-duty vehicle systems; heavy-duty vehicle systems; research and development; and supporting analyses.

Development of Light-Duty Vehicle System - This program element is based on the use of proton exchange membrane fuel cell technology because of its high power density and ability to undergo frequent load cycling, a requirement of light-duty vehicles which typically operate only for short periods of time. The ongoing program is based on the use of on-board reforming of methanol. Parallel development of a light-duty passenger/utility vehicle powered by a proton exchange membrane fuel cell system with on-board hydrogen storage is scheduled to begin in 1993. Both projects are expected to advance to the proof-of-concept vehicle stage before a decision is made to proceed to the prototype development stage. Advances in proton exchange membrane fuel cell technology and in fuel reforming and hydrogen storage will be directly incorporated into the vehicle system development activities.

Development of Heavy-Duty Vehicle System - Fuel cells are being developed for use in heavy-duty vehicles such as buses, railroad locomotives, and trucks. The ongoing Urban Transit Bus Program is based on the use of phosphoric acid fuel cell technology. The bus application is typical of heavy-duty vehicles in general and will provide significant public visibility and valuable guidance for development efforts on other applications, such as trucks and commuter trains. The first target market for this bus is urban areas with acute air quality problems.

DOE and South Coast Air Quality Management District will pursue a joint program to develop fuel cell-powered railroad locomotives. The South Coast Air Quality Management District will begin a feasibility study for fuel cell use in locomotives in FY 1993. The choice of the specific fuel cell technology to be used will be made during a feasibility evaluation.

Research & Development - The R&D program will focus on the development of key subsystems and fuel cell technologies to enhance performance and reduce costs of fuel cell systems. Component development activities address three areas common to all fuel cell vehicle applications:

- Reformer technologies specifically designed for use in transportation applications, incorporating such attributes as load following, low weight and size, and adaptability to multiple fuel use. This program draws heavily on experience with reformers by the chemical process industries and stationary fuel cell developers, so that resources can be focused on transportation-specific issues.

- On-board hydrogen storage systems appropriate for use on a broad range of vehicles. Special attention is being given to transportation-specific issues such as safety, weight, and size, and supporting infrastructure requirements (e.g., compressors).

- Development of power management devices and concepts is scheduled to begin in FY 1993. These include high power batteries and ultracapacitors that can store energy recovered from regenerative braking, improve dynamic response, and handle load surges.

Fuel cell research will provide support for advanced technology concepts that show long-term promise for major improvements in performance and cost. Primary attention will be given to technology concepts attractive for transportation applications. Currently of interest for exploratory research are: 1) solid oxide fuel cell technology, which shows promise of very high power density, low cost, and ability to directly use a variety of different fuels; 2) direct methanol fuel cell technology, which can utilize methanol directly, thus eliminating the need for a fuel reformer; and 3) materials development, such as advanced membrane technology for proton exchange membrane fuel cells, novel electrocatalysts, and advanced materials for hydrogen storage.

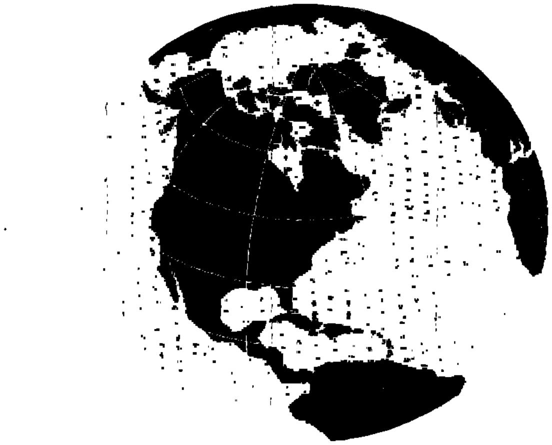
Supporting Analyses - supporting analyses are structured to help ensure that the program proceeds on a sound technical basis. Efforts under this program element include: 1) economic analyses for each fuel cell transportation application; 2) environment, safety, and health studies in the manufacture, operation, maintenance, and disposal of fuel cell vehicles; and 3) infrastructure related analyses. The results of these analyses will be important to determine programmatic needs and establish future program priorities.

Q *What Fuel Cell Systems R&D Programs are DOE coordinating with other Federal and State agencies?*

A The DOE is currently coordinating three large fuel cell systems R&D programs. These programs are being conducted by the Federal Transit Administration (FTA), the South Coast Air Quality Management District (SCAQMD), and the California Transit Authority (CALTRANS). The FTA program involves buses, the CALTRANS involves locomotives, and the SCAQMD involves both buses and locomotives.

Q What is being done by other countries?

A The large potential benefits of fuel cell vehicles are widely recognized, and many organizations throughout the world have initiated active R&D programs on fuel cells for transportation. The Japanese government has devoted $2 billion to the Clean Energy Network Using Hydrogen Conversion Project, of which fuel cells are an integral part. A government-sponsored national program for the development of proton exchange membrane fuel cells for transportation applications was initiated in 1992, and major multi-year development contracts were awarded in 1993. In addition, most Japanese automotive companies have very active internally-supported proton exchange membrane fuel cell R&D programs now underway.



A hydrogen-fueled bus is scheduled to begin operation in Belgium in 1993. It will be powered by a 78-kW alkaline fuel cell with Ni/Cd batteries to provide acceleration power and to store energy recovered through braking. In Germany, a 100-

kW alkaline fuel cell system has been demonstrated on a submarine, and one is being developed for the European space shuttle. In addition, a 20-kW proton exchange membrane fuel cell system is under development for terrestrial applications.

Development of proton exchange membrane fuel cell stacks for transportation applications is underway in Italy and will ultimately lead to the building and testing of demonstration vehicles. In Canada, a hydrogen-fueled bus powered by a 120-kW proton exchange membrane fuel cell has been developed and work has begun on development of proton exchange membrane fuel cells for automotive applications.

Q *What U.S. laws affect fuel cell vehicle development?*

A

Several U.S. laws affect fuel cell vehicle development including: 1) Matsunaga Hydrogen Research, Development, and Demonstration Act of 1990 (P.L. 101-556); 2) 1990 Clean Air Act Amendments (P.L. 101-549); and 3) Energy Policy Act of 1992 (P.L. 102-486).

Q *Where can I get more information on fuel cell vehicles?*

For additional information on fuel cell vehicles, **A**
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