

## SOME ENGINEERING ASPECTS OF THE HYDROGEN-OXYGEN FUEL CELL

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### Introduction

There is no doubt that the hydrogen-oxygen cell possesses a number of important characteristics which have made it much easier to develop into practical units capable of generating a useful amount of power, compared with hydrocarbon-air cells. It is perhaps worthwhile briefly to recapitulate these characteristics, and this will make plain the reasons for the choice of the particular system which was developed at Cambridge, England.

First of all, it is well known that hydrogen reacts electrochemically much more easily than any hydrocarbon fuel; this of course makes electrode design much easier.

Secondly, the use of pure hydrogen and oxygen makes it possible to use an alkaline electrolyte, which has obvious advantages in the lower cost of materials which can be employed for the electrodes, current collectors and other cell parts.

Thirdly, the use of pure gases means that an unvented system is possible, and this eliminates the additional problems which have to be faced when an inert diluent, such as  $\text{CO}_2$  in a reformed hydrocarbon fuel, have to be vented from the system at the correct rate under all load conditions; this would seem to present quite an intricate control problem, if undue waste of fuel is to be avoided. Moreover, groups of cells would presumably have to be fed in series with the fuel gases, each group having its own control valve; it would clearly be too complicated to have a monitoring device on each cell to regulate the gas flow individually. Some of these arguments would also apply if air is used instead of pure oxygen; and in addition, control of the rate of water removal from the vented system may be difficult under conditions of varying air temperature and humidity. This is in contrast to the hydrogen-oxygen system, in which the only reaction product is steam which can easily be separated from the hydrogen in a simple air-cooled condenser, provided that the operating temperature of the cells is somewhat above ambient; parallel flow of hydrogen through all the cells in a battery can be used without difficulty, and small inequalities of flow through individual cells are of little consequence. Besides this, the higher partial pressures of the reacting gases, using pure hydrogen and oxygen, lead to a higher cell performance and a higher limiting current.

It must be admitted that even with very pure gases, occasional venting of the system to atmosphere is usually necessary, owing to the gradual build-up of inert diluents; but this, in our experience at Cambridge, need only be done very occasionally, especially if electrolytic gases are used, and can easily be done by hand.

Fourthly, there is the possibility of operating the battery at considerably elevated pressures. This has the advantage of reducing activation polarization of the electrodes and so yielding possible savings in weight, bulk and electrode cost. The use of elevated pressures also makes it possible to operate with an increased partial pressure of water vapour and hence a higher electrolyte conductivity and a more compact condenser. It is relatively simple to supply pure hydrogen and oxygen at elevated pressure, but, with a hydro-carbon-air cell, there would be complications and a heavy parasitic load due to the compressors.

Fifthly, there is the important fact that hydrogen cells can be made self-starting from cold; this was not a feature of the cells developed at Cambridge, where the decision had been taken to operate at the highest practicable temperature so as to minimize the problems associated with electrode activity. However, other workers have demonstrated hydrogen-oxygen cells with lower temperatures of operation, which will start from cold though relatively cheap catalysts are used; alternatively, very small amounts of precious metal catalysts may be employed with good results in this respect; it is assumed that one of the many new types of electrode, which depend on a degree of semi-wetness in the active layers, would be used.

It should be added that efforts were made, quite early in the work to think in terms of a complete working system rather than in terms of single cells, or even a battery of cells; and before the work was closed down at Cambridge, a complete working system was evolved, including gas admission, and control of temperature, electrolyte concentration and pressure difference across electrodes, under both steady and rapidly varying loads, with a unit of 40 cells which would develop up to 6 kw of power. (1)

