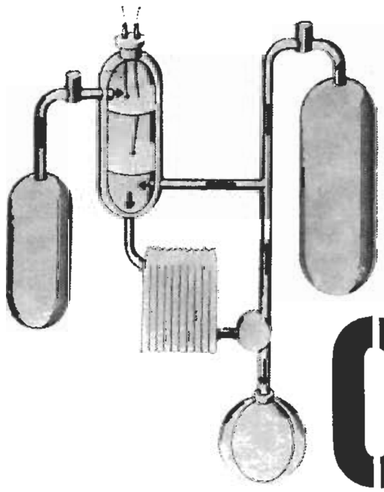
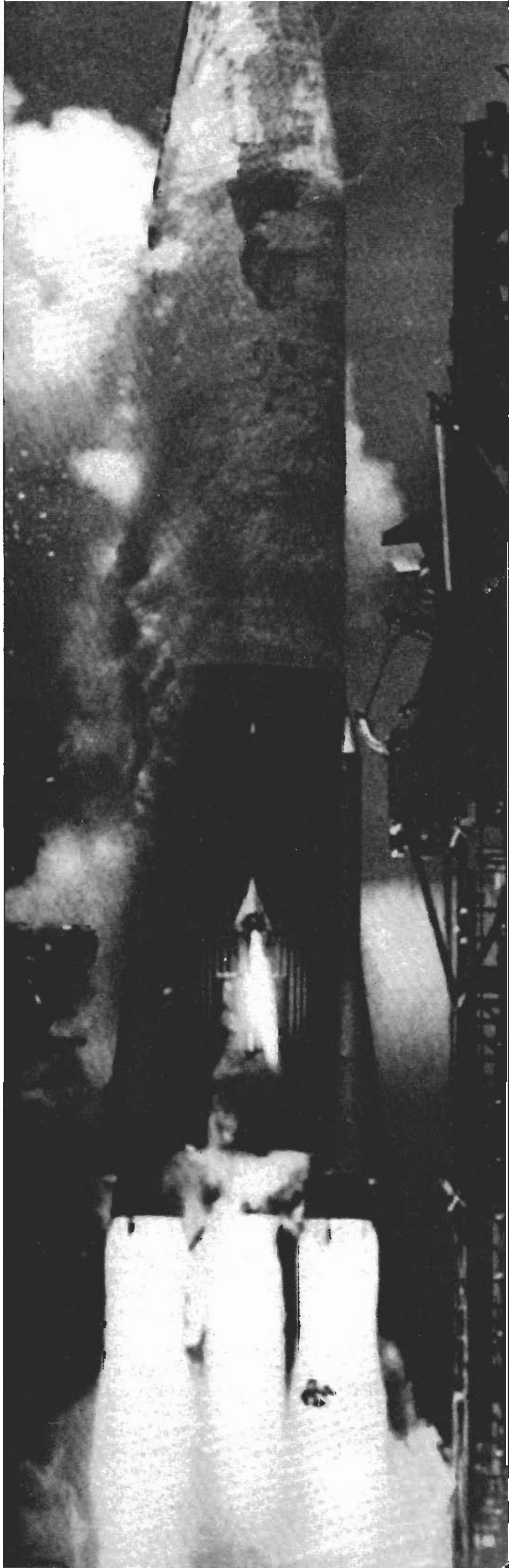
New exotic power sources will supply all electrical needs of space vehicles. These cells produce electricity directly from chemical reactions with efficiencies far greater than any other non-nuclear power system.

By KEN GILMORE



fuel cells



WHEN the "Gemini" space craft with its two-man crew orbits the earth sometime in 1963, the electric power to operate its elaborate electronic and life-support equipment will come from an exotic new source: a newly developed fuel cell. The "Apollo" space ship, our entry in the moon sweepstakes, will also draw fuel-cell power.

The Navy, meanwhile, is financing development work on a fuel-cell-powered submarine. Like an atomic sub, it could stay submerged practically indefinitely, but would be far quieter and harder to detect. Furthermore, it would cost much less to operate.

