SOLID OXIDE FUEL CELLS FOR TRANSPORTATION:
A CLEAN, EFFICIENT ALTERNATIVE FOR PROPULSION

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Fuel cells show great promise for providing clean and efficient transportation power. Of the fuel cell propulsion systems under investigation, the solid oxide fuel cell (SOFC) is particularly attractive for heavy duty transportation applications that have a relatively long duty cycle, such as locomotives, trucks, and barges. Advantages of the SOFC include a simple, compact system configuration; inherent fuel flexibility for hydrocarbon and alternative fuels; and minimal water management. The specific advantages of the SOFC for powering a railroad locomotive are examined. Feasibility, practicality, and safety concerns regarding SOFCs in transportation applications are discussed, as are the major R&D issues.

INTRODUCTION

Fuel cells for propulsion power could dramatically change transportation technology because of their high efficiency, very low emissions, fuel flexibility, and unlimited range with rapid refueling (1). They would be used with electric drive systems, which would provide strong, low-speed acceleration; quiet, vibration-free propulsion; and reduced maintenance compared with internal combustion engines. In major urban areas in the U. S. and around the world, vehicles that have ultra-low or zero emissions will be required in the coming years, and the transportation industry is responding with the development of battery and fuel cell powered vehicles.

The solid oxide fuel cell (SOFC) offers a very attractive option for propulsion power, particularly for heavy-duty transportation applications that have a relatively long duty cycle, such as locomotives, trucks, and barges. The SOFC is a simple, efficient, compact, reliable, and essentially maintenance-free power system. In common with the polymer electrolyte fuel cell (PEFC) and the phosphoric acid fuel cell (PAFC), the SOFC has low pollutant emissions and is, therefore, applicable where air quality considerations are important. Unlike these other fuel cell types, the SOFC will internally reform methanol fuel (or other alternative fuels) to a hydrogen-rich gas mixture and will not require external reformers designed for the specific fuel to be used.

In this paper we discuss the design and operation of the SOFC system for propulsion power, the particular advantages it offers over other fuel cell systems and the conventional internal combustion engines, and the research and development issues that must be resolved successfully to commercialize this technology.

DESIGN AND OPERATION OF THE SOFC SYSTEM

A schematic diagram of an SOFC system fueled with methanol is shown in Fig. 1. In addition to the fuel cell stack, the major components in the system are: an air heater, a spent fuel burner (which may be integrated with the air heater into one physical component), and fuel and air recirculators. Not shown in Fig. 1 are some other components needed to complete the system, such as a feed air blower, a fuel injector, output power conditioner, and diagnostic and control instrumentation. Additionally, the high-temperature components and ductwork need to be contained in a suitable thermal enclosure.

During operation, the feed air, used both for oxidizing the fuel and removing stack waste heat, is heated by thermal exchange with the exhaust air and then injected into the recirculating air stream for the cathode. Similarly, the fresh fuel is injected into the recirculating fuel gas stream for the anode. A fraction of each recirculating stream is drawn off and combined in the spent fuel burner, and the hot burner exhaust is used to preheat the incoming air.

Air recirculation is used to control the temperature rise in the air stream as it passes through the SOFC stack. This, in turn, controls the difference between the minimum and maximum temperatures within the stack, as well as the maximum temperature gradients in the all-ceramic structure. By this means, the thermal stresses in the stack can be controlled well below the maximum allowable values. The degree of recirculation can be adjusted as a function of waste heat generation as the load on the system varies, while the temperatures and temperature gradients are maintained at or below design values at all times.

The fuel stream is recirculated to vaporize and steam-reform the fuel methanol by direct-contact heat transfer between the fresh fuel and the hot recirculating fuel stream. The SOFC, among all the different fuel cell types, is ideally suited for this dual function. Because of the high (1000°C) fuel cell operating temperature, the recirculating fuel stream contains more than enough sensible heat needed to vaporize and reform the methanol. Further, since the electrochemical cell reaction produces water on the fuel side (rather than on the air side, as is the case for the PAFC and the PEFC), the water needed for the steam reforming of the methanol is available in the recirculating fuel gas stream. Thus, once the system is in operation, no additional water is needed to reform the fuel.

