SYMPOSIUM ON FUEL CELLS
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DESCRIPTION OF A FUEL-CELL POWER-PACK OPERATING ON HYDROGEN AND AMBIENT AIR

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INTRODUCTION

Over the past two years, the General Electric Company at Lynn, Massachusetts, has been developing a complete two-hundred-watt power-supply based on the ion-exchange-membrane fuel-cell. This development work which followed the earlier work at the Company Research Laboratory was performed under contract with the Navy Bureau of Ships and the Army Signal Corps. The complete unit is shown in Figure 1. This paper will describe the construction and operation of the unit.

A schematic of the G. E. cationic-membrane fuel-cell operating on hydrogen is shown in Figure 2. The current cells used in battery stacks are about six-tenths of a millimeter thick including the two catalytic electrodes. The hydrogen gas is fed into a dead-ended chamber on one side of the membrane where it is adsorbed on the catalytic anode and is stripped of one electron per hydrogen atom. The resultant hydrogen ions diffuse through the ion-exchange electrolyte while the freed electrons flow along the electrically-conducting catalyst to the current collector contact point, thus producing the negative (-) terminal of the cell. On the other side of the membrane, the oxygen from the air moving over the cell is adsorbed in the cathode. In the region of this catalytic electrode, an overall three-way reaction takes place between the transported hydrogen ions, some form of the adsorbed oxygen, and the electrons which have passed through the external electrical load to form water as the final reaction product. The water, thus formed, may be removed by evaporation or drawn off through a valve at the bottom of the cell casing. About 35 cells of this type, each having an electrode size of approximately 85 square inches, are used in a battery contained in a portable 200-watt fuel-cell system.

CELL PERFORMANCE

The cation-exchange electrolyte is contained in a polymer system reinforced with cloth. The cloth provides the membrane with the structural strength necessary to survive the dimensional changes associated with the differential dehydration occurring during cell operation. The presence of the cloth embedded in the resin impedes the transport of the hydrogen ions through the membrane and thus increases the electrical resistance through the membrane. Therefore, development programs were conducted to decrease the weight ratio of cloth to resin. These have increased performance by approximately 60 percent, from 6.1 watts per square foot to 9.7 watts per square foot.

The effect of reductions in the cell resistance can be observed in Figure 3. The voltage drop from the theoretical open circuit value of 1.23 volts to approximately 0.9 volt is believed to represent irreversibility losses at the oxygen electrode. The remainder of the slope of the polarization curve is strictly a function of the IR drop caused by internal resistance of the cell. Efforts toward reducing these losses result in an increase of cell efficiency and correspondingly a reduction of the heat produced in the cell. Thus, reducing the cell resistance offers a two-fold advantage at a particular power density; first, an increase in fuel efficiency and secondly, a reduction in the dehydration tendencies of the cell.

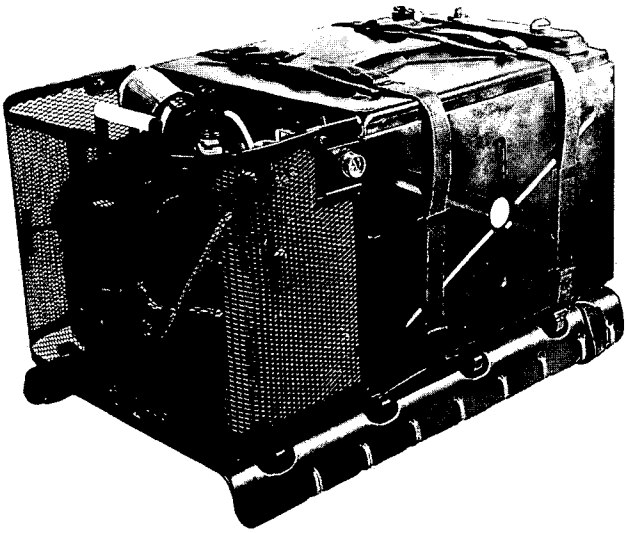
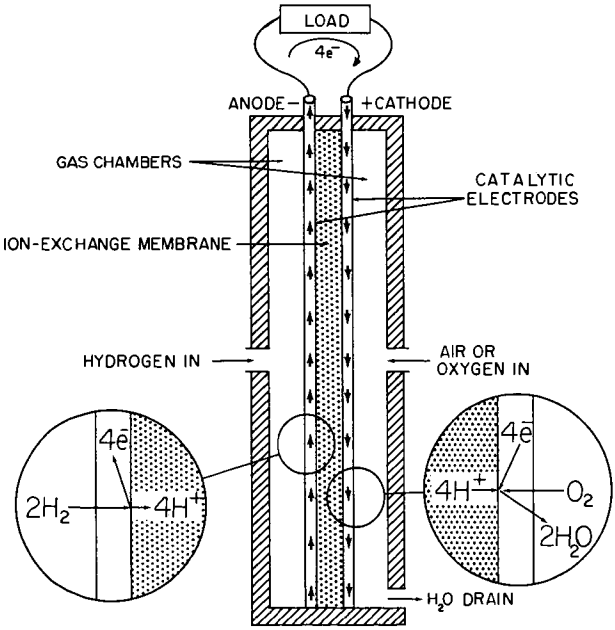


