WHAT CONSTITUTES "CONVENIENCE"?

Such qualities as—
1. High power rating for unit volume.
2. High power rating for unit weight.
3. Quietness.
4. Cleanliness.
5. Operation on air.
6. Continuous unattended operation over long periods.
7. Production of useful water.

In assessing Qualities 1 and 2, the *complete system* (see Figure 5) must be considered. As regards Quality 4, the ultimate is a hydrogen/oxygen battery in dead-ended operation; in other cases, complete oxidation of the fuel is the most desirable way of achieving a harmless battery exhaust. Quality 6 involves reliability, maintenance, and life. Quality 7 is important particularly on space missions.

WHAT MAKES FOR LOW-COST ELECTRICAL ENERGY?

1. High efficiency.
2. Low-cost fuel and oxygen.
3. Low maintenance cost.
4. Long life.
5. Low capital investment.

Not all the factors determining cost have been listed. Research and development costs have been omitted because they are impossible of general assessment: terrestrial fuel batteries benefit from the knowledge gained in developing fuel batteries for space missions. Research and development costs are high absolutely, and development costs are very high relative to research costs. Adequate life tests are expensive.

WHAT ABOUT EFFICIENCY?

The immunity of the fuel cell to the Carnot-cycle restriction (see Figure 1) was for long its greatest attraction. In a modern central station, the Carnot-cycle efficiency could be near 65%, and the overall efficiency near 40%. The overall efficiency of smaller energy sources that the fuel cell hopes to displace is considerably less than 40%. Statements by reputable authorities often mention efficiencies greater than 65% for the fuel cell, and the popular press is sometimes even more optimistic.

There are efficiencies of various kinds. We shall proceed conservatively, and define an overall efficiency called the *comparative thermal efficiency* for the fuel battery and for the fuel-battery system. These efficiencies are comparable with the 40% mentioned above for central stations. The two definitions are analogous.

For the battery (or the system):

$$\mathrm{Eff}_{CT}=\frac{\text{Net useful work}}{\Delta H \text{ of fuel consumed}}$$

In the denominator, ΔH is the *higher* heat of combustion of the fuel actually consumed in making available the net useful work in the numerator; some of this fuel may be consumed by peripheral equipment. In both cases, the electrical energy required by the peripheral equipment (such as pumps) with its demand for parasitic power must be subtracted from the gross electrical work ($\int$ Eidt) available at the fuel battery terminals; the system efficiency may consequently be considerably lower than the battery efficiency.

The efficiency of a single fuel cell will usually exceed considerably the two efficiencies given above. Detailed discussion would take us too far afield. We shall simply say that under most conditions this cell efficiency is determined principally by the *voltage efficiency* under operating conditions. This efficiency is E/E, where E is the actual cell voltage and E is the maximum value of E, which can be calculated from thermodynamic data and could be realized only under completely reversible conditions.

The most important single characteristic of a fuel cell is its current density-voltage curve (Figure 6), which is an index of cell performance and therefore corresponds to an upper limit for the performance of battery and of system. The current *density* (not current) is chosen as abscissa, not only because current density is proportional to the rate of electrochemical reaction, but also be-