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FUEL CELL POWER PLANTS FOR TRANSPORTATION APPLICATIONS

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ABSTRACT

Over the past 35 years, the transportation sector has accounted for approximately 25% of the total gross energy consumption in the United States. As the largest energy user in the United States, transportation accounts for approximately 66% of the country's current petroleum consumption. Fuel cell power plants using nonpetroleum fuels such as methanol could significantly reduce U.S. dependency on petroleum resources. They offer the additional advantage of minimal air pollution thereby addressing another issue of major concern in the U.S. Fuel cell power plant use in city buses and other vehicles is being explored in a number of U.S. Department of Energy and industrial programs that will be described in this paper.

INTRODUCTION

Fuel cell power plants are viewed as a potential replacement for the internal combustion engine in transportation applications (1,2). This is based, in part, on their potential to provide equivalent performance and range. Fuel cells also operate more efficiently than internal combustion engines and are capable of operating on methanol derived from natural gas, coal, or biomass. In addition, they produce virtually no regulated emissions; a feature that is of the utmost importance in the U.S. today. These fuel cell capabilities translate into reduced petroleum dependency, the ability to meet or exceed air quality standards, and consumer appeal through matching internal combustion engine range and performance characteristics.

Power plant efficiency characteristics are illustrated in Figure 1. Because of the nature of its operation, the fuel cell actually becomes more efficient at part load. This is of benefit, for example, in the operation of a passenger car in an urban scenario where 80% of the time the power plant is operating between 20% and 30% load. These efficiency gains and the ability to operate on nonpetroleum fuels could lead to major petroleum savings.

The changes in regulated emissions when fuel cells are used in place of conventional technologies are shown in Figure 2. The emission levels shown for the fuel cell result from the fact that all present day fuel cells use either hydrogen or a hydrogen-rich gas as the fuel. This means that methanol, or other nonpetroleum fuels, must go through a processing step (for example, reforming) to produce a hydrogen-rich gas stream for use in the fuel cell. Most of the emissions result from this step. Therefore, a fuel cell operating on reformed fuels can easily meet the ultralow emission vehicle (ULEV) standards, but will not be a zero emission vehicle (ZEV). If the fuel cell were to operate on hydrogen, it would be a ZEV.

Another emission of interest because of the greenhouse effect is carbon dioxide. Carbon dioxide emissions from a variety of transportation fuel options are shown in Figure 3. The bars are a summation for each fuel of extraction from the source, transport to a processing plant, processing, and end use in a vehicle. The first four columns are for internal combustion engine operation on gas/diesel, compressed natural gas (CNG), methanol from CNG, and methanol from coal. The fifth column is for battery-powered electric vehicles (EVs). The last column is for a fuel cell operating on methanol from natural gas. It is apparent that the fuel cell option offers a significant decrease in carbon dioxide emissions.

Fuel cell power plants could be used in all areas of ground transportation where power is now supplied by internal combustion or diesel engines. Such replacement requires that the fuel cell power plant must be capable of rapid response to load changes, must be able to withstand the shock and vibration of vehicle conditions, must be able to operate over a wide range of environmental temperatures, and must be capable of starting up in a very short time. Issues that must be addressed during fuel cell power plant development are an acceptable initial cost for the application, low maintenance cost, and long service life.

The rapid response to the load changes requirement is worthy of special consideration because it has dictated the direction of fuel cell power plant system development programs. The fuel cell itself is capable of very rapid response as long as it is supplied with fuel and oxidant. Because the systems now being developed are using reformed fuels, the fuel supply rate is governed by the response time of the fuel processor. In current fuel processor designs, response times to load changes are on the order of minutes, which is much too slow for vehicular applications. Therefore, current fuel cell power plant development programs, while investigating fuel processor designs that are capable of rapid response times, are relying on power plant designs wherein the fuel cell is in hybrid combination with a battery. The battery is being sized to handle transient load demands and to reduce response time demands on the fuel processor.

The advantages offered by fuel cell power plants have led to major programs for the development of such power plant systems for vehicular power plants. Two of these programs are described.

