

carried out in the anode chamber to facilitate heat and mass transfer. Indirect systems will be of great interim value.

OXYGEN OR AIR?

For applications such as space missions in which the nitrogen of the air cannot be tolerated, oxygen must be used at the fuel-cell cathode. For terrestrial applications in which the cost of oxygen is prohibitive, or for which it cannot be carried because of weight or volume restrictions, ambient air must be used. But the use of air has important drawbacks that concern the engineer.

Most fuel-cell electrodes are highly porous so as to make their true surface many times the geometric; this is one road to high geometric current density, current density being proportional to true surface area. At high current densities, cathode pores can become filled with nitrogen; this creates a mass-distribution barrier for oxygen and injures cell performance. One remedy is to make the cathodes very thin (10 mils or so thick) and the pores large, but this introduces problems of its own. Especially in a fuel battery, where passages must be narrow to conserve space, forced convection of the air will usually be needed for acceptable current densities (say, 100 amps/sq. ft.). As nitrogen leaves a battery containing an aqueous electrolyte, this gas may carry with it enough water vapor to interfere with cell operation. Particularly at high current densities, the carbon dioxide (about 0.03%) present in the air may give trouble with alkaline electrolytes either by precipitating solids in the electrodes or by reacting with the bulk electrolyte; scrubbing the air to remove carbon dioxide or frequent changes of electrolyte may be necessary. Clearly, "free as air" needs qualifications as regards the fuel battery.

The problems of air operation are important also because various air batteries that are not fuel batteries (e.g., zinc/air batteries) might be attractive for applications (such as vehicular) in which high current densities are needed. One desirable by-product of fuel-cell research are air cathodes that can serve other power sources as well.

HOW DO FUEL BATTERIES DIFFER FROM STORAGE BATTERIES?

Storage batteries do not use conventional fuels. Storage batteries contain the chemical energy they convert; hence they must be recharged when this energy is depleted. Ideally, the fuel battery can be an invariant converter that delivers energy so long as fuel and oxygen are supplied.

These two kinds of power sources are complementary more often than they are competitive. Storage batteries are favored for high power over short times (starting an automobile or short space missions); fuel batteries are favored when the load profile calls for moderate power over longer times (space missions longer than several days). The trade-offs that must be made are not usually simple, and they must be made on the basis of the complete energy system for the load profile in question; in the case of the fuel battery, for example, one must consider energy source plus fuel plus oxygen plus peripheral equipment with proper debit or credit for the reaction products. To handle high peak loads, storage batteries may be used and kept charged by fuel batteries in continuous operation.

Metal/air batteries, such as the zinc/air battery mentioned above, are hybrid devices; as regards the anodes, they are storage batteries; as regards the cathode, they are fuel batteries. A hybrid device of a different kind is the fuel-storage-battery of Figure 4, in which the fuel (methyl alcohol) is stored in the electrolyte (potassium hydroxide) that changes to carbonate as the battery operates; the solution must be replaced when the fuel is exhausted, and the cost of potassium hydroxide, unfortunately not negligible, enhances the energy cost. The cathode operates on air.

WHY DO WE WANT FUEL BATTERIES?

Because they are *convenient* and promise eventually to be *low-cost* sources of electrical energy. Cost must be judged relative to convenience: because of the convenience it offers, a fuel battery may prove successful in an application (e.g., a space mission) though the cost of the energy it produces is prohibitive by central-station standards.