FIGURE 1
THE G. E. 200-WATT POWER-PACK SYSTEM BASED ON A CATIONIC-MEMBRANE FUEL CELL BATTERY STACK



CHEMICAL REACTIONS

ANODE	OVERALL	CATHODE
$2H_2 \rightarrow 4H^+ + 4e^-$	$2H_2 + O_2 \longrightarrow 2H_2O$	$4e^- + 4H^+ + O_2 \longrightarrow 2H_2O$

FIGURE 2
SCHEMATIC OF G. E. ION-EXCHANGE FUEL-CELL OPERATION

CELL ASSEMBLY CONFIGURATION

Figure 4 shows the air side of a cell assembly for the 200-watt Power Pack. The current collector is formed from two pieces of titanium sheet-stock. The inner piece is .0015 inches thick and is in contact with the catalyst-electrode. Its small channels conduct air over the membrane to provide oxygen for the electrochemical process. The outer perforated piece is .003 inches thick. Its larger channels carry additional air for cooling the air side of this cell and the hydrogen side of the adjacent cell in a stack.

Figure 5 reveals the internal construction of a single cell. The membrane is bonded to a plastic frame that is molded around the anode current collector (hydrogen side). This forms a gas-tight chamber for the hydrogen. The hydrogen supply is attached to the inlet at the top of the cell where it emerges through a series of holes and distributes itself throughout the chamber. A manifold molded into the opposite side of the frame is used for the occasional purging of accumulated inert gases.

Since the hydrogen side of the cell forms a sealed and dead-ended chamber the only gas flow is that necessary to make up for the hydrogen consumed in the reaction. Therefore, the frequency of purging is a function of hydrogen purity.

Ambient air, used both as a coolant and a cell depolarizing reactant, is forced under the battery by a small inlet fan powered from the fuel-cell. From this plenum, the air, flowing up through each cell, is split into reactant air flow and cooling air flow. This design of splitting the air flow is to remove from the battery across water-impermeable barriers as much heat as possible. As shown in Figure 5, a network of wicks covers the air side of the membrane. These are fed from distributor wicks at the base of each cell. Legs extend from the bottom of the cell frame to hold the distributor wicks in the water reservoir. This system of wicks in contact with the membrane is a characteristic of the evaporatively cooled air-breathing fuel cell. It supplies water to make up evaporative losses within the air-breathing cell and to maintain the proper moisture content in the membrane for optimum ion transport and dimensional stability.

HEAT AND MASS TRANSPORT

Several factors contribute to the necessity of cells giving off water to reject heat in some ambients. In air-operating cells, voltages are such that more heat is generated that the product water formed can solely absorb in its evaporation. Thus, what heat is not conducted away will require extra water to evaporate. This latter situation is often true in multi-cell stack operation in various ambients. In multi-cell air operation with some liquid electrolytes this may manifest itself in precipitation in the oxygen electrode pores. In hydrated ion-exchange fuel cells, water can come from the gel structure with a resultant loss in ionic conductivity of the membrane and a desire on its part to change dimension to some degree depending on the gel. Note that increasing convective heat transfer by reasonable higher air velocities will not generally help because in air-water systems the weighted mass-transfer coefficient is intrinsically favored over the heat transfer coefficient. Effects can be made by changing driving forces available for heat and mass transfer.

As previously mentioned in this paper, the General Electric Company has done two things to solve this simultaneous heat and mass transfer problem for ion-exchange fuel cells operating on air in light-weight multi-cell stacks. First, is the forementioned splitting of the flowing air into two parts to effect an internal-stack, air-cooled condenser in close proximity to the two reactive electrodes. In fact, in the present 200-watt design, the distance of the condenser surfaces from the electrode is of the order of 1 or 2 mm. and set only to avoid water droplet bridging. Secondly, when necessary the forementioned make-up water, is supplied by a system of wicks. These approaches prevent a membrane dehydration condition and allow the satisfactory control of membrane temperature - rise.