FUEL CELL-POWERED BUS PROGRAM

A feasibility study (3) conducted by the Los Alamos National Laboratory for the Department of Transportation, Urban Mass Transportation Administration (DOT/UMTA) recommended developing a fuel cell/battery hybrid powered propulsion system. The transit bus was selected as the best vehicle for the first installation for several reasons (2,3,4). It is large enough to accommodate first generation fuel cell power plant designs. This type of fleet operation allows testing under controlled conditions. The long service life of transit buses allows the application to be life cycle costed, which alleviates the impact of high initial acquisition costs. Finally, these vehicles are centrally maintained and centrally fueled, which reduces the support infrastructure requirements.

The phosphoric acid fuel cell (PAFC) was selected for near term use in the bus program based on the guidelines established for the study. It is the only fuel cell that has demonstrated operation on reformed fuels and, because of extensive development for utility applications, it is the fuel cell technology that is closest to being an off-the-shelf product.

The transit bus application selected places severe cyclic demands on the power system because of its typical stop and go operation. The PAFC system has considerable thermal inertia, mainly resulting from the behavior of the fuel processing subsystem. Therefore, to meet the peak power required from the propulsion system for hill climbing and acceleration without incurring excessive weight and size penalties, a fuel cell/battery hybrid system is required wherein the battery is used to meet the peak power requirements.

In FY 1987, the Fuel Cell/Battery Powered Bus System Program was initiated co-sponsored by the Department of Energy (DOE), DOT/UMTA, and the California South Coast Air Quality Management District (SCAQMD). The objectives of this program are to demonstrate the feasibility of a methanol-fueled phosphoric acid fuel cell/battery power plant system for the transit bus application and to advance the fuel cell/battery and control technologies in integrated fashion with available power train technology. The goal is to provide an alternative to diesel-powered buses.

The overall program is divided into four phases. Phase I has been completed. This was a system design/integration effort aimed at demonstrating proof-of feasibility for the fuel cell/battery propulsion power system. Key activities in this Phase were (A) conceptual design of the bus system, (B) trade-off analyses and performance specifications, and (C) the design, fabrication and laboratory evaluation of a half-scale fuel cell/battery brassboard propulsion power system. Two separate cost-shared industrial contracts were initiated to evaluate both air-cooled and liquid-cooled phosphoric acid fuel cell systems. The air-cooled system was investigated by a team led by Energy Research Corporation (ERC) and the liquid-cooled system was investigated by a team led by Booz-Allen & Hamilton (BAH)

The design specifications were met or exceeded by both the BAH and the ERC brassboard systems. No fundamental design problems were revealed and both systems demonstrated the capability to meet load transients. Testing also confirmed that the power systems produced low emissions and low noise levels.

Results of an economic analysis indicated that a methanol-fueled fuel-cell-powered bus could have a life-cycle cost that is competitive with a comparable diesel-powered bus. Initial capital cost of the fuel cell bus will be higher than the diesel counterpart; however, the lower fuel and operating costs of the fuel cell bus will compensate for this difference.

The results of the Phase I effort led to the conclusion that a fuel cell/battery powered urban bus is technically and economically feasible. In addition, benefits that have not been quantified can accrue through improved acceleration, lower noise, and very low emissions. Because both brassboard systems demonstrated the feasibility of meeting the bus requirements, DOE is proceeding with the Phase II development effort on a competitive procurement basis.

In Phase II, a system design and integration contractor will design and build three test-bed buses utilizing a PAFC/battery power source. The Request for Proposals for this work was issued in May 1990 and the contract was recently awarded to a team led by H Power Corporation for the development of a liquid-cooled PAFC system. In Phase III, track testing and field evaluation of the test-bed buses will be carried out. Phase IV will provide field testing of small fleets of prototype buses in a variety of urban applications. Phase IV results are needed to provide the data and experience for making commercialization decisions.

