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US Department of Energy fuel cell program for transportation applications

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Abstract

Fuel cells offer promise as the best future replacement for internal combustion engines in transportation applications. Fuel cells operate more efficiently than internal combustion engines, and are capable of running on non-petroleum fuels such as methanol, ethanol, natural gas or hydrogen. Fuel cells can also have a major impact on improving air quality. They virtually eliminate particulates, NO_x and sulfur oxide emissions, and significantly reduce hydrocarbons and carbon monoxide. The US Department of Energy program on fuel cells for transportation applications is structured to advance fuel cell technologies from the R&D phase, through engineering design and scale-up, to demonstration in cars, trucks, buses and locomotives, in order to provide energy savings, fuel flexibility and air quality improvements. This paper describes the present status of the US program.

Introduction

If we were to project ahead to the twenty-first century, to the year 2020, what would we expect the quality of the air we breath to be like. We can speculate by looking at the progress made thus far in this century. We could find that in spite of the improvements we have made in reducing the emissions of our power generating plants and industrial processes, and despite the spectacular improvements in cleaning up the internal combustion engine, that we may have improved the air we breath only marginally. The reason for this is the increased demand for energy in all sectors and, most significantly, the increased use of the automobile and other road vehicles.

By far the major contributor to air pollution is the petroleum-fueled motor vehicle. In the US, 66% of the carbon monoxide emissions come from vehicles alone. As can be seen from Fig. 1, vehicular emissions of NO_x, lead, CO_2, particulates and volatile organic compounds (VOCs) which are the precursors of ozone, are all significantly high in the US even though stringent emission controls are in effect.

In spite of plans to mandate stricter pollution control requirements, the increased number of vehicles on the road and the associated increase in vehicle kilometers traveled will make the future task of cleaning the air we breath very difficult if we continue to burn fossil fuels for transportation power. The global population of motor vehicles on the roads today is one half billion; this is ten times greater than existed in 1950. In the US, the total vehicle-kilometers-traveled increased by more than 35% during the last decade. Projections for the 30-year period between 1990 and 2020 indicate that vehicle travel will almost triple and the resulting emissions will be a serious problem [1].

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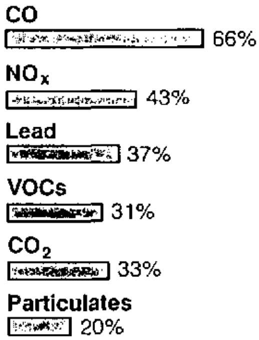

Fig. 1. Transportation share of US emissions in 1987.

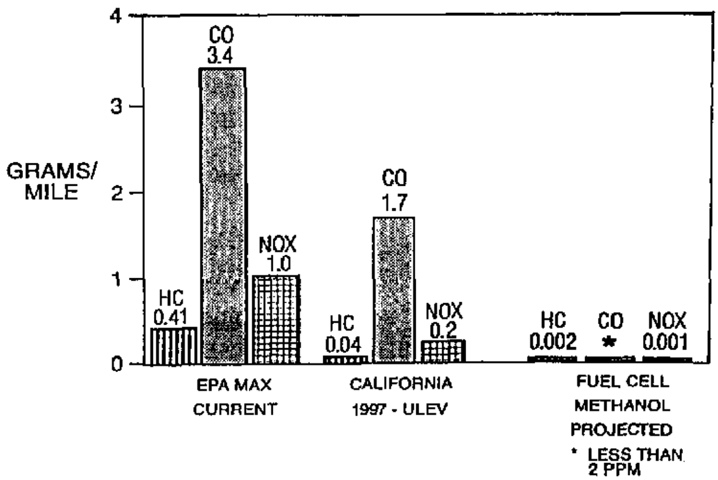

Fig. 2. Regulated emissions standards for passenger cars.