Heat and mass transfer performance has been estimated for a range of inlet temperatures and humidities at a constant air flow, and is shown in Figure 6.

It can be observed that the total amount of water evaporated by the air passing over the cell is greater than the product water for all conditions except at low temperatures. Therefore, the wicks must make up the difference to maintain a stable system. The wicking system used in these cells is the result of extensive testing and evaluation of types of material, purity of material, number of strands, and number of wicks per channel.

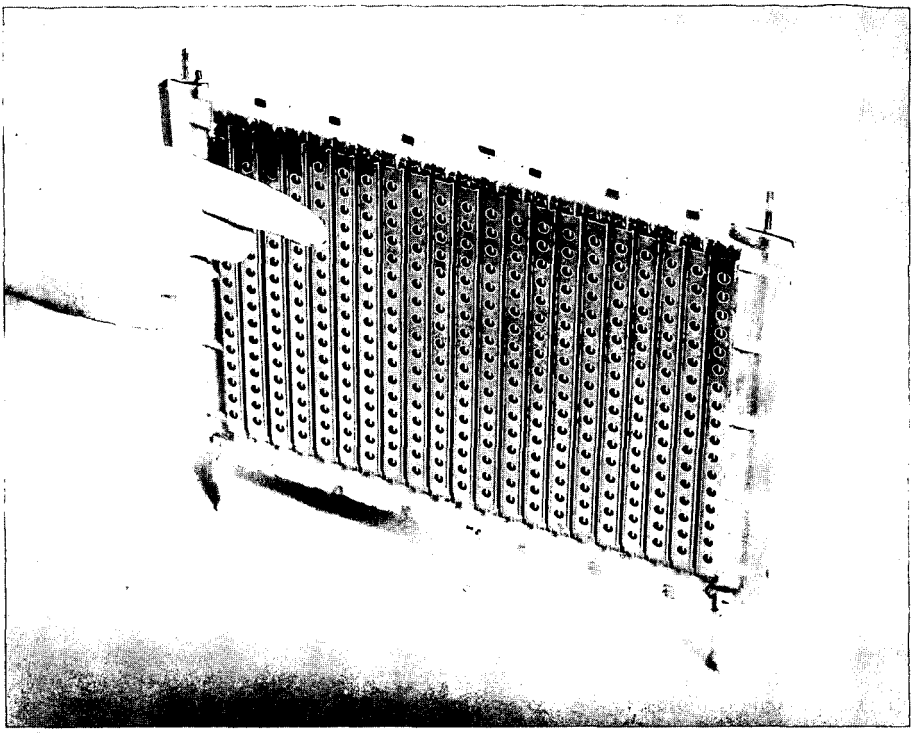


FIGURE 4
SINGLE CELL ASSEMBLY READY FOR BATTERY STACK

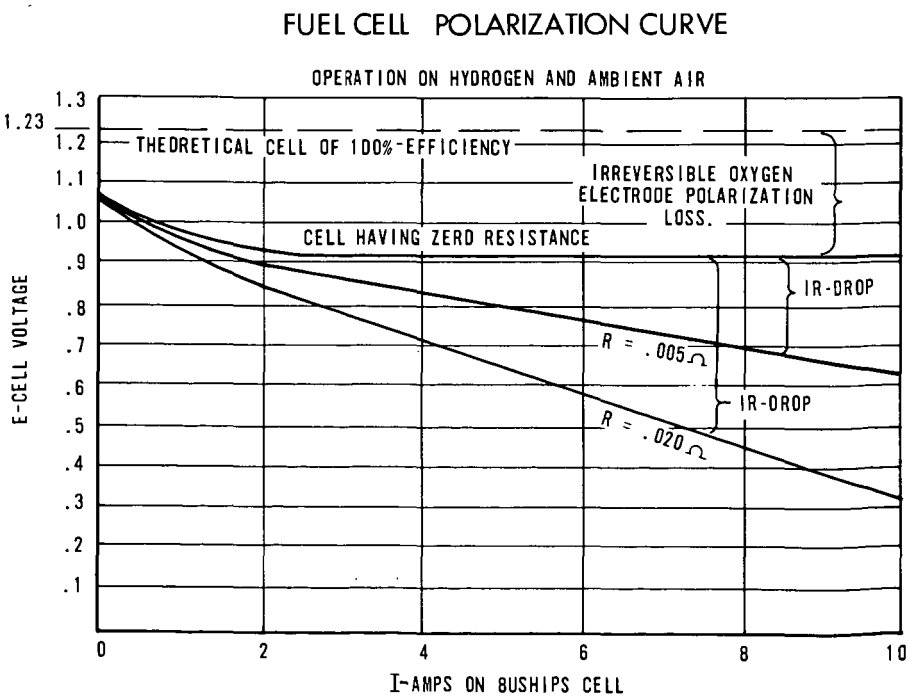


FIGURE 3

Automatic water control is provided by a wicking system that:

1. Has been designed and proven adequate for the conditions of high temperature and low humidity, where the maximum water transport is required.