### Personnel

As it was only possible to employ very small teams, for financial reasons, it was essential to break as little fresh ground as possible, and the practical experience of both battery and electrolyser manufacturers was freely drawn upon; up till 1941, the author worked alone, the work being supported by Merz and McLellan, the well-known consulting engineers. From 1946-51, additional help was given by one part-time consultant, the work being done in the Departments of Colloid Science, and Metallurgy, Cambridge University. After this a small team was gradually built up in the Department of Chemical Engineering, Cambridge, the team consisting of two chemists, one metallurgist, one engineer (author) and three assistants, besides two part-time consultants, one being a physicist and the other an electrochemist. This team was unfortunately completely disbanded in 1956 owing to lack of support. From 1946-56 the work was financed by the Electrical Research Association, with additional help from the Ministry of Fuel and Power, and the Admiralty. In 1957, another team was built up with the help of the National Research Development Corporation, at Marshall of Cambridge Ltd., the total numbers of the team reaching a maximum of fourteen, including one chemist, one metallurgist and three engineers, besides five part-time consultants, one being a chemist, one a metallurgist, one a control engineer and two chemical engineers. Once again the team was completely

disbanded in 1961 owing to lack of industrial support in England. It should be added that the help given by the consultants was invaluable; all were men of wide theoretical knowledge and much practical experience, and without their help some serious mistakes would undoubtedly have been made.

### Further Developments in Hydrogen-Oxygen Cells

The author has not carried out any experimental work since 1961, but it has been most interesting to watch the work of others during this time, particularly the wonderful developments which have taken place in the United States.

The stage has now been reached where completely automatic and reliable batteries, using hydrogen and oxygen, have been produced, these batteries being completely equipped with controls which will deal with all load conditions including rapidly varying loads; in addition to this, many are self-starting from cold. The first cost is still high, but this is systematically being reduced. Is it possible that some commercial application could now be found for this type of cell, apart from space and military uses?

### Storage of Gases

The principal technical difficulty preventing the use of hydrogen-oxygen batteries for say traction purposes is, in the author's view, associated with the storage of the gases, in particular the storage of hydrogen; it seems inconceivable that liquid hydrogen could ever become a commercial fuel. It is, therefore, very important to watch for any new developments in science and engineering which could have a bearing on this difficult problem of hydrogen storage. As recently as 1959, the best ratio which could be quoted for weight of hydrogen carried to weight of container was 1 to 100; this was for nickel-chrome-molybdenum forged steel cylinders, with a working pressure of 3,000 p.s.i. (2). Since that time, considerable development has taken place in the design of gas vessels and a ratio of 1 to 43 can be quoted for weight of hydrogen to weight of steel with a gas pressure of 3,600 p.s.i.; a low carbon chrome-molybdenum steel is used at present, and welded construction; these figures refer to spheres, and assume that all the gas can be used, which is not strictly accurate but which does not introduce a serious error. Taking an average voltage of 0.8V per cell, and assuming the above weight ratio of 1 to 43 for hydrogen, and assuming also that oxygen is carried as well, the weight of gas vessels + hydrogen + oxygen comes out at about 8.1 lb/kwh. generated; with hydrogen alone, the weight would be 4.7 lb/kwh generated.

These gas vessels are not only used in missiles and military aircraft, but also in civil aircraft where very high standards of safety are of course required. Partly as a result of the American space programme, even further improvements in design appear to be under way; but it seems impossible to prophesy when, or even whether, resin fibre glass containers will become a practical proposition for the storage of hydrogen under ordinary commercial conditions. The whole question of ultra high strength materials is being intensively studied in many parts of the world (3), and it seems possible that, in the future, further reductions in the weight of gas vessels will be achieved.

Other factors which must be taken into account are volume, cost, safety and convenience, but it is not possible to go into these closely in this short paper. In the past, it has always been the weight which has made gas storage relatively unattractive.