If we are to make the future 'brighter', more drastic steps than just lowering the emissions level of the internal combustion engine must be taken to assure that we don't proceed into the next century with air quality only slightly better than what we are experiencing now. Today, almost 130 million US residents live in areas that do not attain national air quality standards, according to a report from the US Environmental Protection Agency [2].

Fuel cell powered vehicles could have a major impact on improving US air quality, since fuel cells have virtually no emissions of particulates, NO_x and sulfur oxide, and extremely low emissions of hydrocarbons and CO. Figure 2 shows the emissions of a methanol phosphoric fuel cell compared to the present EPA standards. In addition, methanol-fueled fuel cells do not produce formaldehyde emissions as do methanol-fueled internal combustion engines. While battery-powered electric vehicles would have no on-the-road emissions, the emissions associated with such a vehicle will be displaced to the power station and will therefore depend on the fuel used for electricity generation. Unfortunately, the limited driving range before recharging of a battery powered vehicle prevents it meeting the needs of a large segment of the marketplace, and thus it

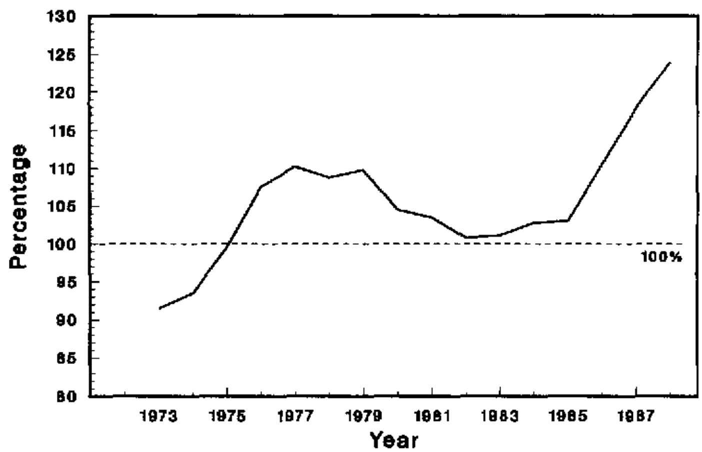

Fig. 3. Transportation petroleum consumption as a percentage of total US petroleum production.

cannot completely replace the internal combustion engine (ICE) powered vehicle. By contrast, a technology which provides the potential for total replacement would have a much more significant effect on the environment. Fuel cell powered vehicles, operating on liquid fuels such as methanol, ethanol or liquified natural gas, would have nearly the same capability for long range and rapid refueling as conventional ICE vehicles.

Fuel cells also have greater energy efficiency than internal combustion engines, yet can provide the same performance. Figure 3 shows the trend in transportation petroleum consumption as a percentage of US petroleum production. In 1988, transportation alone consumed about 14 million barrels/day or 26% more petroleum than the total US production. Since fuel cells are not subject to the Carnot cycle limitations of heat engines, energy efficiencies of over 40% are obtainable with current technology fuel cells, and even higher efficiencies are possible with careful system design to utilize the waste heat. In addition, unlike internal combustion engines, fuel cells maintain high efficiency even at partial loads. Thus, fuel cells could lead to major petroleum savings not only due to the efficiency gains but also from the ability to run on non-petroleum fuels such as methanol and ethanol [3].

Fuel cells can be applied in all areas of ground transportation which now utilize internal combustion engines. This includes passenger cars, vans, trucks, buses and trains. Thus, fuel cells for transportation applications are attractive in terms of environmental benefits, energy savings and petroleum displacement. Other benefits of fuel cell powered electric vehicles include lower maintenance requirements, passenger comforts in terms of lower noise and vibration levels, capability for passenger compartment heating from the waste heat, and smoother acceleration and deceleration. These features together with the environmental and efficiency benefits make fuel cells an attractive alternative to internal combustion engines for transportation applications.

US program goals and strategy

In the US, strategies are being implemented to reduce both energy consumption and emissions in the transportation sector. Specifically, the development of fuel cell propulsion technology has been identified in the US National Energy Strategy (NES) as a means to promote greater energy security.

