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STATUS AND OUTLOOK FOR ENERGY CONVERSION VIA FUEL CELLS

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INTRODUCTION

Fuel cells have the potential of providing good solutions to a variety of energy-related problems. As our supplies of conventional fossil fuels are depleted, their cost will rise, and there will be increasing difficulty in obtaining certain premium fuels at any price. It behooves us, then, to use our remaining reserves of fuels as efficiently as possible. Energy conversion via fuel cells represents one of the best ways to achieve this goal, because it is possible, simultaneously, to obtain more work and less pollution from a dollar's worth of fuel with a fuel cell than with any other device.

ADVANTAGES OF FUEL CELLS

Although much of the interest in fuel cells is due to their efficient use of fuel, there are considerable pollution control advantages to be gained as well. Because the fuel reacts electrochemically rather than by burning in air, no nitrogen oxides are formed. For the same reason, emissions of unburned and partly burned gaseous and particulate products are essentially nil. The only moving parts in fuel batteries are fuel pumps and, perhaps, electrolyte pumps, so operation is inherently very quiet. There is relatively little thermal pollution because less energy is lost as heat.

The overall efficiencies of a number of systems are compared in Fig. 1.[1] The efficiencies shown in Fig. 1 are generally rather optimistic, and tend to be relatively more so for the low efficiency devices. While there are a number of different kinds of fuel cell systems whose efficiencies vary from somewhat more to considerably less than the 60% shown for fuel cells, the message remains that more useful energy can be extracted from fuel with fuel cells than with any other energy conversion device.

Figure 2, the U. S. energy flow pattern for 1980,[2] shows the incentive for improved energy utilization. While it is difficult to assess what fraction of the energy is used and what is lost, it is clear that there is a great deal to be gained from more efficient use of our energy resources. Almost half of the energy consumption will be "lost" in 1980, projections for beyond 1980 show an even greater fraction lost.

APPLICATION OF FUEL CELLS

The uses to which fuel cells may most profitably be applied are electric power generation and transportation. Most of the non-electrical energy in the industrial sector, and nearly all in the commercial and residential sector is used for heating. Conversion of fuel to heat usually proceeds with high efficiency, so relatively little application of fuel cells in these sectors is seen.

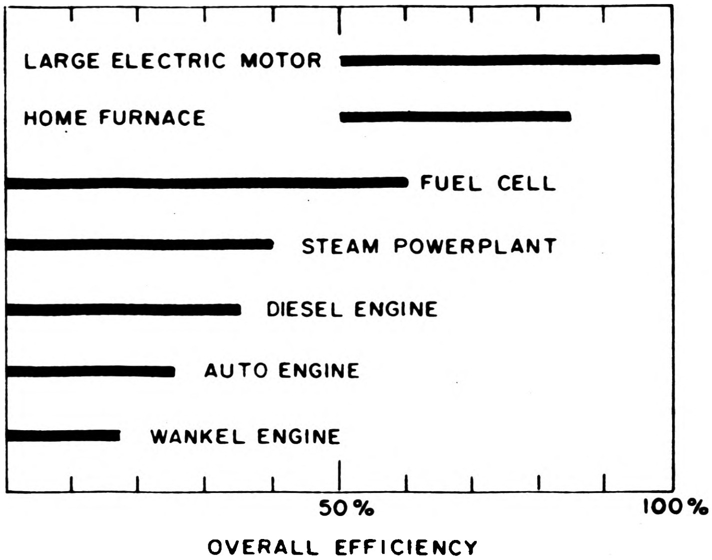

Fig. 1. Efficiencies of Several Energy Conversion Systems.

Because the fuel cells convert chemical energy directly to electrical energy, electrical power generation is probably their most natural application. While the output of each cell is low voltage DC power, cells may be connected in various series and parallel arrangements to give whatever voltage is desired, and large highly efficient inverters are available for conversion to AC.