PROTON EXCHANGE MEMBRANE (PEM) FUEL CELL SYSTEM FOR TRANSPORTATION

The PEM fuel cell was originally developed for space power in the 1960s. After this technology was used in the Gemini flights, there was very little further development of the fuel cell aspects until the 1980s. In 1982, based on a series of studies, Los Alamos National Laboratory selected this technology as the most promising for use as a vehicular power source. Several factors led to this selection including (A) lowest weight and volume of an carbon dioxide rejecting fuel cell technology, (B) high power density, (C) long life, (D) low corrosion, and (E) a cold start capability resulting from the ability to deliver approximately 50% of rated power at ambient temperature. The operating temperature of PEM systems is from 80° to 100°C, and these temperatures can be attained very rapidly from ambient start via heating resulting from internal resistance. From 1982 until the present, considerable effort has been expended by the government and industry to improve the performance and reduce the cost of this technology. This development has reached the point where performance is acceptable for proceeding into system considerations. Initially, because fuel processing problems are the same as those for the PAFC systems, the power system evaluated will be a PEM fuel cell/battery hybrid where the fuel cell provides the range capability and the battery provides the necessary power for acceleration.

The promise of the PEM fuel cell technology has led to a joint government/cost-shared funded effort between DOE, SCAQMD, General Motors' Allison Gas Turbine Division, the General Motors Technical Staffs, Los Alamos National Laboratory, Dow Chemical Co., and Ballard Power Systems Co. to develop an advanced, methanol-fueled, PEM fuel cell propulsion system for vehicular applications (5). The first phase of this program was initiated September 1, 1990. This initial 2-year effort is viewed as the first stage of a 6-1/2-year program that develops an advanced reformate/air PEM fuel cell power plant and culminates in a fuel cell/hybrid vehicle demonstration.

General Motors envisions a four-phase program leading to the final test and evaluation of a PEM fuel cell/hybrid vehicle demonstrator. The objectives of the on-going first phase are the delivery of a conceptual design study of a PEM-based propulsion system, R&D on limiting components to advance the system to meet transportation needs, and integration and testing of a complete 10-kW PEM fuel cell system including fuel cell stack(s), fuel processor, batteries, power conditioning, and controls.

Pending successful completion of the first phase and a positive go-ahead decision, the second, 2-year, phase of the program will be initiated. The objectives of this phase are the development of a 40-kW brassboard power plant, its integration with vehicle drivetrain components, and the start of brassboard power plant dynamometer testing. This second phase will also include further system optimization of the 10-kW unit and continuing design, fabrication, and procurement of the components and drivetrain of the vehicular propulsion system. Optimization of the 10-kW system will provide the basis for producing the control capability required for a 40-kW power source system. Towards the end of this second phase, some effort will be focused on preparing a "mule", or laboratory vehicle, to accept the components/drivetrain and 40-kW fuel cell power source.

The third phase extends for 18 months and emphasizes the development of an 80-kW fuel cell power source prototype, dynamometer testing of this prototype, and its installation in the mule vehicle. Test programs will be optimized by evaluating a 40-kW power source thoroughly, first on a dynamometer and then in the mule vehicle. Following the development of an 80-kW reformer, the 80-kW power source will be integrated, dynamometer tested, and then installed in the same mule vehicle.

The final phase of the program lasts for one year. This phase includes further prototype mule testing, installation in an actual demonstration vehicle, and proof-of-concept evaluation of the fuel cell/hybrid vehicle.

The initial phase of this program, currently under contract, emphasizes the development of technologies that have been identified as being critical to the success of this propulsion system concept. The intent of this phase is to produce a 10-kW, methanol-fueled power source that demonstrates system feasibility and also provides a basis for the evaluation of fuel cell power plant system use in transportation applications. Essential to this effort are tasks addressing the PEM fuel cell, a methanol fuel processor, electronic controls, a gas pressurizing system, responsive water and heat management systems, system designs with low thermal inertia, an appropriate battery (to assist with transients and start up), and other ancillaries. Delivery to DOE of a fully operational 10-kW reformate/air PEM fuel cell power plant system will demonstrate technology feasibility. The design efforts of this phase will involve a propulsion system conceptual design study that will serve to define the actual reference power train design specifications for a full-scale fuel cell/hybrid vehicle.