Fuel cells will soon be pouring their power into devices designed for the civilian market, too. *Allis Chalmers Company* has announced plans to market a fork-lift truck driven by the potent power makers. (The company demonstrated a prototype fuel-cell-powered tractor more than two years ago.) And, although no one is ready yet to make predictions as to *when* fuel cells may appear in automobiles and trucks, their ad-

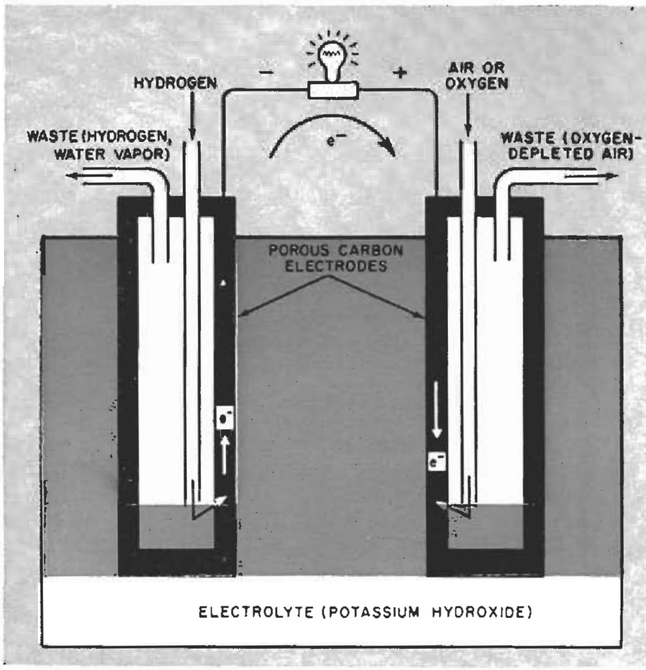


Fig. 1. Basic hydrogen-oxygen fuel cell consists of two porous carbon electrodes submerged in electrolyte and supplied with gases.

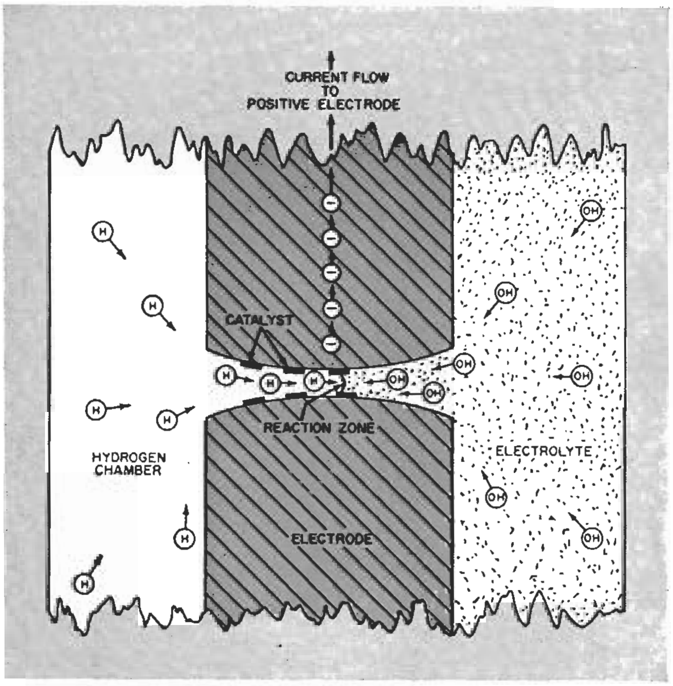


Fig. 2. Hydrogen and hydroxide react in pores of electrode, producing surplus electrons that flow toward the positive electrode.

vantages lead many engineers and scientists in the field to believe that most of us may ultimately drive fuel-cell-powered cars.

Fuel cells, in fact, could bring about the biggest electrical revolution since the dynamo launched the electrical age in the closing years of the last century. The reason: they generate far more electricity per pound of fuel than any other non-nuclear method of power production. The most modern turbine electric generating plants, for example, strain to operate at 40% efficiency, that is, to turn 40% of the energy stored in the fuel into usable electrical power. Automobiles run at about 20% efficiency, motor boats at 10%. Present-day prototype fuel cells, on the other hand, wring 50 to 85% of the potential power out of every pound of fuel.

Even though the excitement about them is relatively new, fuel cells themselves are not. Sir William Grove, an Englishman, built the first primitive model in 1839. A half century later, two of his countrymen, Ludwig Mond and Carl Langer, developed a more advanced model, dubbed it a fuel cell. But the electric dynamo was just coming into its own at that time and it captured the attention of scientists and engineers. Fuel to run the machine was plentiful, efficiency wasn't important, and the dynamo appeared simpler and was easier to build.

Poor efficiency has plagued the dynamo through the years, though, and there's not much engineers can do about it. The trouble comes from the fact that in the process of releasing the energy of the fuel, we throw most of it away. We extract the fuel's energy by burning it. The heat is converted to mechanical energy by a turbine or some other heat engine, the engine drives a dynamo which generates electricity. Energy is wasted at every step.