In this application, fuel cells must compete with large steam turbines, which are remarkably efficient devices. (At rated load, a large modern unit can approach 40% efficiency.) However, the demand for electrical energy is far from constant, as may be seen in Fig. 3.[3] Over the course of a year, the actual power output of a large utility may vary by nearly a factor of four, and the daily variation in load can be almost a factor of three. To adjust to this changing demand, either the large base load plants must sometimes operate at part power, or smaller cycling or peaker units must be used during periods of high demand. Either way, efficiency suffers and pollution increases. Contrast the part-load efficiency of fuel cells and heat engine power plants in Fig. 4. The fuel cell system not only has a greater efficiency at full load, but this efficiency is retained and even increases as load

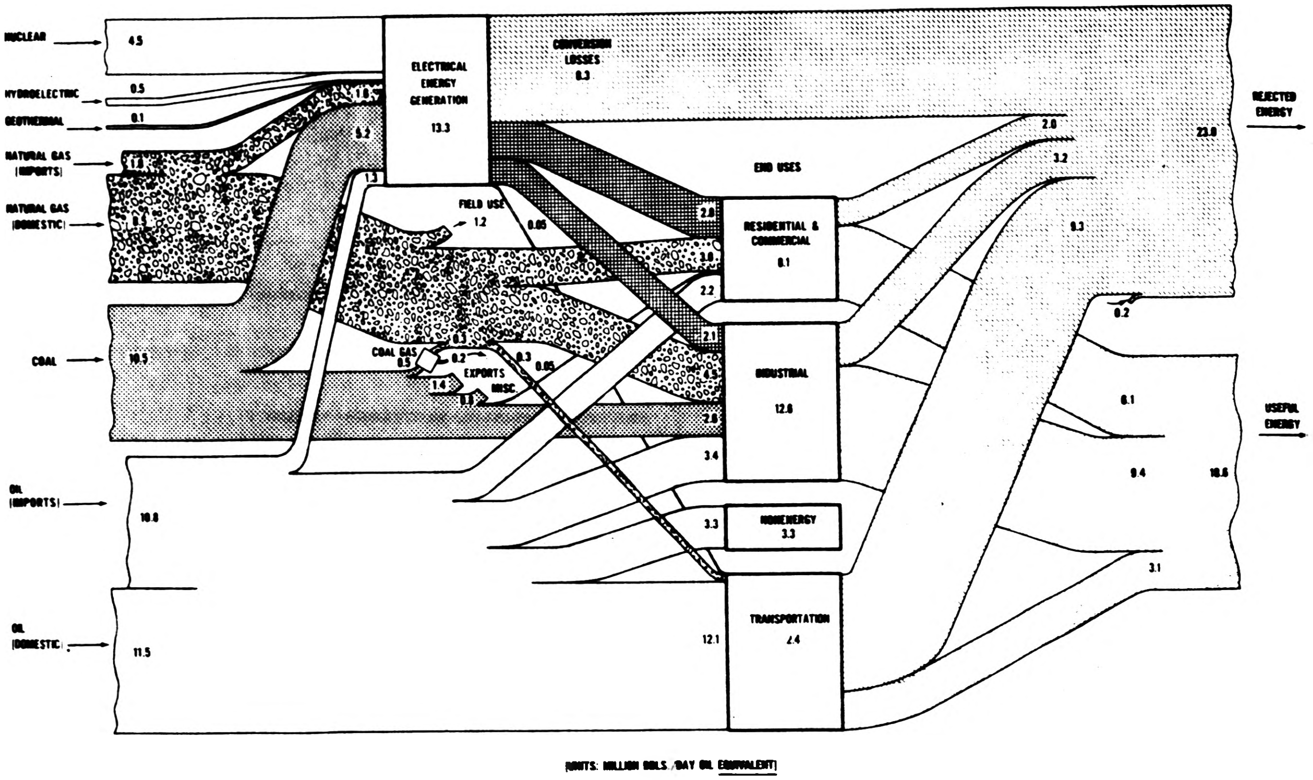

Fig. 2. U. S. Energy Flow in 1980.

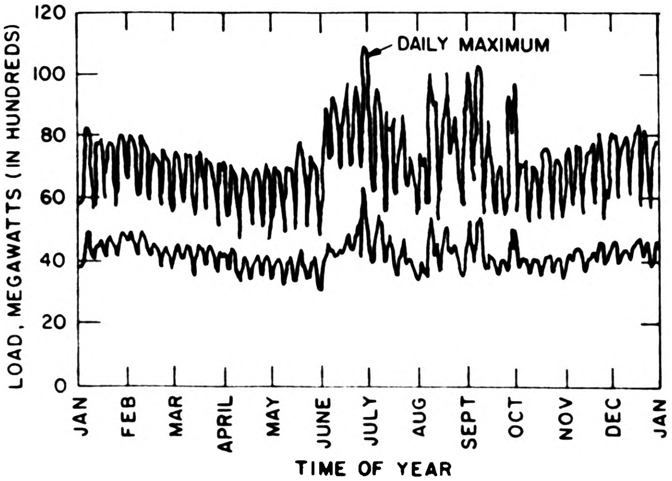

Fig. 3. Variation in Daily Maximum and Minimum Loads. (Commonwealth Edison, 1971)