Near-term efforts are directed at phosphoric acid fuel cells (PAFC) as the most suitable mature technology for application in transportation at this time. Current work is in progress that will result in a methanol fueled, fuel cell/battery powered bus with performance equivalent to diesel buses but with exhaust emissions reduced more than 99%. Three such buses are scheduled for delivery in 1994. An economic analysis indicates that a methanol-fueled fuel cell powered bus can have a life-cycle cost competitive with diesel buses. Although the initial capital cost of the fuel cell bus will be somewhat higher than its diesel equivalent, the lower fuel and operating costs of the fuel cell bus compensate for this difference.

For cars and vans, the program is directed at proton-exchange-membrane (PEM) fuel cells for mid-term introduction, and solid oxide fuel cells (SOFC) for long-term application and greater capability. PEM fuel cells can achieve the power density required for cars and vans, but much additional R&D is required towards performance optimization, system integration, engineering scale-up and cost reduction.

The SOFC system may offer the best long-term prospects since it operates with internal reforming and thus does not require a separate reformer or peaking power source. The SOFC technology is at an early stage of development, and R&D is focussed on materials development to reduce the fuel cell operating temperature, to simplify fabrication, and to improve system reliability and ruggedness [4].

Advanced fuel reforming technology will also be developed to improve the competitiveness of PAFC and PEM fuel cell powered vehicles by reducing system size and cost, reducing start-up times and increasing transient response capability. Fuel flexibility is being sought through development of reformers with the capability of reforming methanol, ethanol, natural gas or other hydrocarbons and by improved systems for on-vehicle storage of hydrogen.

Fuel cell R&D activities

The US Department of Energy (DOE) has two major programs underway, and is initiating a third, directed at advancing the fuel cell technology for transportation to the point where industry has the information to make decisions on commercialization. These R&D programs are described in the following paragraphs.

Fuel cell/battery powered bus system program

The objective of this program is to develop a methanol-fueled phosphoric acid fuel cell/battery propulsion system for a small urban bus as an alternative to diesel-powered urban buses. This program was initiated in 1987 and is co-sponsored by DOE, the US Department of Transportation/Urban Mass Transportation Administration (DOT/UMTA) and the California South Coast Air Quality Management District.

As shown in Fig. 4, this program is divided into the following four phases:

Phase I: proof of feasibility for fuel cell/battery system
Phase II: proof of concept in test-bed bus
Phase III: evaluation of test-bed bus
Phase IV: field testing of prototype buses

Phase I was a system design and integration effort directed at demonstrating proof of feasibility for the fuel cell/battery propulsion system. This phase was begun in 1987 and included: (a) conceptual definition of the bus system, (b) tradeoff analyses and performance specifications, (c) integration of a half-scale fuel cell/battery brassboard

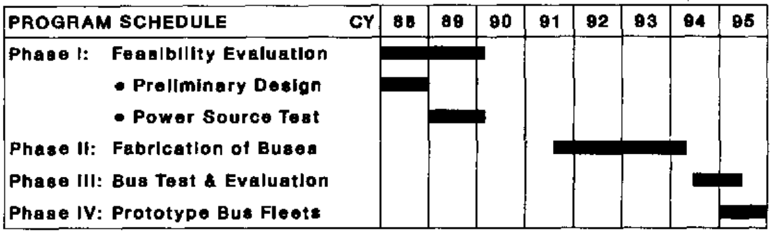

Fig. 4. Phosphoric acid fuel cell/battery bus program.

power source and controls, and (d) laboratory evaluation of the fuel cell/battery brassboard propulsion system. Phase II, which began in Sept. 1991, includes the development of the proof of concept fuel cell/battery power source and the powertrain components and their integration into small urban buses. Track testing and field evaluation of the test-bed buses will be accomplished in Phase III, which will begin in early 1994. Lastly, Phase IV, which will begin in early 1995, will provide the data and experience needed by industry to make commercialization decisions. It is expected that fuel cell buses will be commercially available by the end of the decade.