The fuel cell eliminates the efficiency problems of the dynamo by skipping the heat cycle entirely: it transforms the potential energy stored in the chemical bonds of the fuel directly into electrical energy without the wasteful intermediate heat step. Theoretically, the fuel cell could have 100% efficiency. Certain practical limitations, internal I^2R losses, for example, make it unlikely that we will ever reach this point, but even today's relatively crude devices have little trouble achieving efficiency at least twice as good as the nearest competitors, and, what is more, they're getting better all the time.

Battery with a Gas Tank

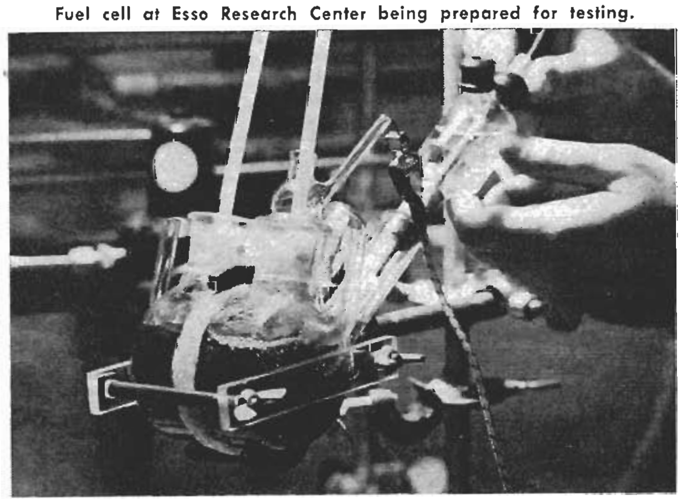
In drawing electrical energy directly from fuel through a chemical reaction, the fuel cell is similar to its close relative, the storage battery. But it is also different in important ways. In a battery, the "fuel" is built in, in the form of expendable or rechargeable electrodes. The fuel cell, on the other hand, has its fuel fed in continuously from the outside. Because of this feature, it has been called a "battery with a gas tank."

The basic principle on which the fuel cell operates is simple. Hydrogen and oxygen combine to produce water. During the process, they release electrical energy which can be tapped off to do useful work. Fig. 1 shows the basic principle of the hydrogen-oxygen cell, one of the types in the most advanced state of development. It consists of two hollow porous carbon electrodes immersed in a potassium hydroxide solution. Hydrogen is pumped into one electrode, oxygen into the other. A potential appears across the electrodes and if a load is connected between them, current flows.

How it Works

Hydrogen molecules consisting of two hydrogen atoms enter the negative electrode, flow into the tiny pores (10^{-5} to 10^{-7} cm. in diameter), come into contact with a catalyst which splits them into two separate hydrogen atoms. See Fig. 2. The atoms then migrate along the surface of the

Fuel cell at Esso Research Center being prepared for testing.



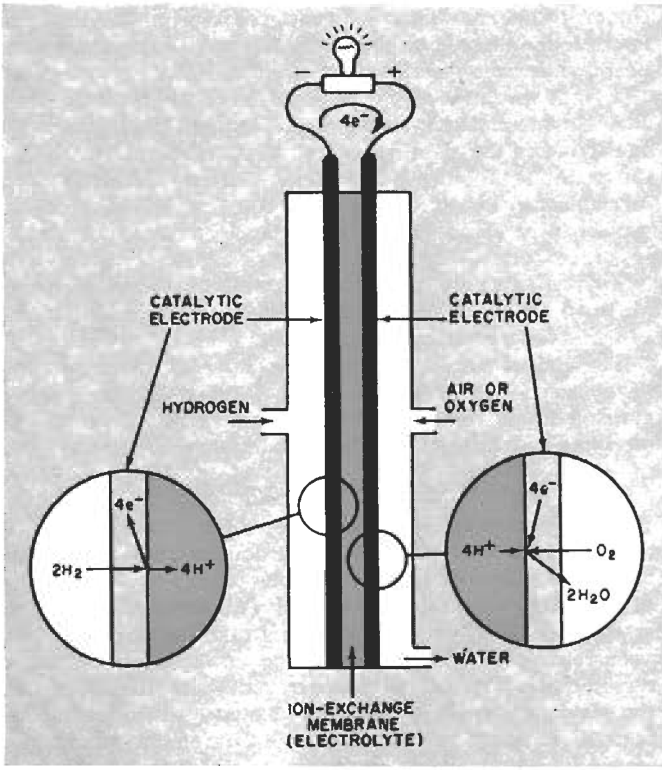


Fig. 3. The ion-membrane fuel cell employs electrolyte in solid form in order to solve problem of contact stability.

pores to the reaction zone. At the same time, hydroxyl (OH^-) ions from the potassium hydroxide electrolyte have migrated toward the reaction zone also. At this point, the hydrogen and hydroxyl ions combine to form water and, in the process, release electrons.

