

very much less. Building a reliable battery of adequate life for, say, \$50 per kilowatt will not be easy no matter what the fuel.

In this early stage in the development of fuel batteries, considerations of unit capital cost warrant the prediction that the terrestrial use of these devices will occur first in small sizes and in military applications.

AT WHAT TEMPERATURES DO FUEL CELLS OPERATE?

The properties of the electrolyte are perhaps the most important determinant of fuel-cell operating temperatures. Of these properties, we shall mention only the electrical conductivity. One function of the electrolyte is to complete the electrical circuit (see Figure 1) by the transport of ions, and it is desirable to keep the resulting $I(2)R$ losses low by close spacing of the electrodes and by choosing a temperature at which there is adequate conductivity.

Typical examples (temperature ranges approximate):

Ion exchange membranes now available, below 100° C (See Figure 9).

Aqueous acid electrolytes, up to 200° C.

Aqueous alkaline electrolytes, up to 300° C.

Molten carbonate electrolytes, 500–600° C.

Doped zirconia (solid) electrolytes, 900–1200° C.

WHERE IS THE BOUNDARY BETWEEN RESEARCH AND ENGINEERING?

It is convenient, though imprecise, to say that the fuel cell belongs to research, and that the steps from cell to battery and from battery to system are engineering assignments.

WHERE DOES RESEARCH STAND?

Though research is never finished, one can say that enough is known about hydrogen/oxygen- and hydrogen/air cells to make the designing and building of good batteries feasible.

Most research problems relating to energy conversion can be formulated as materials problems because the drive for high performance strains materials to their limits. We shall not concern ourselves with the usual types of materials problems, which arise in connection with sealing, corrosion, aging, decomposition, or evaporation.

Electrocatalysis is the main research problem with fuels other than hydrogen. For present purposes, we may (imprecisely) regard electrocatalysis as the process that raises IR-free performance curves like those in Figure 6—that is, the process by which electrode reactions at constant temperature, pressure, and electrolyte are accelerated to give a higher current density at a given cell voltage. A good electrocatalyst must be inert toward the electrolyte, have large specific surface, active morphology, be or resemble a transition metal (see the periodic table of the elements), and (if necessary) double as a catalyst for chemical reactions that accompany the electrochemical reactions. Platinum is the best single electrocatalyst for fuel-cell electrode reactions as a group, though it is not the best for every reaction. But platinum is costly, needed for other purposes, and limited in supply. Science has not yet given us an understanding of platinum's unique position in electrocatalysis, and we have therefore no firm theoretical guide lines for attacking the electrocatalysis problem.

The rates of chemical reactions increase with temperature. Though electrochemical reactions have complexities that enter into the temperature dependence of their rates, one is justified in assuming that higher temperatures bring higher rates, and that the electrocatalysis problems should be less serious at higher temperatures. This advantage will be at least partially offset by the increasing seriousness of the several types of materials problems (see above). To illustrate, an oxide-ion electrolyte resembling doped zirconia, but of greater conductivity, would permit reduced operating temperatures for cells with these solid electrolytes and make them more attractive.

WHAT OF ENGINEERING?

The importance of uniformity in a battery was mentioned above: only if conditions are uniform in a battery can the performance of the battery approach that realized for individual cells on a laboratory bench. The attainment of this uniformity is an engineering assignment because it depends upon the control of transport processes. A fuel battery consumes reactants and generates products and heat and electricity. The processes that transport mass, momentum, heat,