The urban transit bus was selected as the entry point for application of fuel cells for transportation because operation in urban areas will accentuate environmental benefits; the transit route structure is relatively fixed and permits evaluation under controlled conditions; the transit industry has an infrastructure in place to support operation and evaluation of the fuel cell/battery bus; the long service life of transit buses allows amortization of higher acquisition cost over a reasonable time period; and the bus size permits accommodation of the first-generation fuel cell designs.

Two contracts were awarded for Phase I, to evaluate both air-cooled and liquid-cooled phosphoric acid fuel cell systems, to provide a greater probability of success for the successful application of fuel cell technology to transportation needs. A two-year contract was awarded to the team of Energy Research Corporation, Los Alamos National Laboratory, and Bus Manufacturing USA, Inc., who developed an air-cooled phosphoric acid fuel cell/battery brassboard system [5]. A parallel two-year contract was awarded to the team of Booz-Allen & Hamilton, Chrysler, and Engelhard/Fuji who developed a liquid cooled phosphoric acid fuel cell/battery brassboard system [6]. Phase I was successfully completed with the demonstration of the proof of feasibility for a fuel cell/battery powered bus. A preliminary layout for a 27-ft bus is shown in Fig. 5, and the design characteristics for this bus are given in Table 1.

For Phase II, DOE has selected H-Power Corporation of Bloomfield, NJ as the prime contractor. Planned subcontractors on the H-Power team are Booz, Allen & Hamilton, Bus Manufacturing USA Inc., Transportation Manufacturing Corp., Fuji Electric, and Soleq Corporation. The objectives of this 30-month, cost-shared project include the fabrication of three 27–30 ft urban buses, and the design of a 40-ft urban bus.

PEM fuel cell propulsion system program

This program, as shown in Fig. 6, consists of four phases:

Phase I: feasibility evaluation
Phase II: proof of feasibility
Phase III: system scale-up
Phase IV: proof of concept

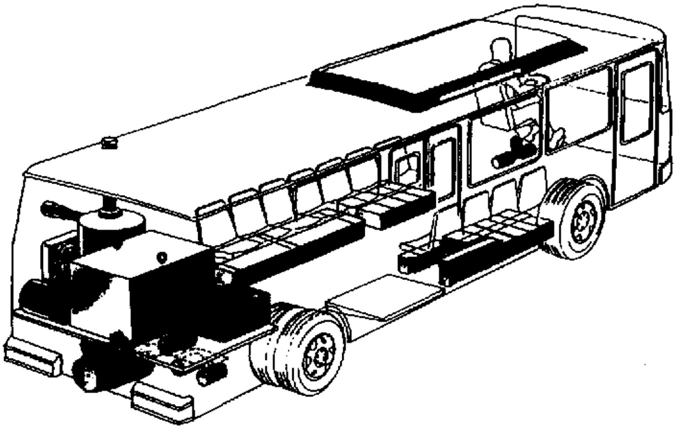

Fig. 5. Fuel cell/battery powered bus layout.

TABLE 1

Bus design characteristics

	Fuel cell bus	Diesel bus
Size	27 ft long 24 seats	28 ft long 24 seats
Weight (lb)	19025	17000
Acceleration (s)		
0–20 mph	10	10–12
0–40 mph	33	34–46
Fuel energy consumption (% of diesel)	65	100

Phase I will lead to the demonstration of a 10-kW breadboard system. This phase includes (a) development of a conceptual propulsion system design based on trade-off studies and economic analyses, to establish the component specifications required for transportation applications and to identify the limiting components; (b) research and development on limiting components to advance the technology to meet the system needs; (c) development and fabrication of controls and interface systems; and (d)