#### Possible Applications for Hydrogen-Oxygen Cells

It has always seemed to the author that road and rail traction are the most promising applications for fuel cells; this applies particularly in the case of short range transport in cities, using public service vehicles. In the United Kingdom quite large numbers of battery driven delivery vehicles are used - the numbers have now risen to over 40,000 - and these are able to compete on level terms with engine driven vans, in spite of the weight and high first cost of the lead/acid batteries; this is basically because of the lower cost per mile of electricity compared with taxed gasoline, and also because of the lower maintenance costs of battery driven vehicles, under the rather special stop-start conditions under which delivery vans have to operate; and this is in spite of a much higher capital cost, part of which is due to the cost of the battery itself, and part to the fact that mass production methods cannot be used for the small numbers of vehicles produced. It is hoped that the fuel cell will eventually extend the field of battery traction into areas where the weight of lead batteries precludes the possibility of electric traction, owing to the fact that a rather higher speed and longer range are required.

The effective capacity of a typical lead-acid traction battery, at 80 amp discharge, has been given as 12.8 kwh.; this was for a 20 cwt. pay load delivery vehicle with a speed of 15-18 m.p.h. and a range of 25-30 miles (4). This capacity would require a weight of hydrogen + oxygen + gas vessels of  $12.8 \times 8.1 = 104$  lb. Assuming that the weight of modern low temperature low pressure hydrogen-oxygen batteries on normal load is about 40 lb./kw., and also assuming that a power of 5.3 kw. is required on normal load (4), the weight of the battery alone would be 212 lb.; complete with gas vessels, the total weight would be 316 lb. Taking an up-to-date figure of 10.5 wh/lb for a lead traction battery, on a 2-3 hour discharge basis, a conventional battery would weigh 1,220 lb. If these figures can indeed be substantiated, it would appear that hydrogen-oxygen batteries cannot be ruled out for short range road traction, on a weight basis; in fact, they appear to be more or less substantiated by William T. Reid (5) in an estimate dealing with a passenger road vehicle with a range of 150 miles at 40 m.p.h. It is admittedly extremely difficult to compete on level terms with internal combustion engines, especially if a long range is required between re-fuellings; but a silent fume-free propulsion system would have many attractions for public service vehicles in cities, where they could easily return each night to a central refuelling station, thus avoiding the high cost normally associated with the distribution of hydrogen in cylinders. Reid (5) concludes that running costs, using electrolyzers for gas production, would compare favourably with gasoline-powered engines, even in the United States, and the comparison should be even better in the United Kingdom, though the analysis admittedly ignores the tax problem. So far, battery driven vehicles have been exempt from any form of fuel tax in the U.K. As regards the engineering problems

associated with the storage and transfer of compressed gases, much experience was obtained in England, before and during the Second World War, in the use of compressed coal gas as a fuel for propelling buses, and no special difficulties were encountered (2).

### Conclusion

It has for many years been realized that there are two alternative applications for fuel cells; one is the task of producing batteries which will consume a hydrocarbon fuel and air; the other concerns the possibility of storing electrical energy; the author has always been drawn towards the latter application. It is true that the overall efficiency of the double process is not likely at present to exceed 50 per cent (6) and might indeed initially be somewhat below this figure (7); but it is hoped that, before long, some of the knowledge acquired by fuel cell workers will be applied to the process of electrolysis; this would entail extensive tests for endurance, in view of the present trouble-free life of at least ten years, which is now expected with existing designs. Further, it is likely that, in the foreseeable future, very cheap off-peak power will become available in the United Kingdom; in an article on "Large Scale Storage of Energy" A. B. Hart (8) states that with nuclear stations off-peak power may be available for storage at a generating cost of 0.25 penny (or 2.9 mils) per kwh, though this does not mean that it could be sold to a consumer at this very low price.

If practical power plants for short range road transport can be achieved, it would not be a very big step to design a larger plant suitable for propelling railcars, where the problems of weight and space are much less severe than with road transport; many battery driven railcars are now in use in Germany, where conditions are favourable for this application.

Lastly, it is hoped that the suggestions contained in this paper, which may be regarded as very reactionary, will not be taken as detracting in any way from the magnificent work which is being done in many parts of the world on hydrocarbon-air cells; but the latter project still seems some way from complete fulfilment, and it would, in the author's opinion, be of immense benefit to the whole fuel cell scene if some substantial commercial application could be found quite soon, even in a limited sphere such as the one suggested.

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