These definitions are more important than they seem. Though restrictive to make the subject manageable, they still include devices of great diversity. *Fuel* as used here excludes important substances often included, such as atomic "fuels" (e.g. uranium) and metals such as zinc or sodium (1).

The words *directly* and *usefully* imply that the device has an anode at which fuel is oxidized and a cathode at which oxygen is reduced; and that the conversion proceeds at voltages not greatly below the maximum possible, and at reasonably high current densities. *Low-voltage* and *direct-current* are important to the electrical engineer, who knows of course that electrical energy of this kind, although different from that ordinarily generated and transmitted, is of greatest importance to the electrochemical industry.

The reaction between conventional fuels and oxygen liberates only enough energy to give us about 1 volt per cell under ideal conditions. As Figure 1 shows, electrochemical reactions normally generate direct current. Schemes have been proposed to produce what has been loosely called alternating current from fuel cells, but the electrical engineer need not concern himself with such cells in the foreseeable future.

WHAT ARE THE IMPORTANT CONVENTIONAL FUELS?

In order of decreasing reactivity: hydrogen (in a class by itself); compromise fuels; and hydrocarbons.

Hydrogen belongs by itself because it is simple and highly reactive, the first characteristic probably being responsible for the second. When hydrogen reacts at an anode, it loses only one electron per atom and forms simple products. This probably explains why hydrogen can give us high current densities (amps/sq. ft. of geometric electrode surface) with minimum loss of voltage from the theoretical. Current density and rate of electrochemical reaction are proportional.

Hydrogen has had a dominant position from the first in the fuel-cell field (see Figure 2), and hydrogen fuel cells and fuel batteries will be emphasized in this article. Hydrogen has serious disadvantages, among which only high cost and difficulties in handling and storage need be mentioned here. Because of these disadvantages, we must look to other fuels for the future.

The hydrocarbons, especially the liquid hydrocarbons, are among the most important and desirable of all fuels. Unfortunately they are low in anodic reactivity, and their reactions are complex and can lead to many products. They are strong where hydrogen is weak, and weak where hydrogen is strong. The direct hydrocarbon fuel cell is a most difficult research assignment, but its successful accomplishment entails rewards that would outweigh the difficulties.

As their name implies, compromise fuels are of reasonable reactivity, cost, availability, energy content, and not too difficult to handle or store. Methyl alcohol and ammonia are prime examples. Hydrazine would be for specialized applications were its price to drop ten-fold or more. The compromise fuels are likely to be the earliest successors to hydrogen in direct fuel batteries; hydrazine qualifies now for special military applications in which fuel cost is unimportant, and the toxicity of hydrazine can be tolerated.

So far we have not mentioned the commonest fossil fuel, coal. At the beginning of the century, scientists and engineers began to wonder whether the dream "electricity direct from coal" could be realized, whereupon the fuel cell, which had been almost dormant since Grove, suddenly became popular. In 1900, the overall efficiency of steam plants was only about 10%. At this efficiency, they would have offered much less serious competition to a fuel-battery central-station than today, when this efficiency is 4 times as great. Figure 3 shows how far one man, Jacques, progressed in making electricity directly from a carbon much purer than coal. The caption of the figure explains why we need not consider coal seriously in direct fuel cells today.

CAN INERT FUELS, SUCH AS HYDROCARBONS, BE USED TODAY?

Yes, but *indirectly*, by changing them to substances, mainly hydrogen, more reactive at fuel-cell anodes. Examples of such changes are the reaction of carbonaceous fuels with steam, which is being widely investigated, and the decomposition ("cracking") of ammonia, which will be used to provide hydrogen for a fuel-battery-powered submarine in Sweden. Indirect systems thus combine a chemical plant with a fuel battery, and the combination brings problems not present with the fuel battery alone. Ideally, the chemical process should be