2. Will transport only the required makeup water to maintain a stable system under any less severe operating condition. Since the wicks work from the bottom, there is no flooding problem because they can only lift water to areas that become less than saturated.

Figure 6 also indicates that at the lower ambient temperatures product water can be generated faster than it can be evaporated. Under these conditions it becomes necessary to reduce the air flow to prevent drowning of the catalyst. A reduction in air flow reduces the convective cooling, thus allowing the membrane temperature to rise. The air passing through the cell also takes a larger temperature rise and thus can evaporate the excess product water from the cells.

The required air flow has been determined experimentally and proven over a considerable number of operating hours at ambient conditions of 40°F. and 100 percent relative humidity.

Thus multi-cell stack operation of fuel-cells on air required detailed consideration of the heat and mass transfer problem which can only be defined experimentally in multi-cell stocks great enough to give a few cells operating in a condition free from end effects or the presence of heavy-weight testing fixtures. Sometime hours are involved in reaching steady state so transients must be considered in the analysis.

BATTERY DESIGN

Figure 7 is a schematic view of the fuel cell battery and its container, showing the cells stacked in series. A single strap clamps them together with the oxygen current of one cell in contact with the hydrogen collector of the next cell. The ribs on the air-side current collector are designed to act as springs, assuring equal pressure distribution to all points of contact with the electrode surface. The end plates are honeycombed epoxy assemblies contoured to distribute the loading uniformly across the current collectors of each cell.

The ambient air is drawn into the unit through a dry mechanical filter by a small fan powered from the fuel cell battery. The air then passes through a calibrated inlet control valve that is manually adjustable to match the air flow to the ambient temperature. The entering air is ducted to the bottom of the battery, flows up through each individual cell, and then out the exhaust.

The makeup water is introduced through a fitting in the cover. Since metal ions will contaminate the membrane, a water purification bed is included as part of the unit. This contains an ion-exchange resin bed that filters and deionizes sufficiently any potable water for use in the fuel cell.

Figure 8 is a translation of the single cell polarization curve showing voltage regulation versus output power. This indicates that inherent voltage regulation of the fuel cell power source is possible between the specification limits of 21 to 28 volts D. C. for loads between 50 and 115 percent.

Observed from the two curves in Figure 8 is a slight performance drop during an operating cycle. This amounts to approximately an 8 percent drop in output voltage. Following a half-hour rest period at open circuit conditions, the performance will recover to its original lever. This phenomenon suggests a tendency toward a concentration polarization effect typical of the presence of small amounts of free electrolyte anions in the cell.

FUEL SUPPLY

Two interchangeable fuel supply systems have been developed for the power pack, each of which will operate the 200 watt unit for approximately seven hours per charge.

In Figure 9, the unit is shown with the guard raised to reveal the bottled hydrogen system. Here, the gas is stored in a steel cylinder at 5000 psig., and is fed to the cells through a two-stage pressure regulator, reducing and regulating the pressure to 1 psig.

The hardware in Figure 10 shows the hydrogen generation system developed to utilize the reaction of sodium-borohydride and a sulfuric acid solution. The system