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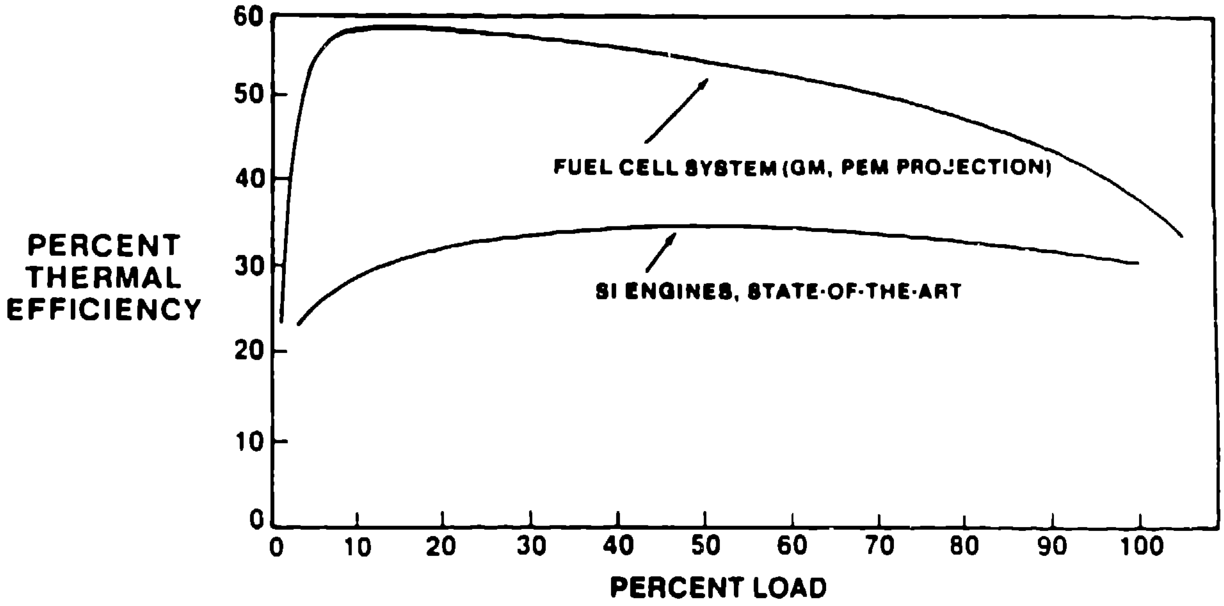

Figure 1. Power Plant Efficiency Characteristics (Courtesy of Allison Gas Turbine Division, General Motors Corporation)