These electrons are attracted by the potential on the positive electrode, and flow through the load toward it, doing useful work on the way. At the positive electrode, atoms of oxygen have flowed into the pores where they combine with one water molecule from the electrolyte plus the two electrons which have just arrived from the negative electrode. This reaction forms perhydroxyl (O_2H) and a hydroxyl (OH^-) ion to replace those being used on the negative electrode. The hydroxyl ion now migrates through the electrolyte to the negative electrode to start the chain all over again.

Actually, at ambient temperatures, these reactions take place very slowly. Consequently, many early fuel cells—and some present-day ones—operated at high temperatures to speed up the process and produce more electricity. Another way to encourage rapid reaction is to supply the proper catalytic agent.

Catalytic Agents

Catalysis has always been something of a "black art," dimly understood and imperfectly applied. But research in recent years has led to a more basic understanding of the field. Consequently, fuel-cell engineers have been able to find catalysts—usually fine particles of platinum or palladium coating the carbon pores—which speed up the ordinary low-temperature reaction by as much as a million times. Using such catalysts, low-temperature cells can be built to deliver practical amounts of power.

But there have been massive problems of chemical engineering—just now being solved—which have kept the fuel cell from being a practical power generator.

Some Problems

In order to deliver usable amounts of power, for example, a cell had to be designed in which large amounts of gases and electrolyte could come together in a cell of practical size. The porous carbon electrode, used in a cell designed

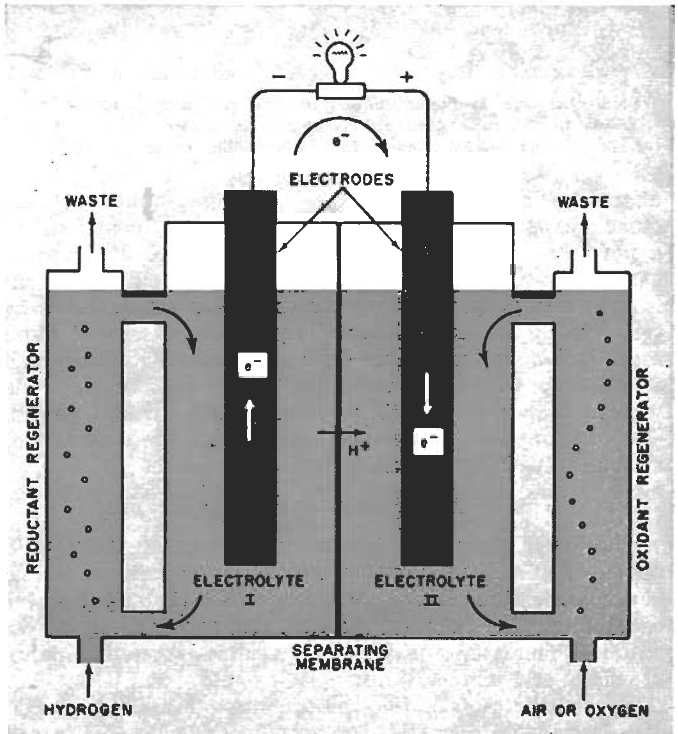


Fig. 4. "Redox" cell has two electrolytes separated by membrane.

by *Union Carbide (Eveready)* is one approach to this problem. Dr. D.M. Gage, technical manager of Electrochemical Products, showed the author a two-ounce bottle of carbon pellets which could almost be concealed in a fist. "The carbon in this bottle," he said, "contains a surface area equivalent to seven football fields." Electrodes built of such carbon provides tremendous amounts of reaction surface even in small cells.

Perhaps the biggest problem to bedevil fuel-cell designers is polarization—chemical changes at the surface of the electrodes which tend to block off any further reaction. Many apparently attractive fuel-cell combinations are completely worthless because no one can figure out a way to stop excessive polarization. In the hydrogen-oxygen cell, the

COVER STORY

THIS month's cover shows a simplified schematic representation of a fuel-cell power plant designed by Pratt & Whitney Aircraft for use in space flights. A photo of a model of the actual power plant is also shown. The system will provide the full electrical requirements of the spacecraft. Moreover, the exhaust product is potable water—useful for all space crew needs, including drinking.

Oxygen and hydrogen gas are supplied under modest pressure to the fuel-cell assembly. Here a number of porous nickel electrodes (only two are shown in the drawing for simplicity) are submerged in a solution of potassium hydroxide. Chemical reactions occur within the cell, producing electricity, water vapor, and heat. By using a number of cells in series, a higher output voltage may be obtained. This voltage is then used to power an external load. An excess of hydrogen removes the water vapor and heat and transports it to the radiator-condenser where the heat is rejected and the water vapor condenses to form water droplets. These are removed by a pump-separator and the water is stored in a tank for later use. The pump recirculates the exhaust hydrogen and returns it to the inlet connection of the cell assembly.