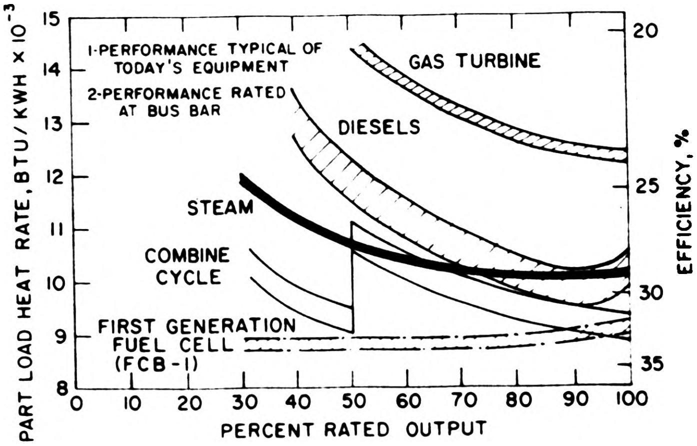

Fig. 4. Energy Systems Comparison (Part-Load Performance)

diminishes, so that inefficient peaking generators may not be needed.

A fuel cell system, unlike a heat engine, need not be big to be efficient. Figure 5[4] shows how efficiency varied with rated capacity for several generating systems. This characteristic, taken together with two others - low emissions and capability of operation on a variety of fuels - allows fuel cell systems to be operated almost anywhere. A small community power company can operate a power plant on the optimum fuel available locally with nearly the same efficiency achieved by a large central power station. A large metropolitan utility can disperse a number of generators throughout its area and match capacity to local demand, substantially reducing the expense and other problems associated with transmission and distribution of electricity.

Some idea of the savings to be made in energy transportation can be obtained from Fig. 6. The costs shown[5] for transporting electrical energy are for long distance transmission of energy. Costs and other problems involved with local distribution of electrical energy are likely to be greater, especially as more utilities go to underground lines in urban areas. Also, the cost of transmission should be reduced by a factor of two rather than three for comparison with fuel cell generating systems, because fuel cells require less fuel per kilowatt hour of electricity gen-

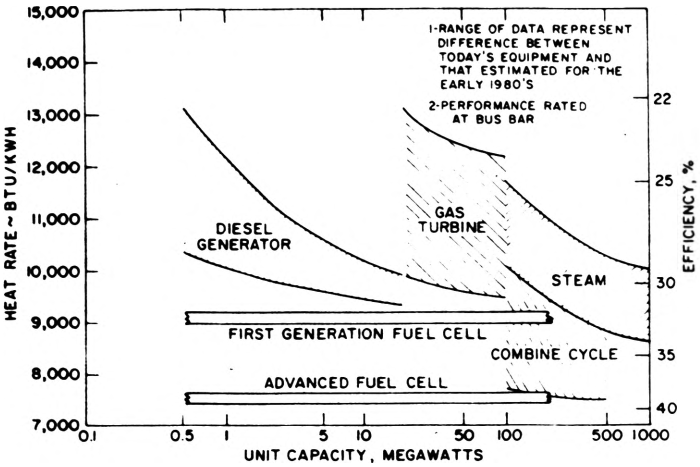

Fig. 5. Energy Systems Comparison (Performance *vs.* Unit Size)

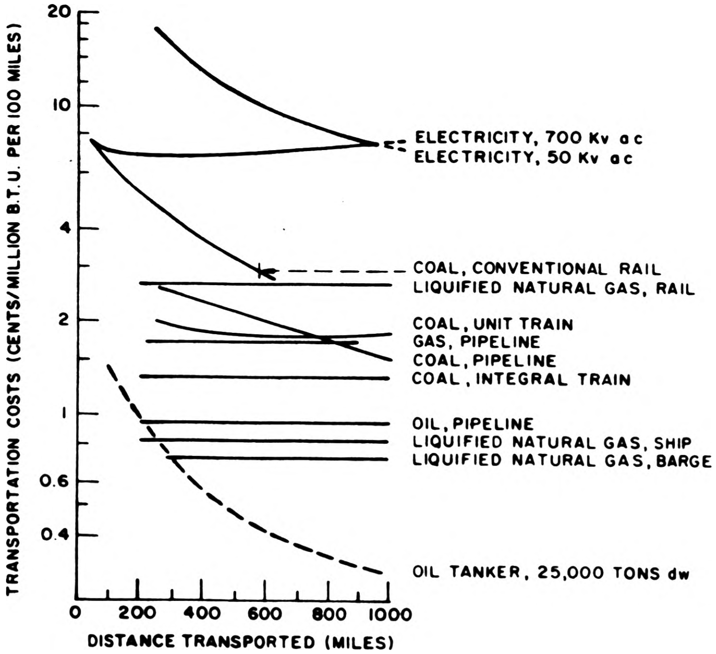

Fig. 6. Costs of Transporting Energy.