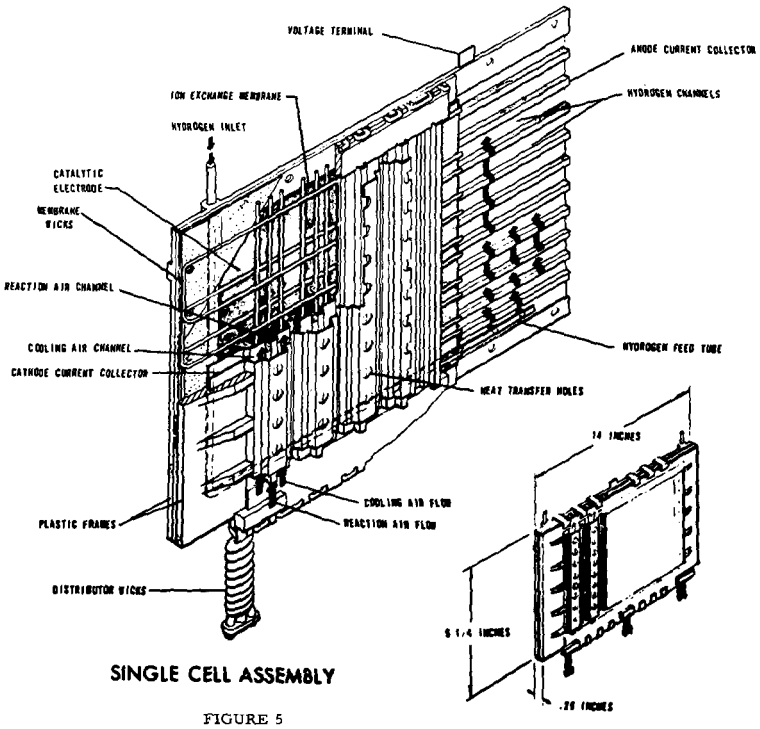


FIGURE 5
DETAILED SCHEMATIC OF SINGLE CELL ASSEMBLY

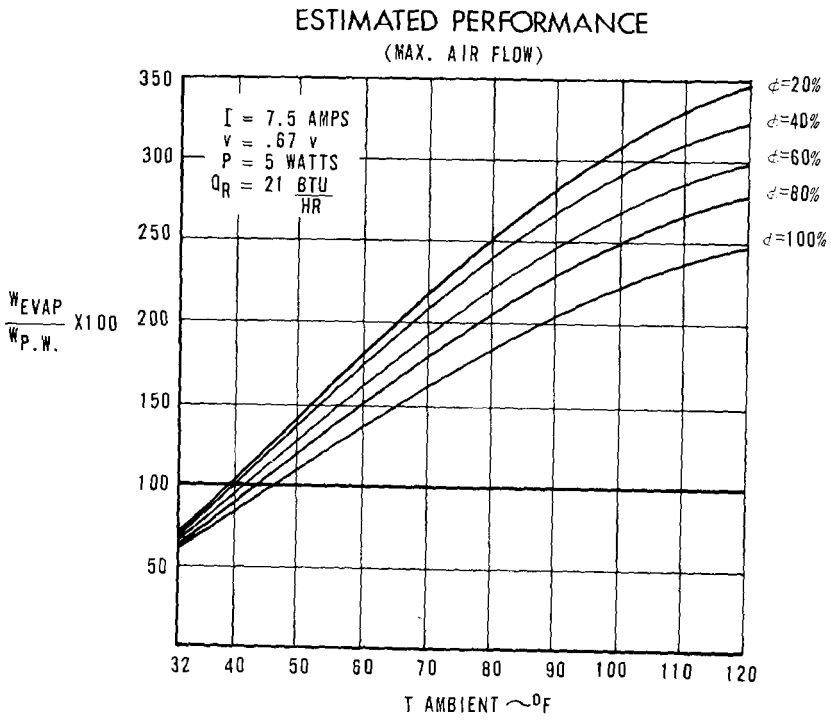


FIGURE 6
ESTIMATED EFFECT OF AMBIENT INLET AIR HUMIDITY AND TEMPERATURE ON MAKE-UP WATER REQUIREMENTS

consists of a two-part tank or canister containing the sodium borohydride in pellet form in the top section and the acid solution in the bottom. The surge tank is also made in two parts.

Gas generation is started by stroking the primer assembly to force the first charge of acid into the borohydride. The gas is accumulated in the surge tank and fills up the displacement volume. Once the system is started, a reference pressure is maintained through a regulator to the acid chamber. As the gas is consumed by the cells, and the pressure in the top half of the system drops below the reference pressure in the bottom half, a quantity of acid will be forced into the chemical. The generation of gas will build up the pressure again, closing the check valve until the next demand signal.

This boot-strap pressurized system generates hydrogen only upon demand, and operates at pressures sufficient to produce good acid distribution to the chemical and to prevent internal components from clogging. The principal purpose for using an acid solution is to depress the liquid freezing point to -65°F. The chemical canister is equipped with a hand-operated blow-down valve and quick disconnect fittings for easy replacement of spent canisters.

Currently, a 700 gram charge of sodium borohydride and a 1300 cc charge of sulfuric acid is consistently producing 50 cubic feet (S. T. P.) of hydrogen gas. This performance represents approximately an 85 percent utilization of the sodium borohydride with 155 percent of the theoretical acid solution requirements. The purity of the hydrogen gas generated has been measured as 99.8 percent with water vapor as the remaining constituent.

LIFE AND RELIABILITY

Life and reliability testing has produced encouraging results and has also contributed a great deal of information toward the better understanding of the elements affecting cell life. At this time, a number of the small 1.8 square inch area cells are running after two years of continuous operation. Several stacks of the large air-breathing cells have operated for 500, 650, and 750 hours. Many cells have also been operated for some 60 hours without failure at ambients of 120°F. and 15 percent relative humidity.