Other fuels of interest for an SOFC system include distillate fuels and liquefied natural gas (LNG). A system fueled with LNG, for example, would be similar to that shown in Fig. 1, with the possible addition of an external vaporizer to vaporize the LNG before it is injected into the recirculating fuel stream. Of course, the amount of water needed to reform natural gas differs from that needed to reform methanol. Therefore, the fuel recirculation ratio for the LNG-powered system is likely to differ from that for the methanol-powered system. In all other respects, the two systems would be very similar.

The SOFC system is the simplest among the various fuel cell systems, with only a few major components, as shown in Fig. 1. There is no liquid electrolyte or coolant. Indeed, the operational simplicity of the SOFC is comparable to that of an air-cooled internal combustion engine. The only inputs are the fuel and air; the only output is a single exhaust gas. There are no problems with electrolyte dilution or freezing. No water management is required. Waste heat is simply removed by means of the hot exhaust gas. System control for load variation could be as simple as control of the fuel injection rate and the proportionate air input flow rate, similar to control of today's engines. Normal operational control is likely to be mainly the control of air and fuel recirculation rates.

There are many other advantages of an SOFC propulsion system. It can operate at high current and power densities, thereby offering high volumetric and gravimetric power densities. Due to the absence of a liquid electrolyte or coolant, the SOFC system lends itself to a variety of orientations and configurations, an important consideration in packaging the system for transportation applications. The fuel cell itself uses no platinum or other expensive electrocatalysts. Because the operating temperature is high (1000°C) and because the product water is produced on the fuel side rather than the oxidant side, the SOFC can "internally" reform any non-hydrogen primary fuel used in a given application. Also because of its high operating temperature, the electrochemical performance of the SOFC is not degraded by the presence of carbon monoxide in the fuel gas; indeed, carbon monoxide can be used as a fuel as effectively as hydrogen.

AN EXAMPLE: THE LOCOMOTIVE APPLICATION

Locomotives are used for hauling freight, pulling passenger trains, and moving individual freight cars and groups of cars in "switch" yard service. Line haul locomotives are the largest, having engines of up to 3700 kW (5000 hp) and operating at constant loads for extended periods of time. In contrast, rail-yard locomotives typically have a 750 kW (1000 hp) engine that undergoes frequent and large load variations. The standard locomotives used by the railroads in the United States are powered by diesel engines that drive electric generators. Propulsion power is provided by individual electric motors on, in most cases, six drive axles. The locomotive is thus

already equipped with an electric drive system, and replacing the diesel engine with a fuel cell would not necessarily require a complete redesign of the locomotive. However, simply switching the power source from the diesel engine to a fuel cell would then constrain the volume of the fuel cell system to that of the equivalent diesel engine. For example, the engine compartment volume in the 2237 kW (3000 hp) SD40-2 locomotive built by General Motors Electromotive Division for line haul service is about 55 m^3; if the engine compartment is widened to the handrails, the available volume increases to about 95 m^3 (2).

Converting locomotives from diesel-electric to SOFC power is attractive from several aspects. These include low emissions, high efficiency, fuel flexibility, and system simplicity.

Existing locomotives contribute 5-10% of the pollutant emissions from all mobile sources in southern California (3). In common with the other fuel cell types, the pollutant emissions from the SOFC are very low, orders of magnitude lower than the emissions from internal combustion engines. For example, Table I shows a comparison between the pollutant emissions from a diesel-electric locomotive (4) and those from PAFC (5) and SOFC (6) systems. The hydrocarbon, sulfur oxides, and particulate matter emissions are very similar for the two fuel cells and are orders of magnitude smaller than the emissions from the diesel-electric locomotive. Because of the absence of an external reformer (with its associated burner), the SOFC has CO and NO$_x$ emissions even lower than those of the PAFC.

Table I. Pollutant emissions from a diesel-electric locomotive and two fuel cell systems, mg/MJ of fuel energy content

	HC	CO	NOx	SOx	PM
Diesel-Electric	123	556	1589	224	36
PAFC	<1	3	1	<0.01	none
SOFC	<1	<1	0.6	none	none

HC = hydrocarbons; PM = particulate matter.