erates than do conventional generating stations. This figure was drawn up in 1972, and should be viewed with some appreciation of changing economic conditions, especially in the last year or so.

In the transportation industry, the same virtues of efficiency and low pollution make the fuel cell attractive. Here there are at least two other major requirements which must be met. These are the needs for a relatively high available energy/weight ratio (so-called energy density) and for a large power/weight ratio (power density). Fuel cells may be expected to meet the first criterion handily, since the amount of energy available is determined by the size of the fuel tank. A fuel cell powered vehicle can have a good long range without refueling and can be refueled rapidly, just as can present day internal combustion vehicles. This represents a substantial advantage over battery powered vehicles, which are the competition for efficient, low pollution personal transportation.

The criterion of high power density is considerably more difficult to meet. It is very much worse for small personal vehicles than for large busses, trucks, trains and ships. Figure 7 gives power density/energy density relations for fuel cells, internal combustion engines, and a variety of battery systems. To propel a vehicle of weight comparable to an "intermediate" car with speeds and accelerations usable in present traffic conditions, it is probably necessary to achieve a power density of about 100 watts per pound, which is equivalent to about thirteen pounds per horsepower. It may be possible to meet that goal by hybridizing a fuel battery with one of several high power energy storage devices, such as one of the new generation of flywheels.

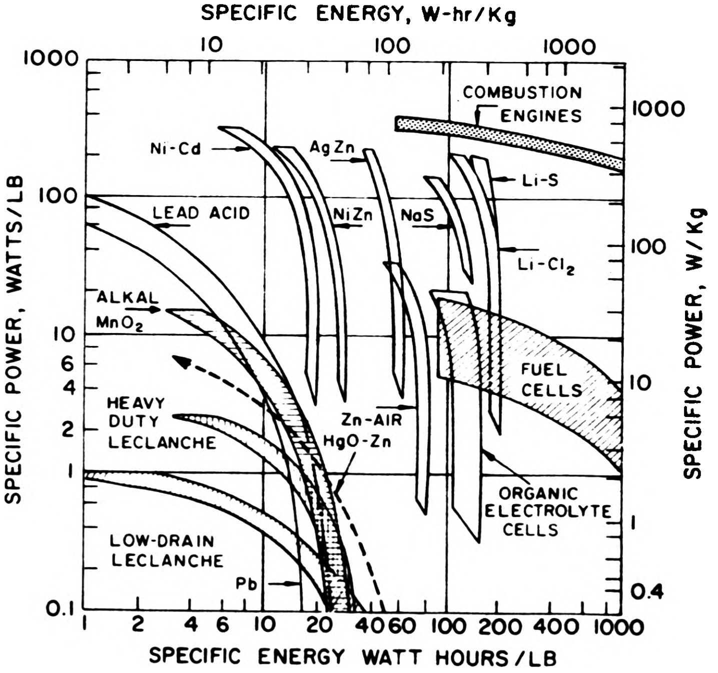

Fig. 7. Energy Density *vs.* Power Density for Several Energy Sources.

Two factors will act to mitigate the necessity for high-power densities. One is increasing cost and decreasing availability of fuel, which is even now limiting the speeds and hence the power required for road vehicles. The other is that the presence on the road of low power vehicles will tend to change driving patterns in the same direction of decreased speed and acceleration requirements.

Fuel cell systems of adequate performance to propel railroad trains, barges, and ships can probably be built with existing technology, at least, as far as cells themselves are concerned. The detailed engineering necessary to actually build the power plant and ensure reliability and control is another matter. Although essentially all of the basic technology is available, considerable effort would have to expended to develop a viable system. The power plant would be very smooth and quiet, virtually pollution free, and could operate on conventional fuels. A detailed economic analysis would have to be undertaken to determine the break-even point where increased fuel costs would balance against lifetime and initial cost considerations.