Experience gained from space programs such as this should accelerate the evolution of an economical fuel-cell power plant using readily available fuels and adaptable to a wide variety of industrial applications.

(Cover illustration: George Kelvin. Photo courtesy: Pratt & Whitney Aircraft.)

principal polarizing agent is the perhydroxyl mentioned above. If unchecked, it will soon coat the positive electrode and stop all further reaction. To combat it, scientists built into the electrode catalysts which tend to decompose the perhydroxyl as fast as it forms.

Another difficulty: elimination of water formed during the reaction. It tends to dilute the electrolyte. Sometimes a large amount of hydrogen must be circulated through a condenser where the water is removed. Sometimes, the electrolyte itself must be pumped through an external evaporator to get rid of the excess water and maintain electrolyte concentration. Either of these methods, of course, involves undesirable extra mechanical equipment.

Despite these and many other engineering problems, though, researchers have succeeded in building workable cells. *Union Carbide*, for example, built and delivered to the Signal Corps in August 1957, a 1-kilowatt unit for evaluation at the Army's electronics proving grounds at Fort Huachuca, Arizona. It was used to power the "Silent Sentry," a portable radar designed for battlefield use. The normal gasoline-powered generator used to operate field equipment is noisy enough to give away the unit's position, so the Army was looking for a completely silent power source. More recently, *Union Carbide* has built an improved version which delivers up to 100 amperes per square foot of electrode surface. It has performed well for a two-year test period. The company's researchers say present units are even better, although exact performance figures are secret.

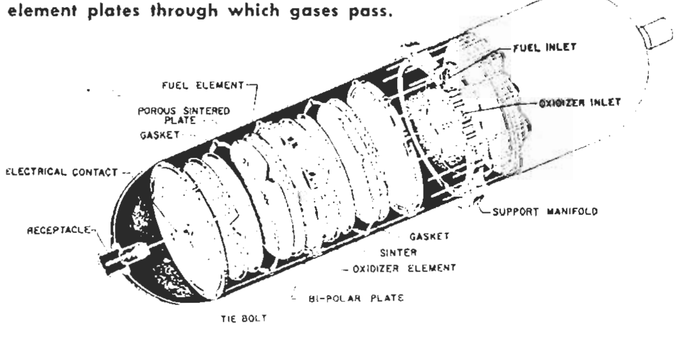
Soldier at right is shown loading a new fuel supply. Metal hydrides in the tank generate hydrogen to power the cell. This unit supplies enough power for the portable radar set at left.

Higher Temperature, Higher Output

The low temperature, low pressure (roughly 100 to 170 degrees F at atmospheric pressure) units are relatively simple in mechanical construction, but are limited in output power capabilities. The chemical reaction, and consequently power output, is increased substantially if a cell is operated at higher pressures and temperatures.

One of the pioneer fuel-cell scientists, Francis T. Bacon of Cambridge University, has been working on such a cell since the early 1930's. The Bacon cell, which uses porous nickel electrodes, operates at temperatures up to 500 degrees F and pressures of some 800 pounds per square inch. Under these conditions, it produces current densities up to six times those available from the low-temperature cells. Bacon cells have generated as much as 150 watts per pound of weight. Because of this high power-to-weight ratio—lead-acid storage batteries used in automobiles and planes put out 10 watts per pound—several companies are looking into the possibility of using the Bacon cell for electrical power in airplanes. The weight savings could be significant. One problem: the cell doesn't begin to produce much power until heated to about 300 degrees F, so engineers would have to devise a fast, light, reliable heater before they would be practical. Once operating, the cell generates enough heat to maintain proper operating temperature.

Pratt & Whitney fuel-cell assembly consists of a number of porous fuel and oxidizer element plates through which gases pass.

