

and electricity must proceed at rates that maintain conditions uniform within the battery. Nonuniformity can result in many ways and have many undesirable consequences, one of the more serious of which will be illustrated in Figure 7.

In addition to ensuring uniformity in the battery, the engineers must also choose materials of construction, regulate the electrical output of the battery, and make the step from battery to system. These engineering assignments have turned out to be more formidable than many had anticipated, and the engineer today carries the principal burden in making hydrogen batteries successful.

WHAT ARE SOME ELECTRICAL PROBLEMS OF THE FUEL BATTERY?

The electrical problems of the fuel battery are inherent in the performance curve of the fuel cell (see Figure 6). Two favorable features stand out: (1) At open circuit, voltage is maintained without measurable consumption of fuel, there being no net electrochemical reaction at zero current density. (2) Voltage efficiency, and hence overall efficiency in the usual case, is higher the lower the current density. These features make the *direct* fuel battery desirable for equipment that must stand ready to perform during long idling periods, or that operates most of the time at low load. These advantages may be reduced in an *indirect* fuel-battery system owing to the energy required to keep converter or reformer ready for operation when load increases.

The low voltage of the single fuel cell leads to electrical problems, which are generally less serious with hydrogen as fuel because it gives higher cell voltages at the same current density than do most others; hydrogen might yield $E=0.7$ volt at current densities where hydrocarbons give $E=0.3$. The obvious way to obtain needed high voltages from fuel cells is to connect them electrically in series.

As was mentioned above, the greater the number of cells in series, the greater the chance one cell in the stack will fail, and this will most often be a failure of the *least* reliable cell. This could simply open-circuit the stack, or it could have more serious consequences. If the failure resulted from an interruption of the hydrogen or oxygen supply, the other cells in the stack could "drive" the one affected and cause unwanted reactions to occur at the electrodes. This is the serious lack of uniformity mentioned above. As Figure 7 shows, this type of failure could lead to the generation of oxygen in the hydrogen (anode) chamber and to the generation of hydrogen in the oxygen (cathode) chamber, clearly an undesirable state of affairs.

For cells connected in parallel, complete failure will usually not occur until the *most* reliable cell has failed although there will have been a decrease in current prior to complete failure. From the standpoint of reliability, it is desirable to minimize series- and maximize parallel connections.

There is a limit to how far one can go. Maximizing parallel connections implies the handling of large currents and the incurring of high I^2R losses, and there is the added difficulty that most electrical equipment operates at voltages considerably above that of a single cell. Solid-state dc-dc converters are now available at ratings from 20 watts to a few kilowatts, but these are inefficient at low input voltages. They are nevertheless valuable because they make it possible to reduce the number of cells connected in series, the extent of maximum reduction being set by the conversion inefficiency considered tolerable, and by the probability of failure of a cell in the stack.

Dc-ac inversion for small loads can also be accomplished, but only with heavier and more costly equipment than dc-dc conversion requires. At present, we do not believe that inversion of fuel-battery power on a central-station scale need be considered; if such power can compete on this scale at all, it will have to compete for dc applications, notably in the electrochemical industry. The industry provides a large market: perhaps 5% of the 200,000,000 kw total American generating capacity serves this market, about half of which produces aluminum.

The performance curve in Figure 6 also permits conclusions about operation at various power levels. As Figure 8 makes clear, operation at maximum power density is possible only at reduced efficiency, and this reduction becomes prohibitive at current densities above that for maximum power density.

HOW ABOUT THE FUEL BATTERY AS A CHEMICAL PLANT?

In space, the water generated by H_2/O_2 batteries will be drunk or used in other ways. The fuel battery will then be not only a degenerating plant but a chemical