As will happen in the evolution of any new product or process, problems have been encountered during the process of cell development and evaluation. Examples of the problems that have been encountered and solved include:

1. Metal corrosion and ion contamination of the membrane.
2. Bonding of the membrane to the plastic frames.
3. Uniform hydrogen distribution throughout the cell.
4. Wicking configuration and wicking materials.

Currently underway is an extensive program of life and reliability testing that will provide greater understanding of the effects of current density and temperature on the life of the cells. Concurrently, an evaluation test of a complete power source is being run.

FUTURE IMPROVEMENTS

Before summarizing this paper, a few comments concerning recent laboratory work with improved electrochemical cells are in order. These improved large cells possess the higher performance curves of volts versus amps shown in Figure 3.

Usually, such curves as shown in Figure 3 are split into an ohmic polarization loss and the two electrode polarization losses. With a nearly reversible hydrogen electrode, almost all the electrode losses occur on the oxygen or air side. At low current densities, the oxygen and air electrode losses are nearly the same for these catalytic electrodes having a thickness of only 50 microns. At higher current densities the presence of nitrogen in the case of air begins to be noticed. But in contrast, the better electrode polarization curves for oxygen operation continue in a nearly flat slope up to current densities over 100 ma./cm^2 at values just over 0.9 volts with respect to a hydrogen (N. H. E.) reference. Thus for air or oxygen operation in the range of present interest, these ion-exchange fuel-cells are being run in a region where internal ohmic resistance controls the power density obtainable at any selected fuel-utilization efficiency or output voltage.