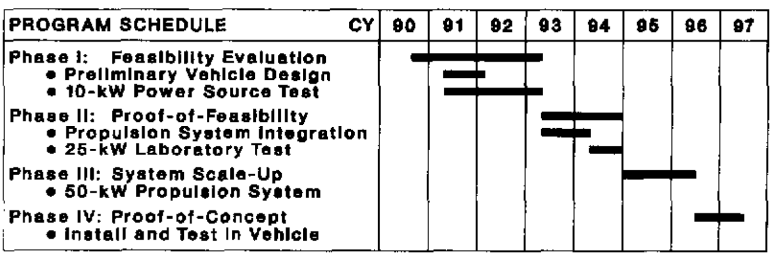

Fig. 6. Proton exchange membrane (PEM) fuel cell program.

integration of a complete 10-kW subscale breadboard system and its evaluation as a potential power source for transportation applications.

Phase II, proof of feasibility, will lead to the testing of a 25-kW brassboard system. Phase III, laboratory scale-up, will result in the laboratory evaluation of a full-scale 50-kW propulsion system. Lastly, in Phase IV, proof of concept, the full-scale system will be installed and evaluated in a test-bed vehicle.

DOE awarded a contract in 1990 to Allison Gas Turbine Division of General Motors for the Phase I work. Allison's subcontractors are Los Alamos National Laboratory, Ballard Power Systems, Dow Chemical Company, and General Motors Research Laboratories and Advanced Engineering Staff [7]. The work under this 32-month, 20% cost-shared contract will be completed in 1993 with the integration and testing of a complete 10-kW PEM fuel cell system; a design concept for such a system is shown in Fig. 7. The expected outcome of this effort is a demonstration of the feasibility of PEM fuel cells for transportation, thereby laying the groundwork for a potential future engineering scale-up for cars and vans.

Advanced multifuel reformer development

Over 60% of the petroleum used in the US each year is used by the transportation industry. Domestic production alone does not supply enough petroleum to meet transportation's needs. However, the hydrogen used in fuel cells can be produced from many sources, such as methanol, ethanol or natural gas. The hydrocarbons are