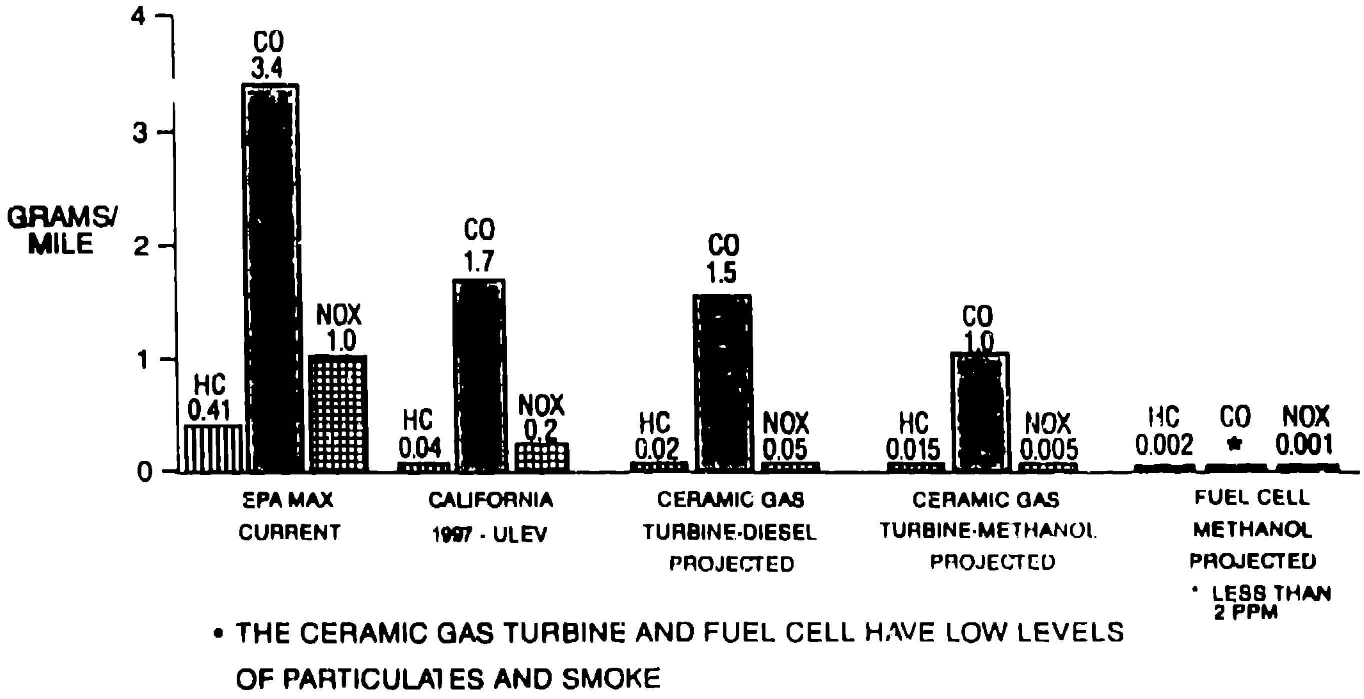

Figure 2. Regulated Emissions - Passenger Cars (Courtesy of Allison Gas Turbine Division, General Motors Corporation)

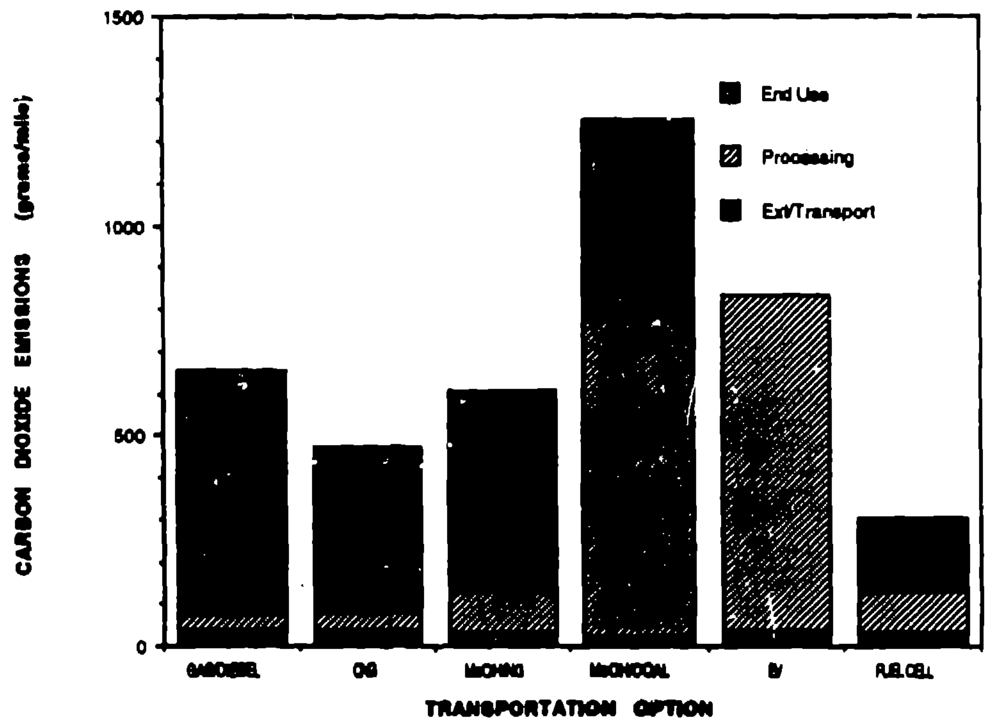

Figure 3. Carbon Dioxide Emissions from Transportation Options