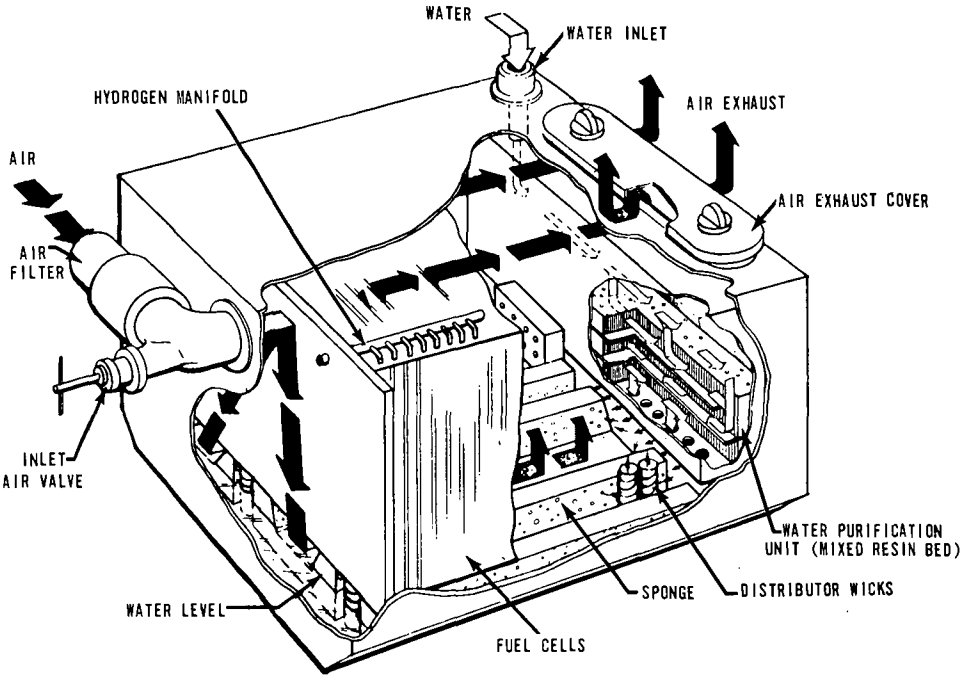


FIGURE 7
SCHMATIC OF POWER-PACK BATTERY-STACK OPERATION ON AMBIENT AIR

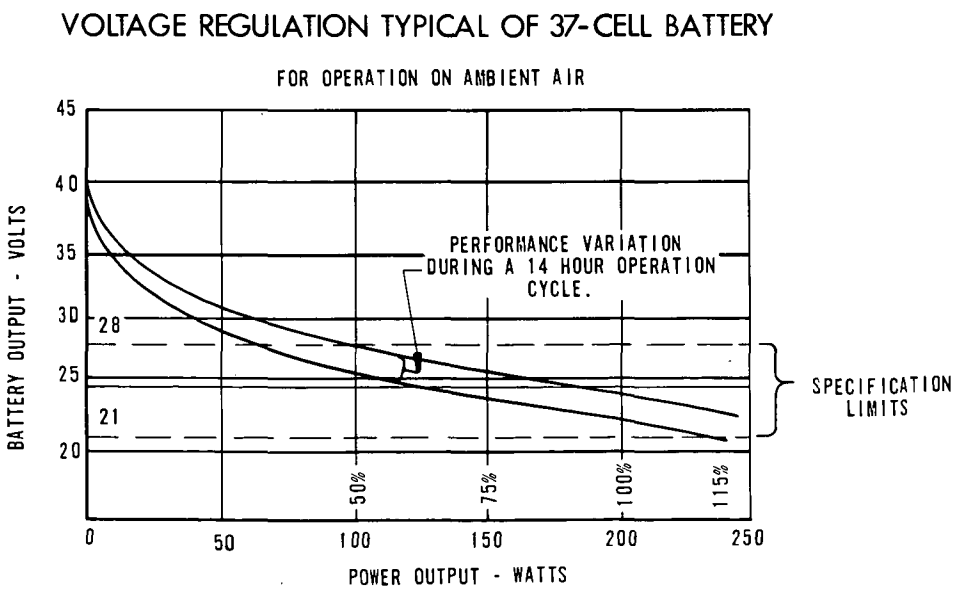


FIGURE 8

During the past year, straight-forward developments in membrane construction have cut our first air-operating cell-resistance by a factor of four. This difference has been demonstrated on several hundred cells of both types made in our laboratory pilot plant. This favorable decrease in resistance has resulted in an increase in performance which may be taken advantage of in two ways. One way would be to increase power output by a factor of two at the same fuel efficiency; the other being to decrease heat rejection by just over 25% at the same power density. Actually, it is usually decided to operate at a point between these two extremes.

Present laboratory programs show on some small cells that we have been able to nearly halve this internal resistance again while obtaining better physical properties.

SUMMARY

The complete 200 watt power source in the present development stage contains 37 cells, measures 12 x 15 x 24 inches and weighs 60 pounds. Included is the 13.5 pound hydrogen generation system that will operate the unit at full load for seven hours.

The feasibility of a small, portable, air-breathing fuel cell power source with an integral hydrogen generation system has been demonstrated in General Electric's 200 watt development program. This program has shown that the ion-exchange membrane fuel cell has the potential for long life air-breathing operation with satisfactory operation at ambient temperatures from 32 to 120°F. and relative humidity from 15 to 100 percent.

We recognize that some further development work is indicated to develop this unit into a piece of practical field hardware. Additional effort is required to evaluate and develop the capabilities of the power supply system to satisfy the requirements of low temperature operation and the appropriate handling, storage, and environmental conditions. Further analysis and evaluation will be required to develop a greater understanding of the heat and mass transfer characteristics of an evaporatively cooled air-breathing fuel cell. Additional life testing of small stacks and 200 watt fuel cell batteries must be run to develop further statistical life and reliability data.

Currently in laboratory development are some new polymer systems showing considerable promise toward superior physical properties, lower internal resistances, and long term stability. It is projected that current desnities may be doubled with the use of the new polymer systems, resulting possibly in a 200 watt air-breathing power source weighing 42 pounds and operating for about 12 hours on one charge of chemical in the hydrogen generator.