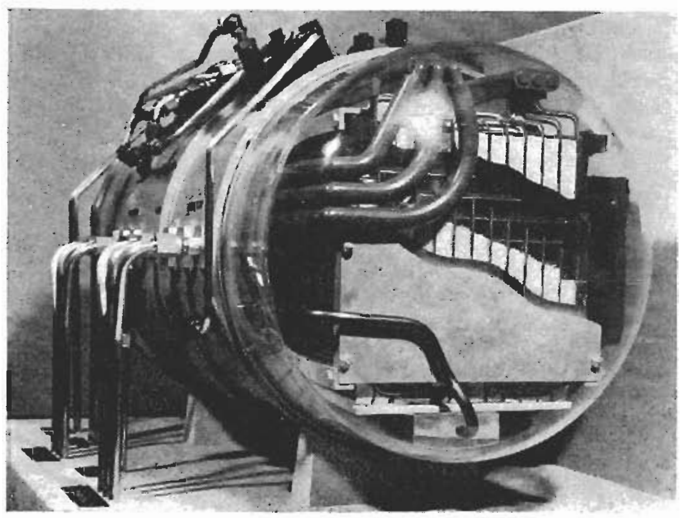


The Bacon cell has advanced so far that space planners have chosen it as the electrical power source for the "Apollo" manned moon vehicle. A model of the type which will be used, built by *Pratt & Whitney*, is shown on the cover.

Ion-Exchange Membrane

Another approach to fuel-cell construction which has reached an advanced stage is the ion-exchange membrane cell built by *General Electric Company* (Fig. 3). The principle of operation is similar to that of the standard hydrogen-oxygen cell. The main difference is that the electrolyte has been replaced by a solid membrane through which the ions can migrate. The cell is compact and water formed during the process is easily eliminated: it simply drips out of the bottom. The unit uses less auxiliary equipment—pumps and so on—than any other cell, and has no moving parts.

General Electric cells have already been built in several prototype models which have been tested by the military. One 55-pound unit produces 200 watts of power, enough to operate the Army's PPS-4 ground surveillance radar. Seventy-two pounds of fuel will operate the unit for a week. It would take a half-ton of freshly charged lead-acid storage batteries to do the same work. The unit produces 20 amperes per square foot of electrode surface—a kilowatt per cubic foot. Another *G-E* cell was sent into space on a test flight in October 1960 and operated satisfactorily.



Cut-away mockup of G-E fuel-cell power source that can provide electricity and drinking water for astronauts. The type of supply shown will be used in NASA's two-man spacecraft "Gemini."

Pure-Fuel Problem

One of the problems associated with most hydrogen-oxygen fuel cells is the fact that gases of high purity are required. Impure hydrogen will speed up the polarization process and poison the cell—sometimes quickly.

One approach to avoiding the need for ultra-pure gases is the "Redox" cell—*red*uction and *ox*idation—shown in Fig. 4.

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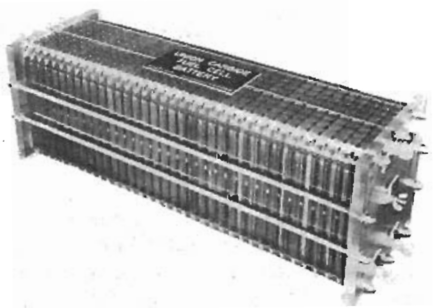
The fuel and oxygen are not consumed in the electrodes, but in two special regenerating tanks. The hydrogen enters the regenerator and reduces—adds electrons to—the electrolyte. Oxygen on the other side oxidizes—takes electrons from—the electrolyte on that side. The two solutions are separated from each other by a membrane, at which the reaction takes place. Ions migrate across the membrane, just as they do across the electrolyte solution in the regular cell, and maintain the reaction.

Although the Redox cell is inherently less efficient than the regular design, it has many attractive features. Polarization is less of a problem, it has lower internal losses, potentially higher current densities, and the ability to operate on impure hydrogen.

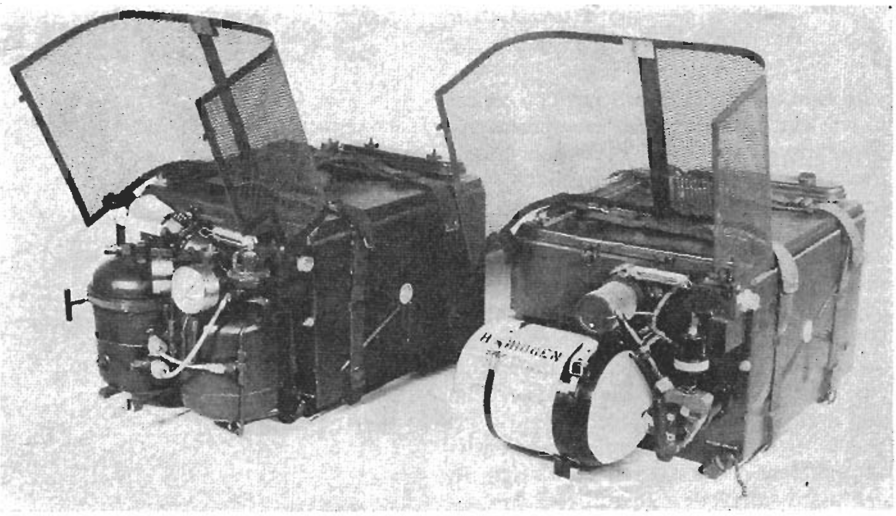


This fuel-cell battery, built by Union Carbide, contains 35 cells in series. It delivers 600 watts of power at 28 volts d.c.