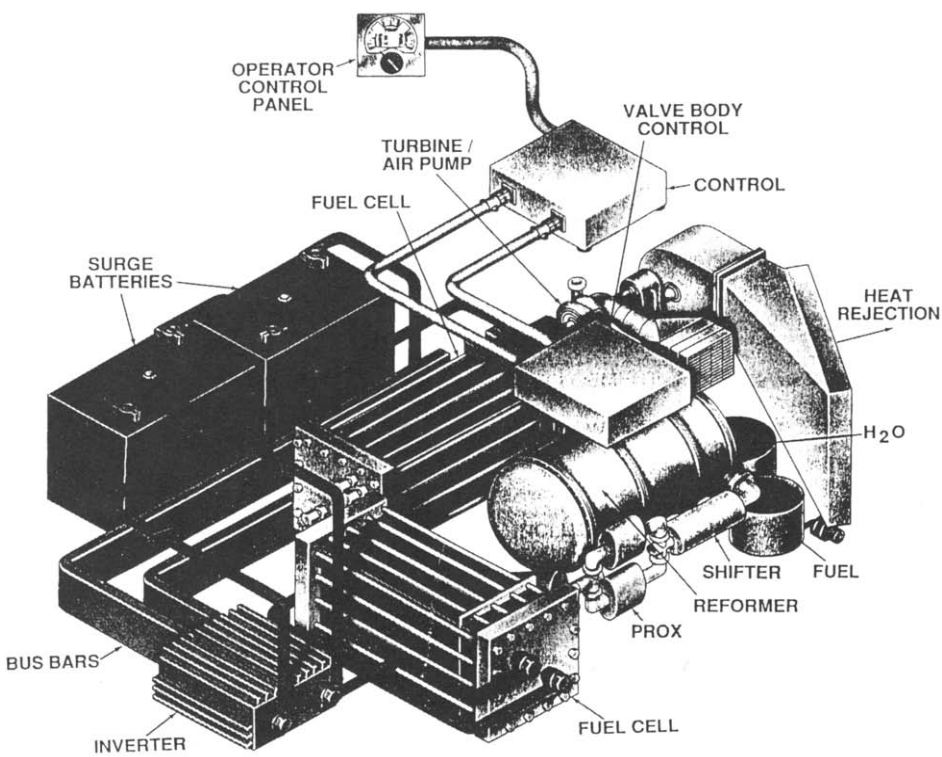

Fig. 7. Conceptual design of 10-kW PEM fuel cell system.

converted into hydrogen and carbon dioxide through a thermal/chemical process in a reformer. Advanced reformer technology is being sought to improve the competitiveness of PAFC and PEM fuel-cell-powered vehicles by reducing system size and cost, reducing start-up times, increasing transient response capability and providing fuel flexibility.

DOE plans to initiate a program in late 1991 or early 1992 to develop and demonstrate the capability of reforming methanol, ethanol, methane and/or other hydrocarbon fuels into hydrogen fuel of the required purity for use in phosphoric acid (PA) and/or proton-exchange-membrane (PEM) fuel cells used in transportation applications. The work will be divided into two phases: the first phase will consist of a feasibility study, and the second phase will be directed towards the fabrication and test of a proof-of-concept reformer system.

The Phase I feasibility study will identify the reformate requirements and specifications for PA and for PEM fuel cells, and then examine the system tradeoffs (i.e. reformer size, weight, efficiency, quality of reformate, life, cost, transient response capability, start-up time, etc.) in the design of reformers for the various hydrocarbon fuels. Steam reforming, partial oxidation or any combination of these or other reforming processes shall be investigated. The expected outcome of the Phase I feasibility study is an identification of the expected characteristics of reformer systems capable of reforming the various hydrocarbon fuels, recommendations for the specifications of the reformer to be developed in Phase II. The Phase II work will then consist of the fabrication and test of the proof-of-concept reformer system.

Market opportunities

In order for any of these technology development programs to be ultimately successful, the fuel cells must be commercialized. In addition to the technological hurdles, market hurdles must also be overcome. In particular, the cost of the fuel cell system must be reduced to make it competitive. For automotive applications, it will be extremely difficult to match the comparative low capital cost of internal combustion engines (ICE); currently, ICEs in the 10 to 40 kW size cost less than $150/kW. This is a difficult target for fuel cells to compete with, and the difference in initial capital cost must be offset by savings in operating and maintenance costs and/or by the environmental benefits.

The cost of competitive diesel bus systems is forecast to range from $135 000 to $170 000 by the year 1995. Studies show that fuel cell bus systems are projected to cost between $163 000 and $193 000 US (using $750/kW) for the same size systems. Because of the higher energy efficiency of fuel cells systems, they should show 20 to 50% lower operating and maintenance costs compared with competing diesel systems. Therefore, fuel cells are projected to be highly competitive on a life-cycle cost basis for these markets. The bus market size is projected to be 2000–5000 buses per year in the US [6].

Conclusions

The objective of the US National Energy Strategy (NES) is to achieve energy independence, clean the environment, and meet the nation's energy needs for the future. Fuel cells will make a major contribution toward achieving the objective in the transportation sector by using non-petroleum-based fuels, being virtually pollutionfree, and having significantly greater energy efficiency than internal combustion engines. Fuel cells will meet transportation performance criteria, be cost competitive, fit existing vehicle packaging requirements, be capable of rapid start-up, and meet criteria for durability, safety and operating life. Overall, fuel cells will aid in achieving the NES objectives and the DOE fuel cell program is a major step forward in this process. The phosphoric acid fuel cell/battery powered bus program has demonstrated this capability. More advanced fuel cells such as PEM and SOFC will offer widespread applicability in the transportation sector.

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