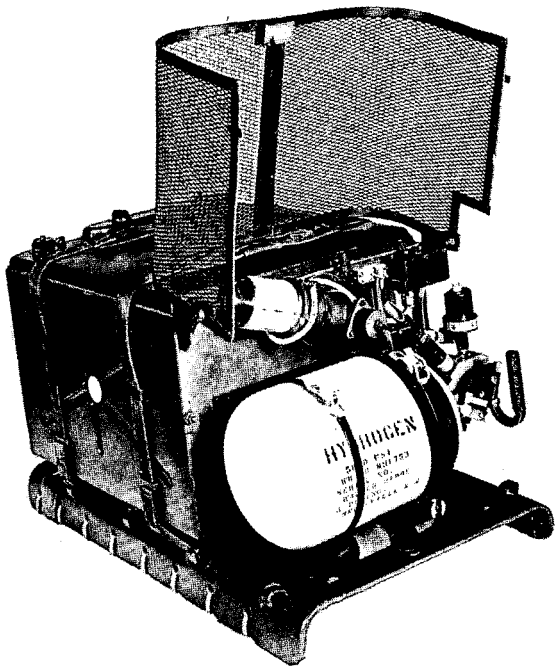


FIGURE 9
END VIEW OF POWER-PACK SHOWING HYDROGEN PRESSURE-BOTTLE GAS SUPPLY

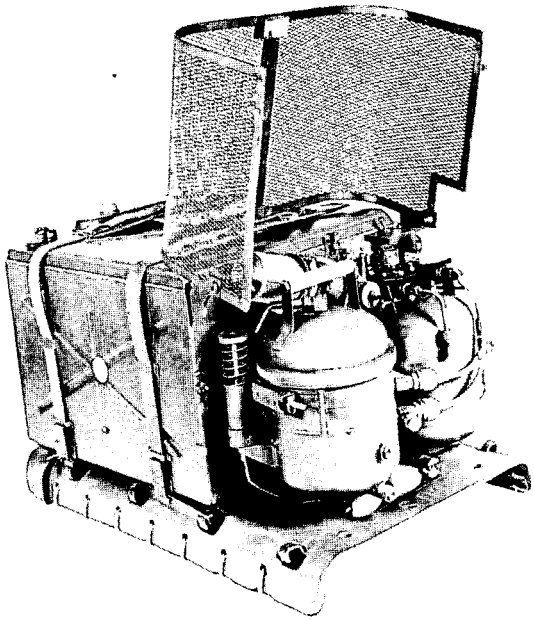


FIGURE 10
END VIEW OF POWER-PACK SHOWING HYDROGEN CHEMICAL-GENERATOR WITH RENEWABLE CANISTER AT LEFT CORNER

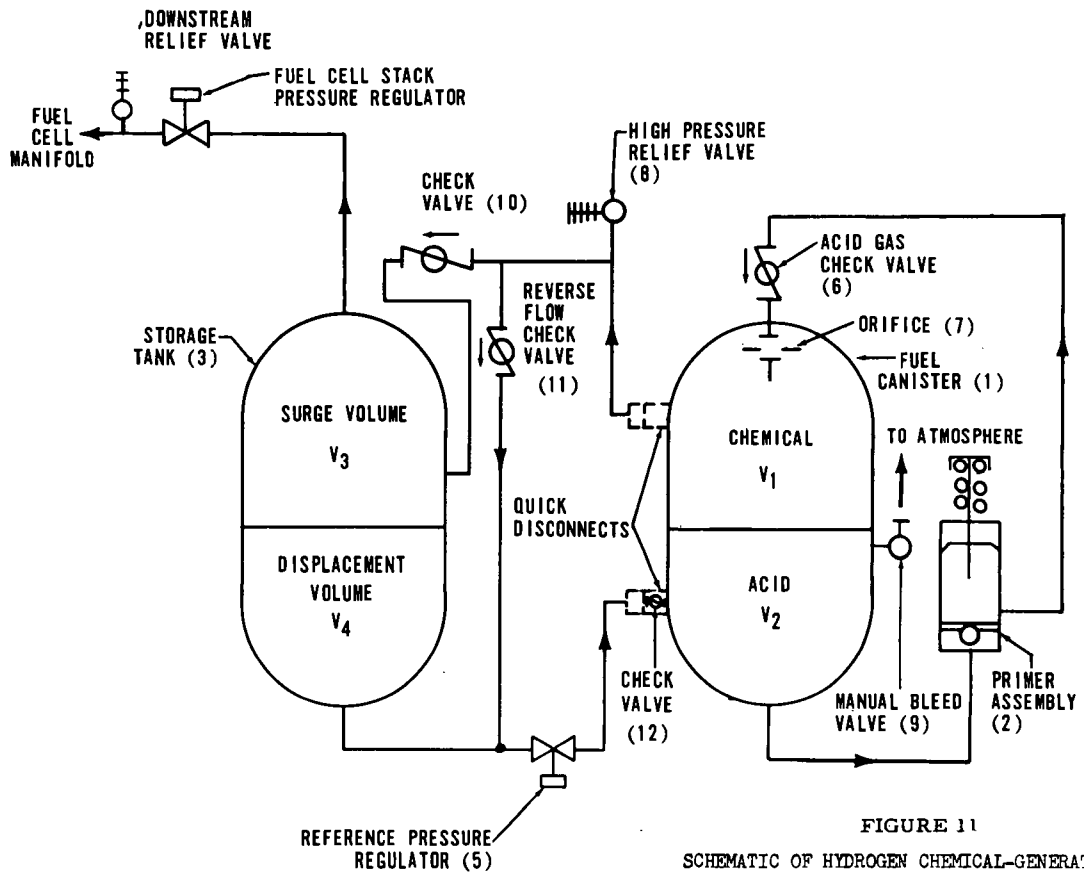


FIGURE 11

SCHEMATIC OF HYDROGEN CHEMICAL-GENERATION SYSTEM