Hydrogen-fueled cells are by far the most advanced at this time and will be the first to go into practical operation. But hydrogen is still expensive, even though it is getting cheaper all the time. For this reason, hydrogen-powered cells will be used only where the convenience of the cell makes the extra cost of fuel justifiable. The "Apollo" and "Gemini" are good examples of this philosophy.

Inexpensive Fuels

Really large-scale use of fuel cells will have to wait for further advances in the technology of cells that operate on cheap fuels. Work on these advanced units is proceeding rapidly. For the most part, present models are high-temperature units, operating in the vicinity of 1000 degrees F. The heat "cracks" the hydrocarbon fuel—methane, propane, vaporized kerosene, or gasoline—into hydrogen and carbon monoxide. Since any water-based solution would vaporize at these temperatures except under extreme pressure, the electrolyte is usually a molten salt, such as potassium carbonate, held in a sponge-like matrix of magnesium oxide. The hydrogen and carbon monoxide react with the electrolyte to form water and carbon dioxide and release electrons. Oxygen at the



These fuel-cell field power supplies are identical except that the one at the left manufactures its own hydrogen fuel from chemicals contained in the two tanks. The power supply shown at the right operates on a small container of hydrogen gas.

positive electrode attracts the electrons for a reaction similar to that which takes place in the hydrogen-oxygen cell. Such cells so far have produced no more than 500 watts per cubic foot—half the output of the *Union Carbide* cell—but undoubtedly this will be raised.

Low-temperature hydrocarbon cells —which would be far easier to manufacture—have also been built. Proper catalysts allow the same reaction to take place at much lower temperatures. *Esso Research Laboratories* has announced the development of a cell which operates at temperatures as low as 150 degrees F on ethane, propane, or ethylene. Its output is low, but the production of a low-temperature hydrocarbon cell which operates at all is a significant step forward.

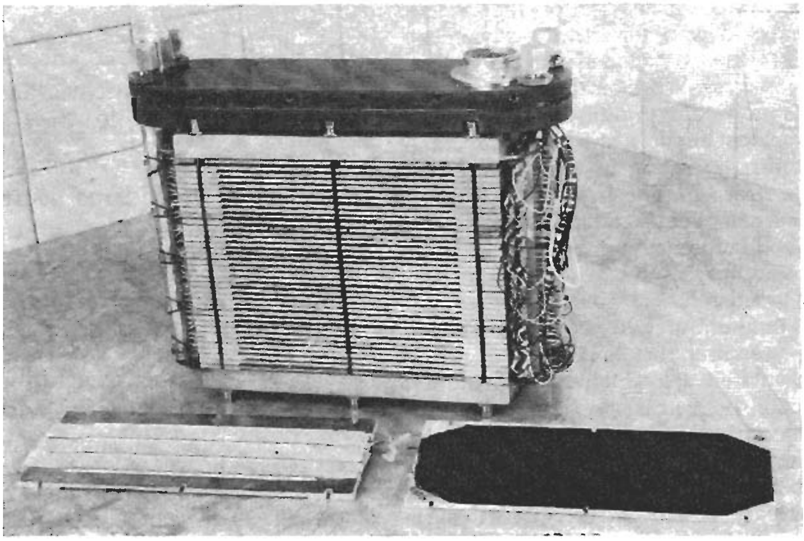
More Exotic Cells

In the search for ever-cheaper fuels and more efficient operation, some workers in the field have turned to biological fuel cells. Ideally, the electrolyte would contain organic matter—corncobs, sawdust, even sewage—and bacteria suspended in seawater. The bacteria produce an enzyme which acts as a catalyst for the electrochemical oxidation of the fuel, in a way similar to the reaction in a regular cell.

General Scientific Corporation of Washington demonstrated such a unit at a press conference several months ago, used it to power a small radio. Dr. Frederick D. Sisler of *General Scientific* said that bacteria could be put to work making electricity, using chemicals found in the sea as fuel. No figures as to operating characteristics or exact principles and no data on materials and fuels were released, however.

Electro-Optical Systems, Inc. of Pasadena, California and *Sonotone Corporation* of Elmsford, New York are working jointly on another kind of biological cell. The *EOS-Sonotone* unit is understood to operate on sugar and various proteins and to use synthetic enzymes rather than bacteria. But no further de-

A G-E ion-exchange fuel-cell battery. One of the individual cells that make up the battery is shown in the foreground.