The SOFC also offers much improved fuel use efficiency compared to a diesel-electric locomotive. Table II shows the diesel engine and fuel cell efficiency at the various power settings for the locomotive application (7). As this table shows, the fuel cell system is more efficient than the diesel-electric locomotive, with the maximum efficiency gain during operation at less than full power. Over the aggregate operating cycle, a fuel cell-powered locomotive would use 35 to 45% less energy than a diesel locomotive.

Table II.   System efficiency versus power setting for diesel-electric and fuel cell
propulsion in locomotive application

Notch	% Power	Diesel Efficiency, %	Fuel Cell Efficiency, %	% Time at Power
1	4 - 5	12 - 15	18 - 22	4
2	10 - 11	17 - 19	24 - 30	4
3	22 - 26	23 - 27	48 - 54	4
4	24 - 28	25 - 30	53 - 57	5
5	48 - 53	30 - 35	51 - 55	4
6	67 - 68	32 - 37	48 - 52	4
7	82 - 83	33 - 38	46 - 50	3
8	100	35 - 40	44 - 48	11
	Idle			49
	Braking			12

As discussed in the previous section, the SOFC can operate on any of a variety of fuels, without the need for an external fuel processor. Thus, for example, the SOFC locomotive could be fueled with LNG just as easily as with methanol, or any of the other conventional or alternative fuels.

PERCEIVED CONCERNS WITH SOFC IN TRANSPORTATION

While the SOFC offers the above advantages, it is perceived to have certain drawbacks. Foremost among these are concerns related to the 1000°C operating temperature. There is a perception that this high temperature can lead to some undesirable characteristics; however, not all of these are valid concerns, and those that are can be alleviated by appropriate engineering solutions, as discussed below.

System start-up would take a long time

This is based on the impression that the ceramic structure would not be able to tolerate the large thermal stresses likely to occur if the fuel cell stack is heated up rapidly. It is also based on an extrapolation of the 45 min to an hour required to start up the PAFC, which operates at a much lower temperature, about 200°C. Neither of these considerations is necessarily valid for the SOFC system. The PAFC stack operates at a low current and power density; hence, it is more massive than the higher current

and power density SOFC. In addition, the liquid electrolyte and coolant inventory in the PAFC must also be heated up to the operating temperature. The monolithic and planar SOFCs under development can be heated up from room temperature to 800°C (at which temperature power can be drawn from the fuel cell) in under 2 min without exceeding permissible thermal stresses in the fuel cell stack. The developmentally more mature tubular SOFC, because of its larger mass for the same power capacity as the monolithic or planar SOFC, would require a longer time to reach the operating temperature.

A large amount of fuel would be consumed during start-up

The amount of fuel consumed is directly proportional to the mass of the system and the heat capacity of the materials in it. As indicated above, because of the high power density of the SOFC, and because of the absence of any liquids, the SOFC is comparatively lightweight. Whatever amount of fuel is used, however, is fuel consumed without corresponding electricity generation, and this detracts from the system's operational efficiency. As a result, the SOFC is most attractive for applications that typically have long duty cycles, i.e., infrequent start-up and shut-down with long periods of operation in-between. Examples of such applications are locomotives, trucks, and barges. For these long duty-cycle applications, fuel consumption during start-up would be only a very small fraction of the total fuel consumed, and would not have a significant impact on the system efficiency over the average duty cycle.

A large amount of fuel would be consumed during idling or standby

Even in applications with long duty cycles, such as a locomotive, there are significant periods of low power at idling or standby, as indicated in Table II. Although the fuel consumed during such times is wasted and decreases the system efficiency, the amount of fuel consumed in this mode is likely to be proportionately no greater than the fuel consumed during idling operation of the conventional internal combustion engine. The high-temperature components of the SOFC system would be contained in a suitable thermal enclosure. Recently developed high-temperature super insulations (such as the evacuated, compressed, multifoil insulation developed for high-temperature batteries) can limit the heat loss during idling to 1% or less of the nominal system power rating.

The ceramic structure will not withstand repeated thermal cycles

Successful development of the SOFC requires the capability to withstand repeated thermal cycling from room temperature to operating temperature and back. The ability of the SOFC to survive thermal cycling is built into the various development programs, and the stacks ultimately developed will be capable of undergoing repeated start-up/run/shut-down thermal cycles.