CHOICE OF FUELS

Fuel cells have been made using a wide variety of fuels; hydrogen, hydrazine, ammonia, hydrocarbons of various sorts, alcohols, natural and synthetic gas, and others. The pragmatic truth of the matter is that the only fuel which performs nearly as well as hydrogen is hydrazine, and hydrazine is both toxic and very expensive. Unfortunately, the hydrogen economy is not yet upon us, and hydrogen is not widely available in large quantities. Technology does exist for conversion of a variety of other fuels to hydrogen where tank or pipeline hydrogen is not available.

Natural gas and petroleum distillates are relatively easy to convert to hydrogen by several processes. One of the best for fuel cell uses is catalytic steam reforming at high temperature (900°C). The raw gas stream contains carbon monoxide, a notorious catalyst poison, which can be removed by the "shift" reaction with steam to form carbon dioxide and more hydrogen. Sulfur must be removed from the feed stream or raw gas stream because it ruins the reforming catalyst, the shift catalyst and the fuel cell catalyst. This is actually somewhat of an advantage, since now there can be no sulfur oxides in the fuel cell exhaust. Sulfur removal technology is well proven and in wide use in the petroleum industry. The pressure and temperature requirements imply that hydrocarbon fuels will be better suited to fixed than mobile uses.

Ammonia can be easily cracked in a simple reactor to provide a very suitable fuel stream containing only hydrogen and nitrogen. The small equilibrium amount of residual ammonia in this stream is easily removed in a trap. The simplicity of the cracker lends itself to easy control and thus, to mobile applications. Ammonia is relatively easy to store, and has a reasonable energy density (2.5 kWh/lb *vs.* 2.76 kWh/lb for methanol and about 5.8 kWh/lb for gasoline).

Methanol has most of the virtues of ammonia, and in addition, can be converted to hydrogen at relatively low temperature (near 250°C) and a pressure near one atmosphere. It is also likely to be less expensive than ammonia (about ten to fifteen cents per gallon at the plant if one has a coal gasification plant that makes high-BTU gas at $1.50/million BTU or less, or if naphtha is available). Methanol is fairly reactive electrochemically, and there is a possibility that it can be used directly in a fuel cell without reforming. It is sufficiently involatile that it can be handled in the present gasoline distribution system without basic changes. All these factors combine to make it the most promising fuel for mobile applications.

As coal gasification technology matures, very satisfactory feed streams for fuel power plants will be available. Present processes convert coal to a carbon monoxide/hydrogen mixture which is scrubbed of sulfur-containing gases and converted to methane. For direct fuel cell use, the carbon monoxide in the sulfur-free stream could be shifted with steam via the water-gas shift reaction to carbon dioxide and hydrogen. The carbon dioxide could be scrubbed from the stream, if necessary, but it would probably be satisfactory to leave it in if the fuel cell station were nearby. If the H_2 were pumped to a remote location it would be removed because of the pumping cost. This stream could also be used in ammonia synthesis; in this case, air would probably be used in the gasification processes to give the correct amount of nitrogen in the gas stream. For synthesizing methanol, carbon monoxide would be left in the stream, since it is one of the reactants in methanol synthesis.

STATUS OF FUEL CELLS

At present, there are essentially no commercial uses of fuel cell power plants in the field of transportation. Dr. Karl Kordesch of Union Carbide Corp. has had a small economy car converted to operate on a gaseous hydrogen fuel battery/lead-acid battery hybrid system for several years, but this is a hobby project, undertaken, perhaps, to demonstrate that it can be done. Six hundred cubic feet of hydrogen gas store 33 kWh of energy, and give the car a range of about 200 miles at 40 mph.[6] General Motors has a fuel cell program which is active and making progress, especially on the air electrodes, but they have not announced any plans for putting fuel cells in even an experimental vehicle in the near future. When sufficient progress has been made that fuel cells of high power density can be constructed, there will doubtless be much more interest from the transportation industry, but at the present there is not sufficient incentive for the automobile makers to launch the large research and development effort that would be required to construct an economically competitive vehicle.

In the utilities field, the situation is considerably brighter. Pratt and Whitney have contracted to put several dozen, 26 megawatt fuel cell power plants in the field for a group of utilities, beginning in 1975. These plants will operate on a variety of fuels; natural gas, methanol, naphtha, or possibly even #2 fuel oil, depending on reformer technology. These are the first commercial units to be developed, and successful application of these plants would mark the beginning of wide-spread use of fuel cells for power generation and the beginning of a new era in our national use of energy.

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