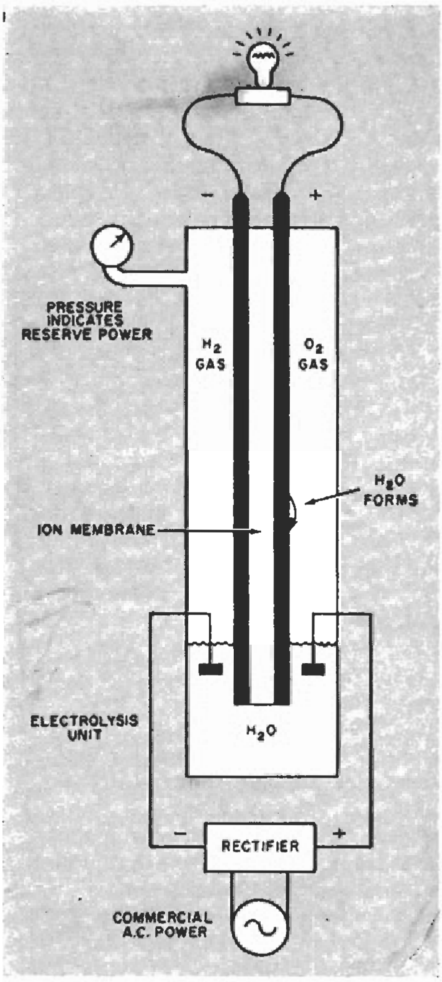


Fig. 5. Use of a fuel cell as automatic emergency power supply. Normally, the electrodes connected to the rectifier separate water into hydrogen and oxygen. These gases are stored in reservoirs on both sides of the membrane, where they generate power used for light. If the line power fails, the cell continues to operate the lights without interruption. When enough water has been electrolyzed into gas, the water level falls below the electrodes attached to the rectifier and the process stops. As power is drawn from the cell, the gases are changed back into water, the level rises, the electrolysis process is initiated again.

tails have been released. If biological cells ever become practical, they would be ideal for use in extended space journies. Garbage, human waste, and other useless substances could be used as fuel.

Future Power

Whatever the final form, though, there is little doubt that fuel cells will occupy an important place in future power generation. Military and space use will, of course, come first since reliability, not cost, is the prime requisite in both fields. But with the development of the hydrocarbon cell, civilian uses will be close behind. The comeback of the electric car and truck, whispered about for some time now, looks more likely with the advent of the fuel cell.

The efficient electricity maker is a natural for automotive power. Cars could be designed with an electric motor in each wheel, eliminating transmissions, drive shafts, and, of course, the engine and all its complications. The fuel cell car wouldn't even need brakes. A load resistor thrown across the wheel motors would make them act as generators, slowing the car. Electric trains now use this type of dynamic braking. Then, too, fuel cells would produce no noxious exhaust—the only output of the cell is water—and would use no fuel while stopped at traffic lights. And, of course, they'd be some four times as efficient—and thus far cheaper to run—than today's autos.

Finally, since the cells wouldn't have to be lumped in one place like a gasoline engine, car designers would be free to design for superior roominess, riding qualities, and streamlining, distributing the cells around the body in convenient places. Troubleshooting in such a car would be done with a v.o.m.

Large-scale power generation—although it would be more efficient with fuel cells and thus cheaper—will face more serious problems. The low-voltage, d.c. current produced by the cells is perfect for autos, but not for our present a.c.-oriented power distribution system. Some simple, cheap method of changing cell output to high-voltage a.c. would have to be found.

In the meantime, one possible use for fuel cells might be to help nuclear electric plants run efficiently. To perform near maximum efficiency, nuclear plants must operate "wide open." Fuel costs per kilowatt hour rise sharply as plant output decreases. But electric usage varies substantially through the day and year.

Future nuclear plants might be adjusted to run at a rate just high enough to produce the total power needed over a long term. During periods of low consumption, excess power would be used to generate hydrogen and oxygen from water. In peak load periods, the gases would run fuel cells to meet the power demand.

The most important fuel-cell application ultimately may be the self-contained home power plant for either regular or emergency use. *Esso Research* and other firms have this in mind as a long-range possibility. Such a small "black box" in the basement would furnish power for lights, appliances, heating, air-conditioning, and so on. *Esso* engineers have gone so far as to estimate that the energy costs for an average six-room home might be cut from the present $380 a year to $125.

Fuel cells are, of course, only one of the exotic power sources being developed for future use. Others—magnetohydrodynamic, thermoelectric, and thermionic generators—all have their strong points, but none of them rivals the efficiency of the fuel cell. ▲