DISCLAIMER

The multi-component ceramic stack will not withstand vibration/shock

Stress analyses for the monolithic and planar SOFC indicate that the structure is rugged enough to withstand the vibrations and shock stresses expected in transportation applications. Similar analyses and tests are needed to verify that the tubular SOFC can also withstand these stresses.

The high-temperature SOFC is a fire/explosion safety hazard in an accident

This is based on the perception that in the event of an accident, fuel from the fuel tank may come in contact with the 1000°C surfaces and burn violently. While this is a possibility, good engineering and design practice would ensure that the fuel tank and the high-temperature enclosure are separated by fire walls of adequate strength. Even in the conventional internal combustion engine systems, the exhaust system is typically hot enough to be above the flash point of gasoline or diesel fuel, but in a vast majority of accident situations, the fuel and the hot surfaces do not contact each other. By use of an appropriate amount of dilution air, the temperature of the exhaust from the SOFC can be reduced to any desired value; the surface temperature of the thermal enclosure itself will be well below 100°C.

MAJOR R&D ISSUES IN SOFC FOR TRANSPORTATION

The major SOFC research issues for transportation applications concern the stack configuration and fabrication, temperature of operation, performance verification, and the balance-of-plant components.

At present, the tubular, seal-less SOFC is the only type of SOFC that has been built for multi-kilowatt power levels and operated on natural gas; development plans for this SOFC include scale up to multi-megawatt power levels within the next few years. The monolithic and planar designs have potentially higher power density but are still at an early stage of development. Thus, at present, the tubular SOFC is the only contender for transportation applications in the near to mid-term future. To be successful, however, it will probably need to be repackaged to permit installation in the available space.

The planar and monolithic SOFCs under development promise to be more compact for the same power capability as the tubular SOFC. However, effective fabrication and assembly methods (sealing, manifolding, etc.) must be demonstrated, and cell and stack designs must be scaled up to the power sizes needed for transportation.

The present SOFCs operate at 1000°C. Solid oxide fuel cells operating at lower temperatures (800°C or less) are also under development; if successful, this lower temperature operation would attenuate the materials problems associated with the SOFC. These new SOFCs require development of new fabrication techniques (to decrease

electrolyte thickness and hence resistivity) or new electrolyte and electrode materials.

Some of the balance-of-plant components also need to be developed. Chief among these are the high-temperature air and fuel gas recirculators, and the spent-fuel burner and air preheater.

Once SOFC stacks are built for use in transportation applications, their performance must be verified with regard to the expected advantages of high power density, internal fuel reforming, dynamic load operation, tolerance to fuel impurities, and stable long-term performance.

CONCLUSION

Fuel cell propulsion has the potential to radically alter transportation technology. The SOFC propulsion source can be an important component in the conversion of the heavy-duty vehicle market from internal combustion engines to cleaner, more efficient, and cost-effective fuel cell systems.

ACKNOWLEDGMENT

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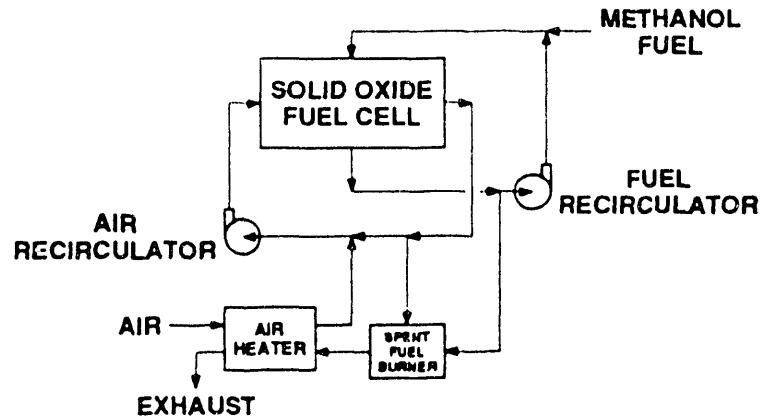
Fig. 1. Schematic diagram of an SOFC system.

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